SVERIGES GEOLOGISKA UNDERSÖKNING
SER. Ca AVHANDLINGAR OCH UPPSATSER I A4 NR 68

INGEMAR CATO

ON THE DEFINITIVE CONNECTION OF THE SWEDISH TIME SCALE WITH THE PRESENT

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ABSTRACT

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This paper deals with the results of an investigation of the late postglacial and recent sediments in the lower part of the Ångermanälven river valley in northern Sweden. The Swedish geochronological time scale mainly established by G. De Geer and R. Lidén has in this area been extended up to, and for the first time definitively connected to the present time (1978) by means of varved clayey-silty sediments. This was only possible in consequence of the unique deposition, still in progress, of varved sediments in the Ångermanälven non-tidal estuary. The results show that the previously calculated gap of 980 years between R. Lidén's youngest varve 7522 found at Prästmon and the historical year 1900 A.D. should be extended with 365 years. This implies that the revised, commonly used zero year (Borell & Offerberg 1955) in Döviken (Indalsälven river valley), marking the boundary between the finiglacial and postglacial epochs in Sweden, can be dated to 7288 B.C. (9238 years B.P.) instead of the old date 6923 B.C. given by E. Nilsson in 1960.

Preface

An exact connection of the Swedish Geochronological Time Scale with the present has long been a matter of urgency to both Swedish and foreign geologists. Despite several attempts in the 20th century none of these improved on the provisional connection achieved by Ragnar Lidén (1938) with the help of the land elevation curve from the Ångermanälven Valley. R. Lidén soon realized, however, that an exact connection of the Time Scale with the present would only be possible via the collection of drill cores from the delta area of the river. Professor Bertil Kullenberg of Göteborg University, Assoc. Professor Erik Fromm and Dr. Lars Granar of the Geological Survey of Sweden (SGU) carried out the first attempts with this method in the 1940's and 1950's but no connection with R. Lidén's varve series was thereby attained.

It was against this background that Dr. Åke Hörnsten in connection with his investigations of the chronology of the glacial clay varves in the coastland of Ångermanland, after consultation with R. Lidén, began his preparations for a new attempt at a linkage, for which funds were requested for the first time in 1969. The funds were, however, returned to the National Environment Protection Board since no suitable survey ship was available etc.

Within the framework of the IGCP Project "Quaternary Glaciations in the Northern Hemisphere" (IGCP 24) with Professor Jan Lundqvist (Stockholm University) as project leader Å. Hörnsten, after several applications, in 1978 obtained an initial grant for this project from the Swedish Natural Science Research Council. The Geological Survey of Sweden has since financed the project and finally the Research Council paid for the printing of the Report.

The layout and planning of the project in 1978–84 were executed by Å. Hörnsten and the author in consultation with J. Lundqvist and E. Fromm.

The author was responsible for the processing, compilation, and authorship of this Report. The computer programmes were devised by Jan Schedin. Irma Ortman digitalized the clay varves diagram while the author saw to the computer runs. Assoc. Professor Valter Axelsson of Uppsala University contributed X-ray photographs of two sediment cores drilled in the context of another project. E. Fromm placed unpublished clay varve measurements from 1945 at the disposal of the project for a comparative study of independently executed measurements of clay varve thicknesses.

Field work was carried out under the leadership of Å. Hörnsten and/or the author in the years 1978, 1982 and 1983 by G. Ekman, U. Åsbrink, B. Henriksson, B. Kjellin, R. Smedberg, B.Thunholm (all from SGU) and by J. Lundqvist (Stockholm University) and A. Jonasson (Göteborg University). The drawings were made by A.-C. Sjöberg, at SGU and the paper was linguistically corrected by T.J.M. Gray.

Reports from this project have earlier been given by Cato in 1981, in 1985 and in 1986.

The National Board of Fisheries placed the survey ship R/V Argos at the disposal of the project in 1978.

Valuable comments on the MS. were offered by Assoc. Professors Bo Strömberg (Stockholm University) and Birgitta Ericsson of SGU.

I express my deep gratitude to all.

