Present uplift rates and groundwater potential in Norwegian hard rocks

ERIK ROHR-TORP

Rohr-Torp, E. 1994: Present uplift rates and groundwater potential in Norwegian hard rocks. *Nor. geol. unders. Bull. 426,* 47-52.

The postglacial isostatic uplift of Fennoscandia is here regarded as the most important factor in keeping fractures open for groundwater flow in Norwegian hard rock aquifers. The present rate of uplift is assumed to represent a measure of the total uplift of an area. The greater the uplift, the more tectonic disturbance is created, and the more open are the fractures. To test the theory, five areas in the Precambrian of southern Norway with different yearly uplifts, and containing a total of 1278 drilled wells have been considered. A linear relationship is found between depth and water yield in the wells and the yearly isostatic uplift. This is hardly coincidental, and it is proposed that further work should be performed as a joint project between the Scandinavian countries.

Erik Rohr-Torp. Norges geologiske undersøkelse Oslokontoret, P.O. Box 5348 Majorstua, N-0304 Oslo, Norway.
Present address: Asplan Viak AS, Storgaten 8, 3600 Kongsberg, Norway.

Introduction

The matrix of unweathered hard rocks, between faults, fractures, joints and fissures (henceforth called fractures) is regarded as impermeable for practical water-resources purposes. The exploitable porosity and permeability of hard rocks is thus overwhelmingly controlled by the existence of fracture systems. Natural fracture systems can be exceedingly complex and have been created during various periods of tectonic disturbance throughout the Earth's history. Furthermore, most of the systems have been reactivated several times due to younger disturbances. Marked periods of tectonic activity younger than the Precambrian in Norway occurred during: (1) The Caledonian orogeny, approximately 425-400 Ma B.P.; (2) Permian activity in Southeast Norway, c. 250 Ma; (3) Tertiary uplift, most prominent in western Norway, at c. 60 Ma.

It is a common opinion among Norwegian hydrogeologists that the youngest fracture systems are the most permeable. In other words, a Permian fracture system is considered more open than a Caledonian fracture system, and is generally believed to give higher yields in drilled wells (Englund 1980). This may be partly true, but even 'young' fractures formed during the Tertiary uplift have existed for approximately 60 million years. Fractures from this period have had the possibility of transporting solutions over an extremely long period of time, during which they may have been subject to e.g. chemical alteration or precipitation. The possibilities of being tightened by secondary mineralisations are equally as great as for a Precambrian fracture system.

Glaciation and isostasy

The Weichselian glaciation, the last of at least four glaciations in Fennoscandia, started more than 100,000 years ago. Climatic changes caused large variations in the thickness and extent of the ice, but at c. 17,000 - 21,000 B.P. the ice-sheet reached its maximum extent with its southern margin in northern Germany and Denmark. In its central parts, the thickness of the ice was probably up to 3,000 m. From that maximum, the ice-sheet started to melt, the margin withdrew, and the thickness decreased. The coastal areas of Norway were the first to become deglaciated some 10,000-11,000 years ago. The final deglaciation of the central parts happened rapidly, and at c. 8,500 years ago most of Fennoscandia was ice-free (Lebesbye 1989).

The weight of the ice had caused an isostatic depression of the Fennoscandian crust. As the ice melted, this depression was gradually compensated by an isostatic uplift or 'rebound'. In general, contours of the postglacial uplift have a dome-like shape with its maximum located in the Gulf of Bothnia, coinciding with the maximum thickness of the ice-sheet. Thus, the uplift was

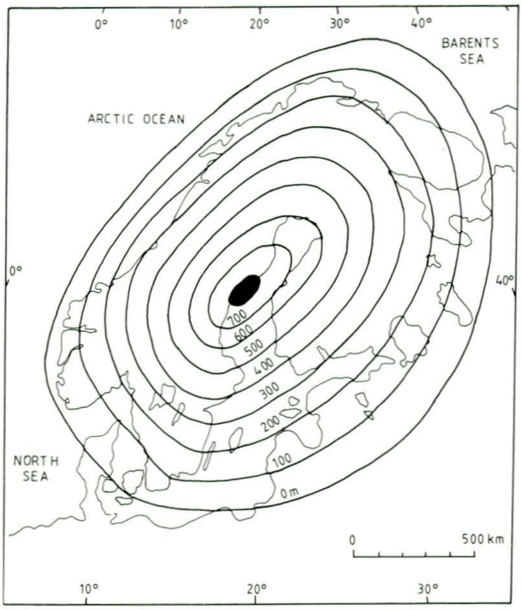

Fig.1.100 m contours for the Fennoscandian 'postglacial' absolute uplift. Minor irregularities occur, especially in the Skagerrak - South Norway region and in the central Baltic Sea. After Mörner (1980).

greater in the eastern parts than in the coastal areas of southern Norway.

