Introduction: Measuring uplift and erosion – proposal for a terminology

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To avoid confusion in further discussions concerning uplift and erosion a number of terms are defined, e.g. uplift of rocks, tectonic and isostatic uplift, surface uplift, net uplift and erosion. A proposal for a Norwegian terminology is also presented. The terminology is discussed with reference to a hypothetical subsidence/uplift history relevant to the Norwegian shelf. Further aspects of Late Tertiary uplift and sedimentation in Norway are discussed in relation to two regional profiles: one from northern Norway and the Barents Sea and one from Telemark to the Central Graben.

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This volume of *Norsk Geologisk Tidsskrift* comprises presentations from the 7th TSGS conference in Stavanger (1990), where post-Cretaceous uplift and subsidence, erosion and sedimentation were discussed. A considerable amount of research has been focused on this topic in the last few years, but in spite of that many aspects of the Tertiary and Quaternary vertical movements of Scandinavia are not yet understood. As an introduction to this volume we discuss the methodology used for measuring, and propose a terminology for the basic concepts of uplift and erosion. Hopefully this will facilitate further discussion.

Terminology of uplift and erosion

This proposal for a terminology of uplift and erosion is based on the definitions and discussions of Brown (1991), Molnar & England (1990) and England & Molnar (1990). The confusion in the literature arises from the fact that 'uplift' is used in different senses (England & Molnar 1990). Two types of uplift have to be clearly distinguished. These are:

1. *Uplift of rocks* (U), which refers to the vertical movement of a rock body or marker horizon with respect to a given datum. U is the difference in elevation with respect to the chosen datum at a given point at two different instants in time. Upward movement is positive (i.e. uplift, *Norwegian: heving*), downward movement is negative (i.e. subsidence, *Norwegian: innsynkning*). Uplift (subsidence) of rocks can be due to different causes and the parameter U can be subdivided into components according to the different effects. For instance, *tectonic uplift* (Ut) is the component of uplift in response to tectonic forces or temperature changes, whereas *isostatic uplift* (Ui) is the component of uplift in response to loading (or unloading) of the Earth's crust. In the following we use mean sea level (approximately the geoid, see England & Molnar 1990) as our reference datum. This means that the complicating factor of eustatic sea level change does not enter into the discussion. Also, we have not taken compaction of sediments into account. A hypothetical uplift/subsidence curve of this type is shown in Fig. 1.

2. *Surface uplift* or surface rise (R), which refers to the vertical movement of the Earth's surface (sea bottom or land surface) with respect to a given datum. R is the difference in elevation with respect to the chosen datum at a given point at two different instants in time. Using mean sea level as datum, a hypothetical variation of surface height/depth with time is shown in Fig. 1.

As shown by England & Molnar (1990), the difference between the uplift parameter U and the uplift parameter R is a measure of the *erosion/deposition* (what they call 'exhumation') according to the equation:

$$U = Ut + Ui = R + E \quad \text{and} \quad R = Ho - Hi \qquad (1)$$

where E is the change in the thickness of overburden above the marker horizon at a given point at two different instants of time. Decreasing thickness of overburden (i.e. erosion, *Norwegian: erosjon*), which can be submarine or subaerial, is positive here, whereas increasing thickness of overburden (i.e. deposition, *Norwegian: avsetning*) is negative. In the hypothetical example of Fig. 1, E can be obtained by plotting the difference between the two uplift/subsidence curves. Ho is the present elevation and Hi is the initial paleo-elevation.

Unfortunately, rocks contain no precise paleo-altimeters, and for practical measurements of uplift we are often confined to a thermal or sediment compaction frame of reference. To relate these frames of reference to the sea level, we often need additional independent information