Uppsala 15th October 1984
Ingemar Cato, Assoc. Professor
Geological Survey of Sweden

Introduction

Judging by our present knowledge the valley sediments of the Norrland rivers would seem to be more regularly formed and more completely preserved in the valley of the Ångermanälven (Fig. 1) than in any other of the rivers rising in the mountains of Northern Sweden. This special circumstance was established already at the beginning of the century by Ragnar Lidén when he worked for Gerard De Geer in the extensive geochronological investigations of Sweden in the years 1905–6. Lidén noticed not only the layered structure of the river valley sediment but also that the lamination of these sediments was highly reminiscent of the stratification in annual varves of the glacial clay.

It was in all probability these observations which eventually led Lidén to the successful testing and application also to river valley sediments of the geochronological method devised by G. De Geer (e.g. G. De Geer 1912, 1940). During the years c. 1909–15 Lidén worked on a systematic measurement of the varved structure of the sediments in the Ångermanälven river valley. The purpose of the investigation was to illustrate the geological and geographical development of the landscape chronologically during Late Quaternary time and until the present.

In a lecture entitled "On the deglaciation and the postglacial land upheaval in Ångermanland" Lidén presented his first, preliminary results at a meeting of the Geological Society of Sweden in Stockholm in May 1911 (Lidén 1911).

The definitive results of the geochronology of the deglaciation of Ångermanland were published two years later (Lidén 1913). The postglacial chronology was long delayed however, notwithstanding that according to the documents which Lidén left behind it was more or less ready for publication c. 1915 (see further Lidén† & Cato, in press). Not until 1938 did a breif summary appear of the results of Lidén's very extensive geochronological work on the postglacial sediments in the valley of the Ångermanälven (Lidén 1938). Surprisingly enough no varve diagrams were included in this work. From each delta surface only the chronological number of the youngest varve was given in connection with the account of the course of the Late Quaternary shore displacement in the valley of the Ångermanälven. Lidén's varve diagrams are however now published in their entirety (Lidén & Cato, in press).

Parallel with Lidén's work along the Ångermanälven river De Geer also tried to extend the Swedish Time Scale through the postglacial period in the Ragunda district. Since Lidén had encountered certain initial difficulties during his work in the valley of the Ångermanälven De Geer set his sights on a more limited area which included L. Ragunda, drained by Vild-Hussen in 1796, on the Indalsälven which runs some 50 km south of the Ångermanälven (Fig. 1). In 1911, by means of a very detailed profile comprising both glacial and postglacial varves in a gully at Vikbäcken he tried to measure the entire varve series until the year 1796 and thereby directly connect the Time Scale to historical time. The attempt failed because the uppermost varves were very thin and rendered indistinct by weathering. Nevertheless De Geer estimated the number of postglacial varves at about 7 000 (G. De Geer 1912).