For this first approach in looking for a possible correlation between postglacial uplift and groundwater potential, the above general picture of the uplift seems relevant. However, the form and nature of the uplift is more complex, due to the fact that also a non-glacial component may be incorporated in the crustal movements, as pointed out by Anundsen (1989), Roberts (1991) and Olesen et al. (1992).

By extrapolating the 13,000 B.P. palaeoshoreline curves from the margins of Fennoscandia into the centre of the uplift, and by assuming a global uniform eustasy of 120 m, Mörner (1980) constructed a contour map of the absolute 'postglacial' uplift in Fennoscandia. His map is shown in Fig. 1.

The glacio-isostatic uplift started well before the land was ice free, reached its maximum of up to 0.5 m a year in the Gulf of Bothnia when the land was deglaciated (Mörner 1978, 1980), and has since decreased to less than 10 mm a year today. Mörner (1980) claimed that the total uplift at the centre in the Gulf of Bothnia is 800 - 850 m, and that the uplift started approximately 13,000 years ago. This is a dramatic geodynamic process occurring over a very short period of time.

Fracturing

The very recent and brief glacio-isostatic uplift must have been associated with considerable changes in stress and strain rates in the crust, and seismic activity, fracturing and reactivation of old fracture systems are to be expected. The most active period was at the time of deglaciation, and the presence of several late- or postglacial faults are well documented in Fennoscandia (Madsen 1917, Grønlie 1922, Du Rietz 1937, De Geer 1938, 1940, Bergsten 1943, Kujansuu 1964, Feyling-Hanssen 1966, Mörner 1969, 1972, 1975, 1977, Lundqvist & Lagerbäck 1976, Flodén 1977, Lagerlund 1977, Lagerbäck 1979, 1990, Bakkelid 1986, Olesen 1988, Sollid & Tolgensbakk 1988, Anundsen 1989, Bäckblom & Stanfors 1989, Roberts 1991, Olesen et. al. 1992). Most of these faults are old regional fault zones which have been reactivated. Postglacial displacements of up to 30 m have been described (Muir Wood 1989). Johnston (1989) concluded that: "An ice-sheet will inhibit earthquakes by stabilising potentially seismogenic faults in the underlying brittle crust. This same mechanism may also provide an explanation for the intense late-glacial faulting in Fennoscandia".

Reactivation of ordinary fracture systems and formation of new fractures are more difficult to identify, but there is every probability that such processes took place quite extensively during the postglacial uplift. The dome-shaped uplift must have created an horizontal extension within the crust, both radially and concentrically with respect to the centre of uplift. According to Mörner (1978, 1980), the late glacio-isostatic uplift of Fennoscandia was drastic and rapid compared to long-term events like, for instance, the Caledonian orogeny. He related the intense fracturing of Swedish bedrock to the deglaciation period, with its peak activity at c. 8,000 B. P. Furthermore, similar deglaciations and glaciations took place at several times during the last 100,000 years, thus providing possibilities for the repeated reactivation and formation of fractures over this period of time.

Relevance to hydrogeology

It seems to be generally accepted that there is a good correlation between the general uplift pattern for the last c. 8,000 years and the present uplift rates in Fennoscandia (Balling 1980, Bjerhammar 1980, Mörner 1980). Fig. 2 shows the present estimated crustal uplift in mm/year in relation to mean sea level for southern Norway (Sørensen et al. 1987). By assuming that the present uplift reflects the total amount of postglacial uplift, small in the costal areas and high in the eastern parts, the greatest postglacial changes in stress and strain are to be expected in the eastern parts. This again should be reflected in a higher density of new and reactivated fractures, and generally higher yields in drilled wells in the eastern than in the coastal parts of Norway.