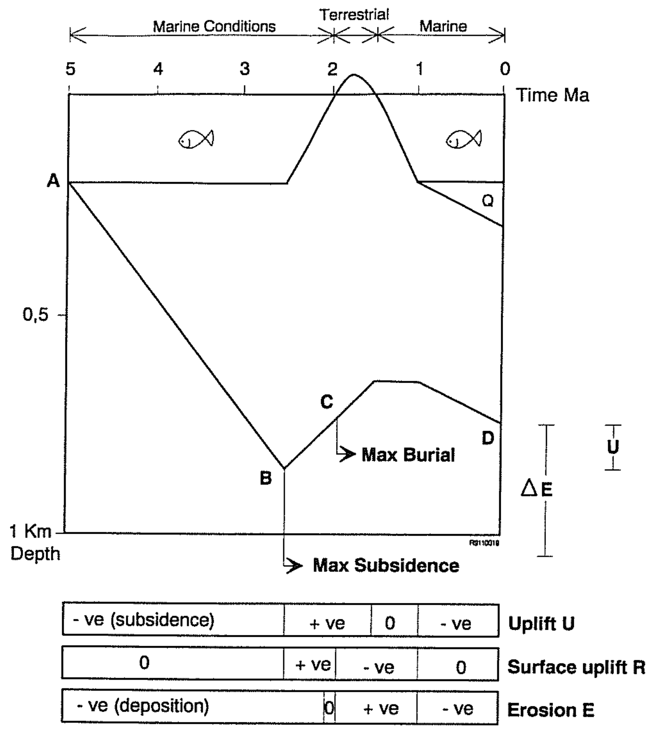

Fig. 1. A hypothetical subsidence/uplift curve (ABCD) for a marker horizon deposited 5 m.y. ago, together with a surface subsidence/uplift curve. Points B and C show maximum subsidence and maximum burial respectively. Q is Quaternary sediments. Indicated at the base of the figure are the times uplift, surface uplift and erosion were positive, negative or zero. The erosion before 1 Ma is indicated with a vertical bar ΔE and the uplift between points B and D is labeled U.

about paleo-elevation. In a thermal frame of reference, erosion is called *denudation* (Brown 1991), and methods such as apatite fission-track analysis (AFTA, Green 1989, Brown 1991), vitrinite reflectance trends (Jensen & Schmidt, this volume) and fluid inclusion studies (Walderhaug, this volume) are used to quantify the erosion. In a sediment compaction frame of reference we measure erosion (i.e. missing overburden) relative to a set of standard compaction curves (Magara 1976; Sclater & Christie 1980).

In addition to the above terminology and definitions, some useful terms are described below.

Denudation and exhumation (*Norwegian: blottlegging*): The process of erosion seen in a thermal (denudation) and general overburden (exhumation) frame of reference.

Maximum burial and maximum subsidence (*Norwegian: maksimal begravning og maksimal innsynkning*): Maximum burial refers to the maximum overburden of a marker horizon, whereas the maximum subsidence refers to the minimum altitude of this horizon. The time of maximum burial (i.e. overburden) is not necessarily equal to the time of maximum subsidence measured from sea level (Fig. 1).

Net uplift (*Norwegian: netto heving*): A quantity introduced by Nyland et al. (in press) and Jensen & Schmidt (in press), who define net uplift as the difference between maximum burial and the present elevation of a marker bed. This parameter is easier to calculate and to contour than erosion. Net uplift may be a useful parameter, in particular in basin modelling studies where the main concern is maturation of source rocks, so that absolute elevations and water depths are not of primary importance. In a marine setting (like offshore Norway) the maximum difference between net uplift and true uplift (U, eq. 1) is the water depth at onset of uplift of the marker horizon (point B, Fig. 1).

Some of the complications inherent in Eq. 1 are illustrated in Fig. 1, which shows the uplift/subsidence history of a hypothetical marker horizon deposited five million years ago, together with a possible surface uplift/subsidence curve (change in depth below, or height above mean sea level). The following points should be noted: (1) Under marine conditions, deposition may continue after the time of maximum subsidence. This means that the time of maximum burial is not necessarily the time of maximum subsidence. (2) Similarly, erosion may take place during periods of subsidence or static conditions as well as in periods of uplift. In our hypothetical case, the period of static conditions is accompanied by considerable submarine erosion by shelf ice. At 1 m.y. deposition resumes due to the retreat of the ice (Quaternary sediments, Q on Fig. 1). (3) Net uplift may differ from both eroded thickness (E) and from the uplift (U). In Fig. 1, net uplift is zero. This illustrates that the net uplift should not be confused with the eroded thickness (e.g. the reduction in thickness of the overburden) or with the uplift (e.g. the decrease in depth of the marker bed).

Methods

Table 1 shows the methods used to quantify uplift and erosion. The regional methods are used on uplift and erosion in a given drainage area, while the local methods are used to calculate uplift and erosion in single wells.

Table 1. Methods used to quantify uplift and erosion.

REGIONAL METHODS (analysis of map, profile and velocity data)
Subcrop maps
Extrapolation from seismic profiles
Geomorphology and paleogeographical reconstructions
Seismic velocity analysis
LOCAL METHODS (analysis of rock parameters and well data)
Shale compaction (sonic velocity, density, porosity)
Sandstone porosity and diagenesis
Clay mineral diagenesis
Vitrinite reflectance trends
Colour of microfossils (TAI)
Organic geochemistry (pyrolysis data, geochemical markers)
Fluid inclusion analysis
Fission track studies
Opal A – Opal CT – quartz transformations
PVT modelling of hydrocarbon accumulations
Drilling parameters (Dx component)
Kinetic modelling

Local methods

Calculations of uplift and erosion by the local methods are based on the physical and chemical changes caused by burial. In general, temperature and lithostatic pressure (sediment compaction) are the most important factors causing these changes. Therefore, the local methods give an estimate of the maximum paleo-temperature and/or overburden. The maximum overburden may be calculated using well/reference well methods (e.g. Magara 1976) or kinetic modelling (e.g. Forbes et al. 1991). Since we are concerned with overburden, the zero level used for the calculations is the ground surface or the sea floor.