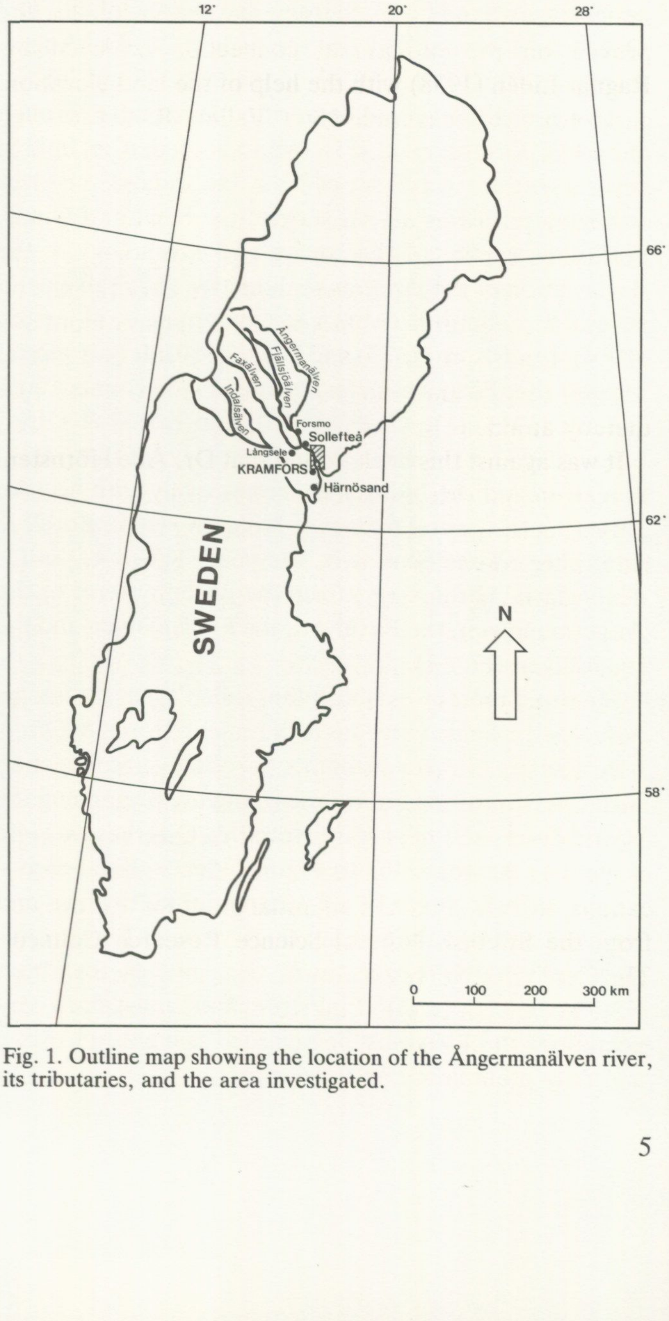


Fig. 1. Outline map showing the location of the Ångermanälven river, its tributaries, and the area investigated.

The work in the vicinity of Ragunda continued, however, until Caldenius (1924) showed that the task was impossible of accomplishment in that the sedimentation in the former L. Ragunda ceased long before the lake was drained.

De Geer's attempts to connect his varves series from the Indalsälven valley with those of Lidén from the Ångermanälven also failed at first although e.g. the profile from Vikbäcken displayed certain, albeit not convincing, similarities.

Thus Lidén's late glacial and postglacial chronology would have remained unconfirmed had not De Geer measured an excellent series of 400 undisturbed varves at a level crossing near Gåsnäs (Resele parish) on the Ångermanälven. This series provided a definitive connection comprising 350 varves (covering the period −210 to +140 in De Geer's chronology, viz. the years 300 to 650 in Lidén's Time Scale) between the Swedish Time Scale devised by De Geer in the south and Lidén's varve series from Sand, and thereby the whole of his late Quaternary chronology in the valley of the Ångermanälven (G. De Geer 1924 and 1940, Pls. 75 and 76).

This connection could be verified much later through Borell & Offerberg (1955), who succeeded in linking several of their varve series from the Indalsälven river valley with Lidén's glacial series from Sand and Utnäs.

Further studies of the course and chronology of the deglaciation of the Ångermanälven, the Indalsälven and several neighbouring rivers were performed by Hörnsten (1964), Lindström (1973) and Fözö (1980). It is of special interest that Fözö was able convincingly to connect both Lidén's (1913), De Geer's (1940) and Borell & Offerberg's (1955) varve series from the valleys of the Ångermanälven and the Indalsälven respectively with his own (covering the period from c. −310 until +70 in Borell & Offerberg's Time Scale, viz. the years 117 to 497 in Lidén's glacial chronology) from the water systems of the Ångermanälven, the Faxälven, the Fjällsjöälven and the Indalsälven (Fig. 1).

He could thereby establish that Lidén's measurements never lack a single varve, as is the case in Borell & Offerberg's series. Fözö's attempts to obtain a connection with Lindström's diagram series (roughly comprising the period from −10 to +70 in Borell & Offerberg's Time Scale, i.e. the years 467 to 497 in Lidén's glacial chronology) were however beset with major difficulties and imposed on Fözö shifts of up to 35 years of Linsdtröm's diagram vis-à-vis Fözö's own. This means that both Fözö's connections with Lindström and Lindström's connections with Lidén must be regarded as highly uncertain and only preliminary at present.

Hörnsten (1964) too achieved good agreement between graphs of glacial varves (covering the period from c. −400 to the year 0 in Borell & Offenberg's Time Scale, i.e. the years 27 to 427 in Lidén's glacial chronology) from the valleys of the Ångermanälven, the Indalsälven, the Nätrån, the Moälven and the Gideälven and the varve diagrams of Lidén and Borell & Offerberg. Unfortunately Hörnsten does not give any clay varve diagrams in his paper so that it was not possible for Fözö to incorporate these in his current work from 1980. Both Borell & Offerberg and Hörnsten state that they lack certain years, or have one or more varves in excess in comparisons between the varve series of the different river valleys. Yet Hörnsten (1964, p. 19) regards this circumstance as being of minor importance since the total error should not be more than a few years. Thus it is feasible to consider that the chronology of the recession of the ice in the great valleys of Ångermanland, and thereby this part of the Swedish Time Scale, is satisfactorily explained.