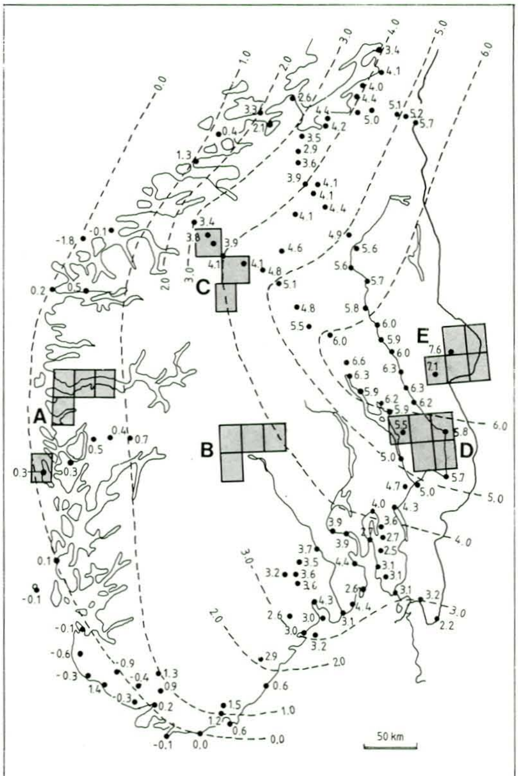

Fig. 2.Estimated annual land uplift (mm/year) relative to mean sea level for southern Norway. After Sørensen et al. (1987). A-E show map-sheets for the five areas considered in the text.

The Geological Survey of Norway has information on approximately 20,000 drilled wells in Norway. To test the above theory, five areas in southern Norway with a high density of drilled wells and with different yearly uplifts were selected, all of them in Precambrian rocks, mostly gneisses, granites and amphibolites. The areas (A - E), outlined as standard 1:50,000 map-sheet areas, are shown in Fig. 2. Some of the map-sheets contain minor areas covered by metasedimentary rocks of Late Proterozoic age and rocks younger than the Precambrian. Wells in such lithologies are omitted. The selected areas are not ideal. Area B has no uplift data, and area A has few such data. With the exception of areas surrounding the Oslo region, however, the selected areas are the only ones with sufficient concentrations of drilled wells within Precambrian rocks in Norway. Areas adjacent to the Oslo region have been omitted to preclude interference from the intense Permian igneous activity in this region. Admittedly, the Permian activity may also have had some influence on areas B, D and E. For this first approximation to the theory, and with limited available information on wells and uplift, the selected areas are at present regarded as the best available. Further information on the areas (A - E) is given in Table 1 along with some statistics on the drilled wells.

The table shows that the higher the isostatic uplift is for an area, the higher are the yields in drilled wells, and the shallower are the well depths. These trends are plotted graphically in Figs. 3 and 4. The almost linear trends for water yield and well depth plotted against yearly uplift are not likely to be accidental. The observed decline in well depth with increasing yield is at first sight a puzzling phenomenon. It has, however, been

AREA	MAPS (M711)	APPROX. UPLIFT (mm/year)	NUMBER OF WELLS	TOTAL YIELD (l/h)	TOTAL DEPTH (m)	YIELD (l/h)		DEPTH (m)		YIELD PR. DRILLED M (l/h · m)	
						MEAN	MED.	MEAN	MED.	MEAN	MED.
A	1115 IV 1116 I 1117 II 1217 II, III	0,4	263	153008	21904	582	250	83,5	81,5	7,0	3,1
B	1515 I 1516 II 1616 II, III	3,5	454	445304	26515	981	500	58,5	57	16,8	8,8
C	1319 I 1419 III 1518 I	4,0	197	246860	11189	1253	600	57	55	22,1	10,9
D	1916 II 2015 I, IV 2016 II, III	5,8	239	329330	14428	1378	800	60,5	55	22,8	14,6
E	2017 II 2117 I, II, III, IV	7,5	125	178290	4994	1426	1000	40	35	35,7	28,6

Table 1.Annual land uplift and some statistics (mean and median values) on drilled wells for five areas in southern Norway. A — Bergen - Høyanger area; B — Gol - Geilo area; C — Lesja - Skjåk area; D — Finnskog - Tangen area; E — Trysil area.