To obtain reliable results using local methods one must establish a reference well which is lithologically similar to the studied well and which has a similar geological history. Also, one must be confident that the temperature gradient of the reference well at present is similar to the temperature gradient of the studied well at its maximum burial, and that the compaction trends were similar (e.g. no overpressure).

Kinetic modelling is a method commonly applied to geochemical reactions in sedimentary basins (e.g. Forbes et al. 1991). In such modelling paleo-temperatures are a major factor of uncertainty. In addition, the present temperatures may not be in equilibrium with the heat flow at depth. In eroded areas temperatures should be slightly higher than expected from the heat flow through the crust, and in areas with rapid deposition temperatures should be lower.

Regional methods

The mass balance method was important in establishing the large amount of glacial erosion in the Barents Sea (Nøttvedt et al. 1988; Eidvin & Riis 1989; Vorren et al. 1990). In this method, the volume of the clastic sediments of a given age in a depocenter is compared with the size of the eroded drainage area. The method gives a qualitative idea of the average amount of erosion in the drainage area. The major uncertainties of this method are discussed by Vorren et al. (1990).

The paleogeographic reconstruction method is used by Riis & Fjeldskaar (in press) and Doré (this volume). This method can be used regionally or on profiles to estimate the eroded section. The simplest way of applying the method is to extrapolate the dipping and eroded Mesozoic and Cenozoic strata to the onshore and measure directly how much has been eroded along the depth-converted profile.

The regional methods (except for seismic velocity analysis) differ from the local methods in that the eroded section is measured directly (in m or m^3), while in the local methods erosion is inferred from rock parameters. Regional methods should therefore always be used together with local methods to ensure geological control on the interpretation.

Post-Cretaceous vertical movements of the Norwegian shelf

Many of the papers presented in this volume give examples of Tertiary and Quaternary vertical movements, and these observations fit into a regional picture. The western parts of Fennoscandia and the Barents Sea were uplifted 1000–2000 m in the Tertiary and Quaternary to form structural domes and platforms which were strongly eroded. Deposition of the erosional products took place on the subsiding parts of the shelf and at the shelf margin. The Paleozoic to Cenozoic sedimentary cover shows a gentle dip away from this basement-cored dome in Scandinavia. This is illustrated in two key profiles (Figs. 2 and 3).

Figure 2a, b shows the relationship between basement and the sedimentary cover in a profile across the southwestern Barents Sea. The profile is based on Gabrielsen et al. (1990) and Sigmond (in press). The Pliocene–Pleistocene Bjørnøya wedge covers the western part of the profile, and the eroded Tertiary and pre-Tertiary strata is seen to the east. The dotted line (Mo) shows the amount of erosion based on vitrinite and pyrolysis data from wells, as well as on seismic interpretation of the opal A to CT transition (Riis & Fjeldskaar, in press). There are no data from the Finnmark Platform and the onshore area. It is interesting, however, that the surface defined by the missing overburden line fits so well with the base of the Pliocene to the west and with the highest mountains to the east. The profile also shows that the Permian and Triassic strata on the Finnmark Platform have such a dip that they can be extrapolated onshore to reach a level slightly higher than the highest mountains.

These observations suggest that much of the dip in the Tertiary section is related to an isostatic response to the Plio-Pleistocene erosion, and that the coastal parts of Finnmark were covered by Paleozoic and Mesozoic sediments before the Neogene and Quaternary uplift. There also seems to be a relationship between the amount of erosion offshore and the summit level of the mountains onshore. The subsidence curves (Fig. 2b) illustrate the importance of the major Late Cretaceous and Eocene tectonic phases as well as the Plio-Pleistocene erosion and deposition.