During the supra-aquatic melting of the inland ice the estuary of the Ångermanälven river was displaced about 20 km by the land upheaval from the Junsele area to Gårelehöjden. According to Lidén (1913) the estuary was located here in the year 747 in his Time Scale, viz. 747 years after the edge of the ice reached Fällön outside Härnösand (Fig. 1). The year 747 denotes the boundary between glacial and postglacial varves in the valley of the Ångermanälven (Lidén op. cit. p. 19).

G. De Geer set the boundary in his chronology between finiglacial and postglacial time at a thick drainage varve which he observed *inter alia* at Vikbäcken and Döviken in the valley of the Indalsälven (G. De Geer 1940). In his view this varve registers a drainage eastward of the Ice Lake of Central Jämtland when it broke through the melting remains of the land ice (the bipartation). Through De Geer's linkage of his own and Lidén's chronologies this so-called bipartation varve or the zero year (G. De Geer 1924) was found to correspond to the year 510 in Lidén's chronology (G. De Geer 1940 p. 172). From Lidén's extrapolation (see below) of his chronology in Ångermanland to the year 1900 A.D. De Geer's zero year could be dated to 6839 B.C. (Fig. 1 in Lidén 1938).

Be that as it may, Caldenius (1913, 1941) and later Borell & Offerberg (1955 p. 23) concluded that the Vikbäcken and Döviken varves were not created at the same time. The Vikbäcken drainage varve derived from a new drainage, which happened at least 80 years later. According to E. Nilsson (1960) the Döviken varve is 84 years older than the Vikbäcken varve, which in turn means

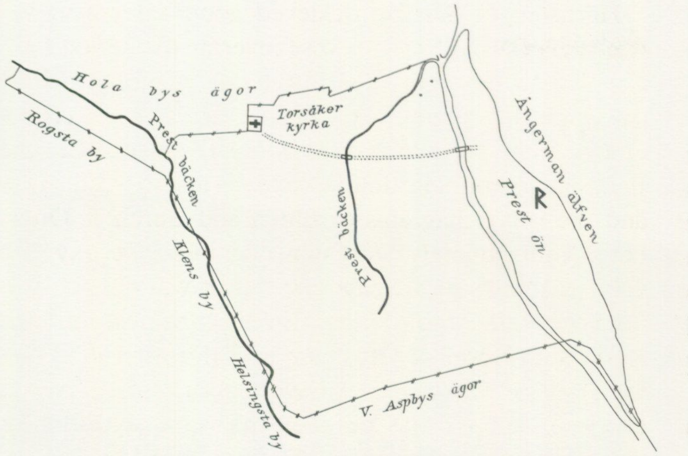


Fig. 2. Map of Torsåker glebe from 1701. The situation of the Styresholm Fortress (constructed during the first half of the 14th century and destroyed in 1434) at Prestön island is marked R.

that the former (from Lidén's extrapolation of the chronology of the Ångermanälven until 1900 A.D.) could be dated to 6923 B.C. (E. Nilsson 1960).

Thus there are two zero year varves, the thicker of which, the Döviken varve, corresponds to the year 427 in Lidén's system, and now constitutes the zero year in the revised conventional Swedish Time Scale. Accordingly several drainage varves have been recorded in the valleys of the Indalsälven and the Faxälven (*inter alios* Borell & Offerberg 1955, Fözö 1980). In addition many ice lakes have been reconstructed, as well as several possible drainage routes (J. Lundqvist 1959, 1973, Fözö 1980) in the precipitation area of the Indalsälven. As a consequence the theory of the incidence of bipartation, and – if it really happened – when it occurred has been discussed and questioned (among others Frödin 1954, J. Lundqvist 1959, 1973, G. Lundqvist 1961, Fözö 1980).

From a chronological standpoint it is of course essential to know which zero year is meant (the Vikbäcken or the Döviken varve), and also that the true varve can be identified.