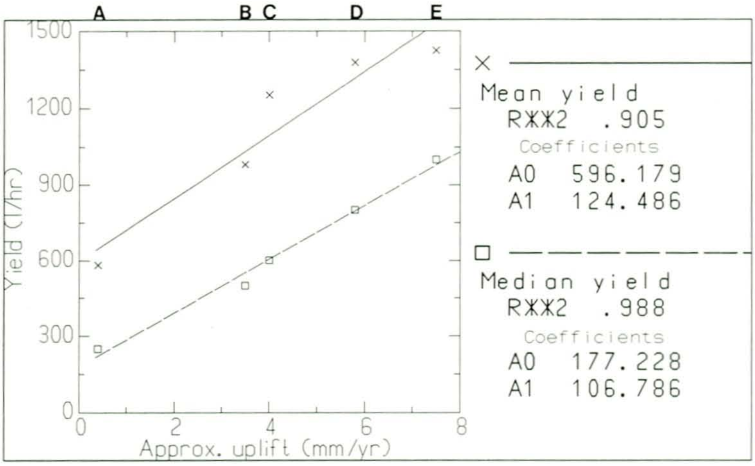

Fig. 3.Mean and median values for yield (l/h) plotted against annual land uplift (mm/year) for five areas in southern Norway. A = Bergen - Høyanger area, B = Gol - Geilo area, C = Lesja - Skjåk area, D = Finnskog - Tangen area, E = Trysil area.

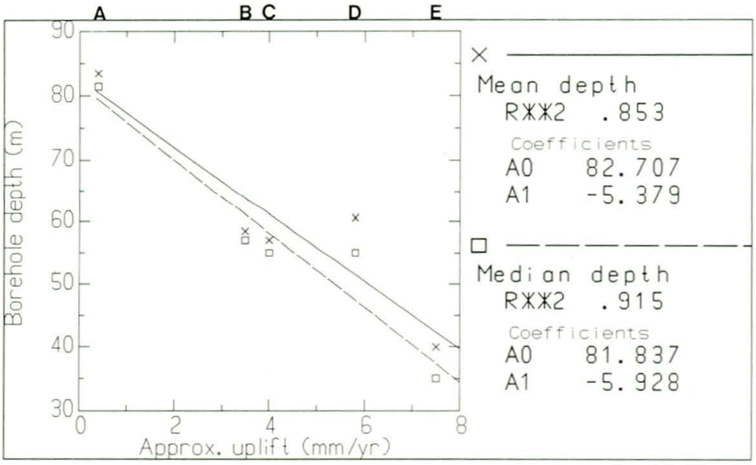

Fig. 4.Mean and median values for well depth (m) plotted against annual land uplift (mm/year). The five areas A - E are the same as in Fig. 3.

observed by many hydrogeologists in Norway (Rohr-Torp 1987, Banks et al. 1992) and is ascribed to a well-driller discontinuing drilling once he has found a satisfactory water yield. At 'dry' sites, however, he may continue to great depth before abandoning the borehole. Dividing the yield by the well-depth gives the yield per drilled metre. This parameter, as expected, has an even stronger positive relationship with yearly uplift than the well yield (Fig. 5).

Conclusions

Very young tectonic events may have rejuvenated old fractures, and such events are probably more important for the permeability of old fracture systems than the original properties of these systems. This brief investigation supports the theory that the postglacial isostatic uplift has reactivated old fracture systems, and most probably also created new fractures. Furthermore, the magnitude of this uplift seems to be decisive for the degree of fracturing. The greater the uplift, the more intense is the reactivation and fracturing.

The median value for water yield in drilled wells avoids placing undue statistical weight on the few unrepresentative very high-yielding wells, and this value is generally accepted as more useful for predicting 'typical' yields than the mean value. For well depth, the mean value is very similar to the median (see Figs. 3 and 4), indicating a symmetrical distribution of well depth.

The graphs indicate a very simple rule of thumb for predicting the 'typical' yield of randomly placed wells in Precambrian rocks of Fennoscandia. Starting at 0 mm yearly uplift, a well can be expected to yield 180 l/h at 80 - 85 m depth. For each mm of yearly uplift, 100 l/h can be added, and the depth required to achieve this decreases by 6 m. It should be mentioned that most Norwegian wells are drilled more or less at random, without the use of hydrogeologists.

Naturally there are several other factors such as rock-type, topography, infiltration area, type of fractures, hydraulic connectivity, etc. which control the water yield in a well. Nevertheless, the above rule of thumb can be useful in giving a simple rough estimate for expected yield and well-depths in a given area. Furthermore, at an early stage in planning man-made caverns and tunnels, it may provide a rough indication of expected leakages; and it should also be taken into consideration when planning sites for hazardous waste.

It is proposed that further work should be done on the practical application of the theory, preferably as a joint project between the Scandinavian nations.