Figure 3a, b shows the relationship between basement and sedimentary cover in a profile from the Central Graben, across the Farsund Basin to the central part of southern Norway. The profile is modified from Jensen & Schmidt (in press). The Neogene depocentre in the central North Sea covers the western part of the profile, and from location 2 (Fig. 3b) the Neogene uplift and erosion increases towards the Norwegian coast. The dotted line (Mo) shows a reconstruction of the eroded strata. The magnitude of uplift and erosion is based on vitrinite reflectance data and shale compaction from wells along the profile. From reconstruction of the eroded strata it is evident that Mesozoic sediments must have covered the coastal parts of southern Norway. The Late Cretaceous

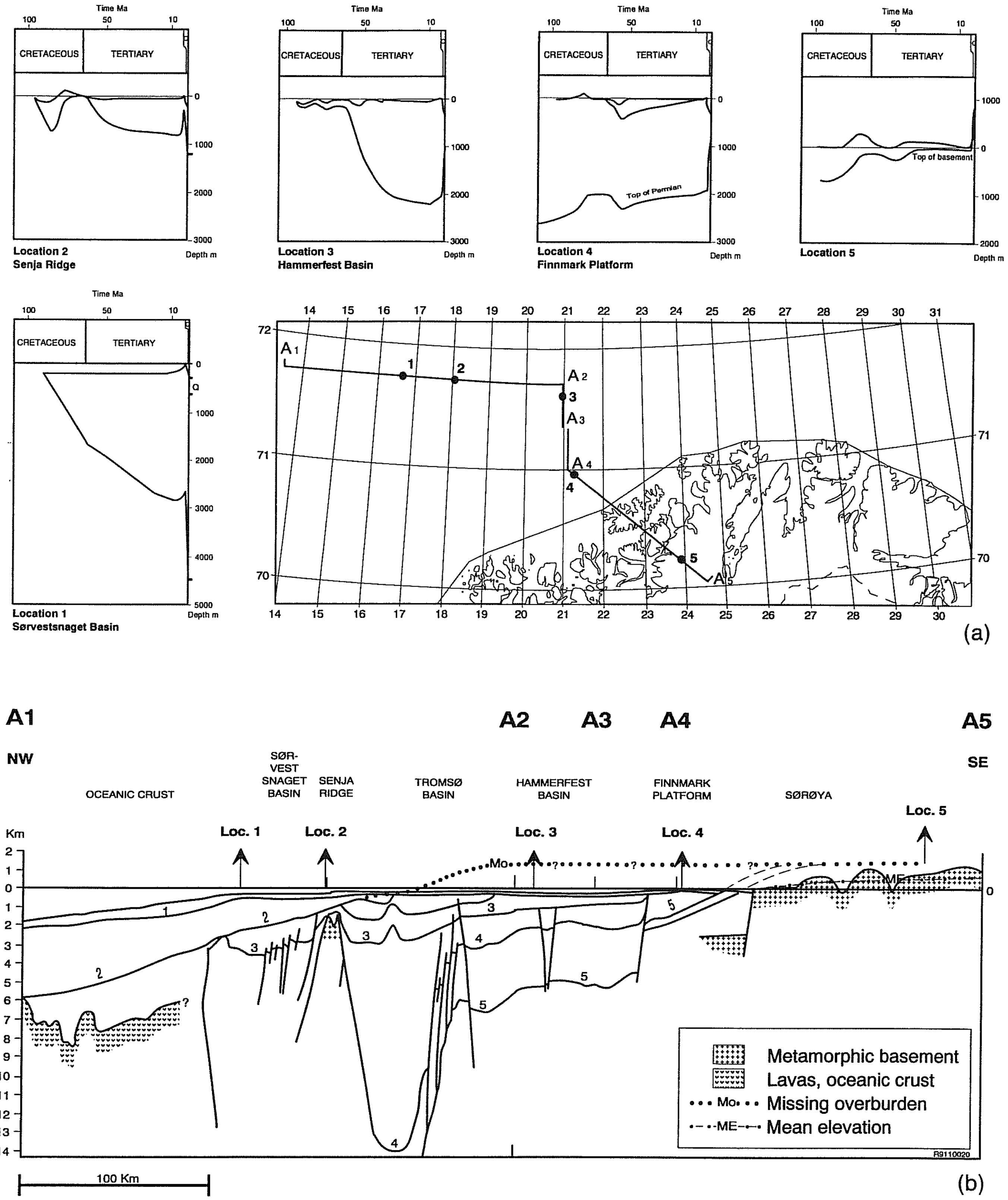

Fig. 2. (a) The location of the regional profile across the Barents Shelf and the subsidence history at five locations along this profile. (b) A regional profile across the Barents Shelf to Sørøya, Finnmark. The five locations shown as subsidence diagrams (Fig. 2a) are indicated. Reflectors: 1 – Base Quaternary, 2 – Base of Upper Pliocene, 3 – Base Tertiary, 4 – Base Cretaceous, 5 – Base Triassic. Depth in km.