Lidén's postglacial chronology comprises over 7500 varves and ends with the surface varve 7522 at Prästmon. This site, a delta terrace, was once an island ("Prästön"), according to a map of Torsåker glebe drawn in 1701 (Fig. 2). The western branch of the river, which still existed at that time, is now wholly dry. On the northern part of the delta terrace stood Styresholm Fortress (Fig. 3), which was founded during the first half of the 14th century (Modin 1933). The fortress incorporates two moats, the excavated bottom of which lies 3 m below the delta plateau. The bed of the moats consists of 3 dm of river sediment overlaid with remains of carbon and eroded soil (Lidén 1938). The latter is assumed to derive from the destruction of the fortress during Engelbrekt's War of Liberation in 1434.

With the help of these historical data Lidén could establish the course of the displacement of the shoreline during the last 600 years, and from this roughly estimate the interval between the formation of the delta surface at Prästmon and the year 1300 A.D. as c. 380 years. In other words Lidén postulates that the 7522 years which his varve series comprises must be supplemented by 980 years to connect the Time Scale with the year 1900 A.D.

Ebba Hult De Geer (1933) arrived at a similar result (1018 years) by means of biochronological teleconnection between a several thousand year old sequoia tree in California and Lidén's varve diagram from Prästmon. Nevertheless it must be remarked that Lidén's varve diagram from Prästmon, which Ebba Hult De Geer presents in her work, differs widely on several points from Lidén's original diagram from c. 1915 (see further p. 41). The comparatively close agreement between Lidén's and Ebba Hult De Geer's results is thereby even less convincing.

There is yet another ground for doubt in this context, viz. as regards the dating of Styresholm Fortress. Lidén assumed the year 1300 (Lidén 1938, p. 402), while Modin (1933, p. 27) states that "the fortress was erected during the first half of the 14th century". This yields a maximum uncertainty of 49 years.

In addition there is Lidén's calculated land upheaval of 1.25 cm/year during the last millennium, which is much greater than the recent land elevation of 0.80–0.85 cm/year in this area (Bergsten 1954). According to Wenner (1968), Tauber (1970) and Fromm (1970) this circumstance implies that the uncertainty in the interval calculated by Lidén (980 years) may be in the order of $+350\pm150$ (Wenner op. cit.), $+200\pm100$ (Tauber op. cit.) and $+200^{+300}_{-100}$ years (Fromm op. cit.) respectively, i.e. between 0 and 500 years.

Lidén's contemporaries must be content with his provisional connection as reported above, even though the postglacial varve chronology, and thereby the whole of the Swedish Time Scale was not "absolutely" connected with the present. The reason was *inter alia* the fact that the sediments deposited by the river between Prästmon and the delta at Nyland were still not sufficiently elevated above the sea, and that the most recent varves still lay below its surface. Thus the varve series essential for the connection were not accessible to Lidén. The possibility arose later with the emergence of modern drilling methods, a possibility which Lidén, too, envisaged at an early stage (Lidén 1938). Despite several

Fig. 3. The Styresholm Fortress by the Ångermanälven river in June 1983 (Photo: I. Cato).

attempts (Kullenberg & Fromm 1944, Fromm 1945 unpublished and Granar 1956) none succeeded in connecting Lidén's profile from Prästmon with the recent varves outside the mouth of the Ångermanälven at Nyland, since the collected recent and subrecent varve series did not include a sufficiency of connectable varves.

According to E. Nilsson (1968) the estuary of the Ångermanälven would still seem to be the only known area in the world where it is feasible by means of varve measurements to connect the Swedish Time Scale with the present era. He also emphasized that this is the most essential task currently facing geochronology. Fromm expressed the same opinion at the 12th Nobel Symposium in Uppsala in 1969 (Fromm 1970), since the largest individual misconception in the Swedish Time Scale may lie just in Lidén's provisional connection with the present as described above. The shortcomings and uncertain factors in the Time Scale were later discussed in detail also by J. Lundqvist (1975). Lundqvist, too, indicates the necessity for a revision of certain parts of the Swedish Time Scale if this in the future is to be considered as definitively established.

With this objective in mind a revision programme for the Swedish Time Scale was begun in 1975 within the framework of the International Geological Correlation Programme, IGCP (*inter alios* Strömberg 1981, 1983 and 1985). The international importance of the execution of such a programme is clearly indicated in Fairbridge (1981) and Schove & Fairbridge (1983), who emphasize the need for an exact year to year chronology as a basis for studies of diverse occurrent Late Quaternary cyclicities.