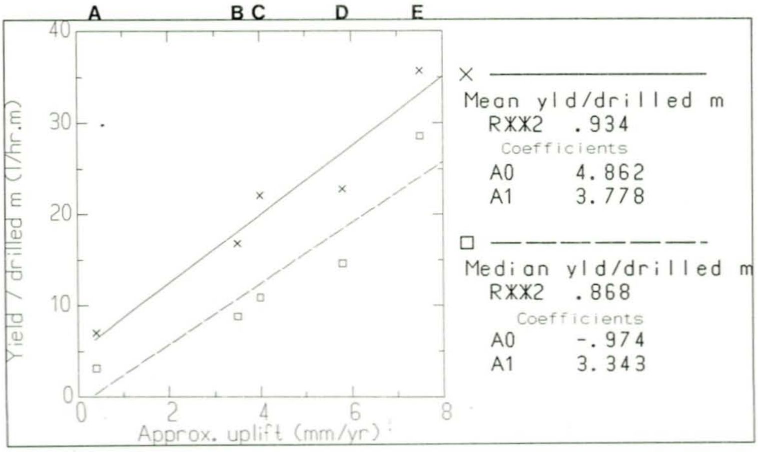

Fig. 5. Mean and median values for yield per drilled metre (l/h·m) plotted against annual land uplift (mm/year). The five areas are the same as those in Fig. 3.

Acknowledgements

The author is grateful to David Banks for his critical reading of the manuscript and improving both the English text and the content. The staff at the Geological Survey's Oslo office is thanked for their assistance at various stages of this work; and Helge Skarphagen especially has brought about many fruitful discussions.

References

Anundsen, K. 1989: Late Weichselian relative sea levels in southwest Norway: observed strandline tilts and neotectonic activity. *Geol. Fören. Stock. Förh. 111,* 288 - 292

Bakkelid, S. 1986: The discovery in Norway of a strongly active geological fault and some of its practical consequences. *Proceedings of the 10th General Meeting of the Nordic Geodetic Commission, Sept. - Oct., Helsinki,* 237 -245.

Balling, N. 1980: The land uplift in Fennoscandia, gravity field anomalies and isostasy. In Mörner, N. A. (ed.): *Earth Rheology, Isostasy and Eustasy,* John Wiley & Sons, New York, 297 - 321.

Banks, D., Rohr-Torp, E. & Skarphagen, H. 1992: An intergrated study of a Precambrian granite aquifer, Hvaler, Southeastern Norway. *Nor. geol. unders. Bull. 422,* 47 - 66.

Bergsten, K. E. 1943: En senglacial förkastning i norra Östergötland. *Svensk Geogr. Årsbok,* 1 - 16.

Bjerhammar, A. 1980: Postglacial uplifts and geopotentials in Fennoscandia. In Mörner, N. A. (ed.): *Earth Rheology, Isostasy and Eustasy,* John Wiley & Sons. New York, 323 - 326.

Bäckblom, G. & Stanfors, R. 1989: Interdisciplinary study of post-glacial faulting in the Landsjärv area, northern Sweden 1986 - 1988. *Svensk Kärnbräslehantering Technical Report 98 - 13.*

De Geer, G. 1938: Jordbävningar i Bromma. *Svenska Turistforen. Stockholm,* 24 pp.

De Geer, G. 1940: Geochronologia Suecica Principles. *Kungl. Svenska Vet. Akad. Handl., Ser. 3, 18: 6,* 1 - 360.

Du Rietz, T. 1937: Recente förkastningar eller sprickbildningar i Västerbottensfjällen. *Geol. Fören. Stockh. Förh.* 112 - 114.

Englund, J. O. 1980: Generell hydrogeologi. *Landbruksbokhandelen, Ås - NLH,* 136 pp.

Feyling-Hansen, R. F. 1966: Geologiske observasjoner i Sandnes-området. *Nor. geol. unders. 242,* 26 - 43.

Flodén, T. 1977: Tectonic lineaments in the Baltic from Gävle to Simrishamn. *KBS Tekn. Rap. 59. Stockholm.*

Grønlie, O. T. 1922: Strandlinjer, moræner og skjælforekomster i den sydlige del av Troms fylke. *Nor. geol. unders. 94,* 39 pp

Johnston, A. C. 1989: The effect of large ice sheets on earthquake genesis. *In* Gregersen, S. & Basham, P. W. (eds.): *Earthquakes at North-Atlantic Passive Margins: Neotectonics and Postglacial Rebound,* Kluver Academic Press, 581 - 599.