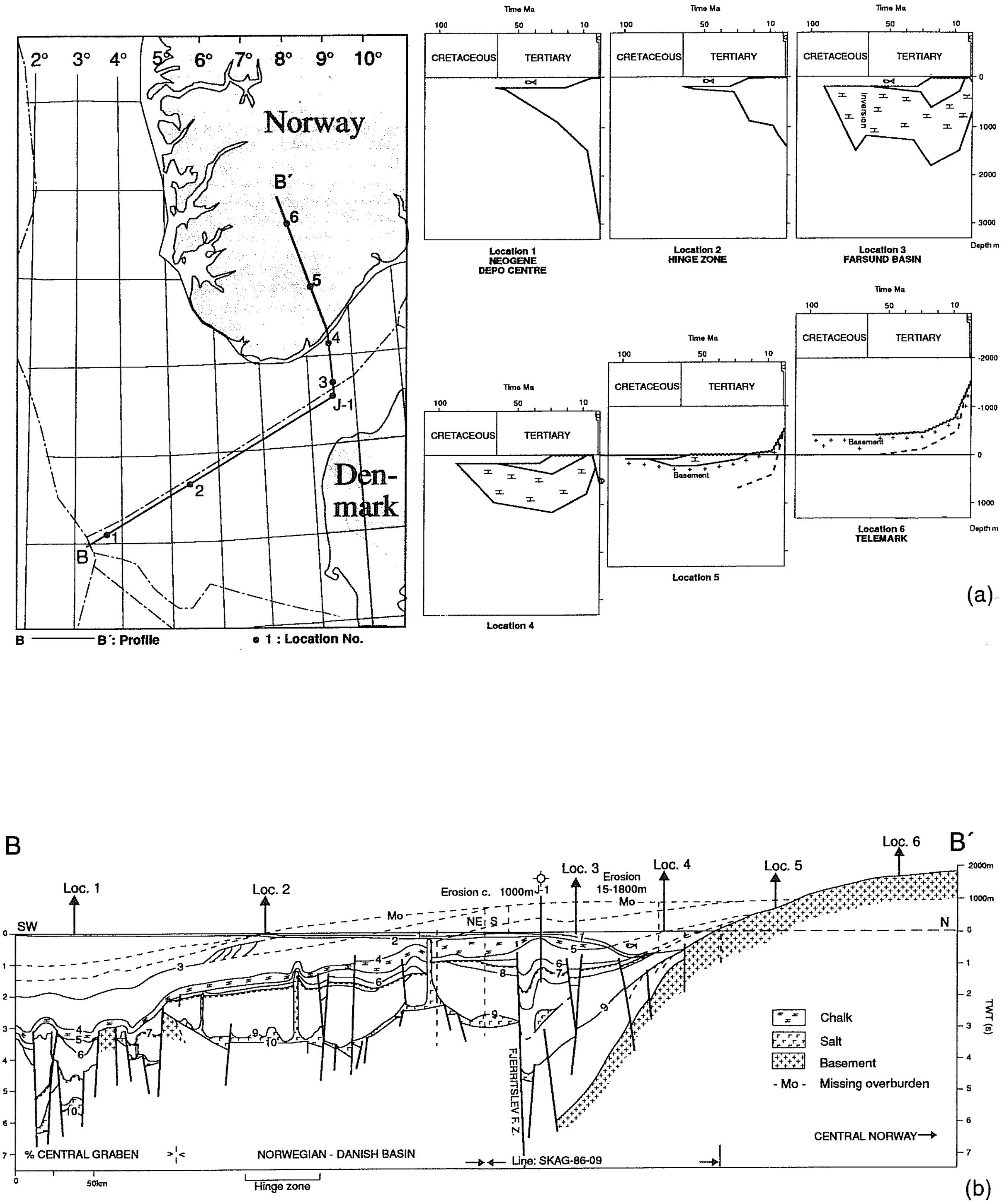

Fig. 3. (a) The location of the regional profile across the central North Sea and southern Norway. The subsidence history at six locations along this profile is also shown. (b) A regional profile across the central North Sea and southern Norway. The six locations shown as subsidence diagrams (Fig. 3a) are indicated. Reflectors: 1 – Sea bed, 2 – Base Quaternary, 3 – Base Neogene, 4 – Base Tertiary, 5 – Base Chalk, 6 – Base Cretaceous, 7 – Middle Jurassic unconformity, 8 – Base Jurassic, 9 – Base Triassic, 10 – Top Pre-Zechstein, Depth in two-way travel time, height in meters.

and Tertiary subsidence/uplift history of six locations along the profile are shown in Fig. 3a.

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