Kujansuu, R. 1964: Recent faults in Finnish Lapland. *Geologie 16,* 30 - 36.

Lagerbäck, R. 1979: Neotectonic structures in northern Sweden. *Geol. Fören. Stockh. Förh. 100,* 271 - 278.

Lagerbäck, R. 1990: Late Quatenary faulting and paleoseismicity in northern Fennoscandia, with particular reference to the Lansjärv area, northern Sweden. *Geol. Fören. Stockh. Förh. 112,* 333 - 354.

Lagerlund, E. 1977: *Förutsetningar för moränstratigrafiska undersökningar på Kullen i Nordvästskane - teoriutveckling och neotektonik.* Thesis 5, dept. Quatern. Geol. Univ. i Lund.

Lebesbye, E. H. T. 1989: Vek'sa. Kvartærgeologisk kart 2135 IV - M 1:50 000. Beskrivelse. *Nor. geol. unders. Skr. 91,* 30 pp.

Lundqvist, J. & Lagerbäck, R. 1976: The Pärve fault: A late glacial fault in the Precambrian of Swedish Lapland. *Geol. Fören. Stockh. Förh. 98,* 45 - 51.

Madsen, V. 1917: En kvartär dislokation ved Sundvik tegelbruk i Skåne. *Geol. Fören. Stockh. Förh. 39,* 597 - 602.

Miur Wood, R. 1989: Extraordinary deglaciation reverse faulting in Northern Fennoscandia. *In* Gregersen, S. & Basham, P. W. (eds.): *Earthquakes at North-Atlantic Passive Margins: Neotectonics and Postglacial Rebound,* Kluver Academic Press, 141-173.

Mörner, N. A. 1969: The late Quatenary history of the Kattegat Sea and the Swedish west coast: deglaciation shorelevel displacement, chronology, isostasy and eustasy. *Sver. geol. unders. årsb. V. C-640,* 487 p.

Mörner, N. A. 1972: Isostasy, eustasy and crustal sensitivity. *Tellus 24,* 586 - 592.

Mörner, N. A. 1975: Postglacial earth movements. *National report of the Swedish GDP Committee, Grenoble 1975,* 1 - 10.

Mörner, N. A. 1977: Past and present uplift in Sweden: glacial-isostasy, tectonism and bedrock influence. *Geol. Fören. Stockh. Förh. 99,* 48 - 54.

Mörner, N. A. 1978: Faulting, fracturing and seismicity as functions of glacio-isostasy in Fennoscandia. *Geology 6,* 41 - 45.

Mörner, N. A. 1980: The Fennoscandian uplift: geological data and their geodynamical implication. *In* Mörner, N. A. (ed.): *Earth Rheology, Isostasy and Eustasy,* John Wiley & Sons. New York, 251 - 284.

Olesen, O. 1988: The Stuoragurra Fault, evidence of neotectonics in the Precambrian of Finnmark, northern Norway. *Nor. geol. Tidsskr. 68,* 107 - 118.

Olesen, O., Henkel, H., Lile, O. B., Mauring, E., Rønning J. S. & Torsvik, T. H. 1992: Neotectonics in the Precambrian of Finnmark, northern Norway. *Nor. Geol. Tidsskr. 72,* 301 - 306.

Roberts, D. 1991: A contemporary small-scale thrust-fault near Lebesby, Finnmark. *Nor. Geol. Tidsskr. 71,* 117 - 120.

Rohr-Torp, E. 1987: Drøbak 1814 II. Description of the hydrogeological map - 1:50 000. *Nor. geol. unders. Skr. 78,* 1 - 19.

Sollid, J. L. & Tolgensbakk, J. 1988: Kvartærgeologisk og geomorfologisk kartlegging på Svalbard og fastlands-Norge. Utført ved Geografisk Institutt, Univ. i Oslo. *Abstract 18. Nordiske Geologiske Vintermøte, København,* 380 - 381.

Sørensen, R., Bakkelid, S. & Torp, B. 1987: Landhevning. Nasjonalatlas for Norge. Hovedtema 2: Landformer, berggrunn og løsmasser. Kartblad 2. 3. 3. *Statens Kartverk.*

Manuscript received October 1993; revised m/s received and accepted April 1994.