It is against this background, and the need existing in Late Quaternary research, that the present undertaking within the framework of the IGCP Project "Quaternary Glaciations in the Northern Hemisphere" (IGCP 24) was launched at SGU at the instigation of Å. Hörnsten in the late summer of 1978. The purpose of the Project was to seek to enlarge Lidén's chronology with new varve series which extend as far as our own time. A definitive connection of the Swedish Time Scale with historical time would then be possible and thus a presumed major uncertain factor in the Scale would be eliminated.

The Ångermanälven River

The riverine area of the Ångermanälven is the third largest in Sweden. From the source in the mountains to the delta in the Baltic the area is 300 km long with a maximum breadth of 150 km in the central parts. The Fjällsjöälven and the Faxälven constitute the most important tributaries (Fig. 1). The total drainage area covers 31 890 km^2, 7.5 % of it consisting of lakes. The height above sea level averages 475 m with a maximum altitude of 1 589 m (Melin 1954). The estuary of the river extends some 50 km inland from the Baltic northeast to north from Härnön, north of Härnösand, to Nyland, 35 km southeast of Sollefteå. The river's course ends at Nyland with a 15–25 m high distal slope where its fresh water is layered over the penetrating salt (brackish) water of the Baltic Sea (Bruneau 1956). This stratification of the water mass is revealed in Fig. 4 which illustrates the vertical distribution of oxygen and density in the estuary on an occasion with "normal" conditions in 1952.

The density isobases show that the sea water mingles more or less immediately with the effluent river water at Nyland. The low oxygen values in the Kramfors Basin bear further witness that not only the depressions but also the entire Basin may at times manifest oxygen depleted conditions (Bruneau op. cit.).

The bottom profile in Fig. 4 shows that the estuary of the Ångermanälven consists of a glacially deepened channel in the fissured valley system of Norrland's checkered plateau landscape (see Rudberg 1954). At Svanön, Sandön, Åbordsön and Hemsön there are sills which reach a depth of between 10 and 18 m, interspersed with depressions which in several cases plunge to 90 m and in one instance, in the Kramfors Basin, right down to 112 m.

The bulk of the bedrock in the riverine area consists of older and younger Archean bedrock (gneisses granites, pegmatites, rapakivi granites) and older sedimentary rocks (greywackes, shales, sedimentary gneiss) (T. Lundqvist 1980). Between 30 and 65 % of the precipitation area consists of till deposits (G. Lundqvist 1958, J. Lundqvist, 1987). Glaciofluvial deposits in the form of short eskers occur mainly in the valleys. In the lower reaches of the Björkån such isolated eskers are to be found *inter alia* at Styrnäs, Prästmon, Aspby, Sandslån, Nyland and on Sandön in the Nyland fjord. These glaciofluvial hills are frequently associated with outcrops of rock (Arnborg 1959).

The highest coast line (HK) in the area (see definition *inter alia* , Cato 1982) or according to older literature the Baltic Limit (BG) (Halden 1933) was formed by the Ancylus Lake.

Below the HK, primarily in the deeply incised valley, fine-grained sediments occur (chiefly silt). These comprise the characteristic valley deposits which consist partly of Late and Postglacial fjord sediments, partly of alluvial sediments, which were deposited concurrently with the continuous elevation of the land and left in the valleys as terrace planes and delta surfaces (Lidén 1913).

Gullies and bluffs which, together with the flat terrace surfaces, are characteristic for the area have been cut out from the fine-grained valley sediments. In the river system of the Ångermanälven the gullies are formed approximately as far as the HK. There is e.g. a very marked gully landscape around Sollefteå, where the difference in level between the highest terrace plane and the gully mouths amounts to some 50 m (Arnborg 1959).

The extent of the alluvial sediments is not known in detail but there is a survey in J. Lundqvist (1987). Alluvial sediment denotes recent gravel and sand deposits which have been carried along the bottom by flowing water, as contrasted with recent accumulation sediments which are transported in suspension. The thinly varved, blue-grey glacial clays occurring in the area are overlaid by postglacial fine silt deposits, so-called postglacial fjord sediments. In some areas these are in turn covered by alluvial sediments (Lidén 1913).

A compilation of the soils along the shores of the Ångermanälven (Fig. 15 in Arnborg 1959) shows that the upper reaches of the river are dominated by glaciofluvial and till deposits, the central sections by fjord sediments, and the lower stretches by alluvial sediments.

Rock outcrops are of very rare occurrence in the investigated area. They have only been observed at Stengrundet (glacial eroded slabs), about 500 m above Hammarsbron.

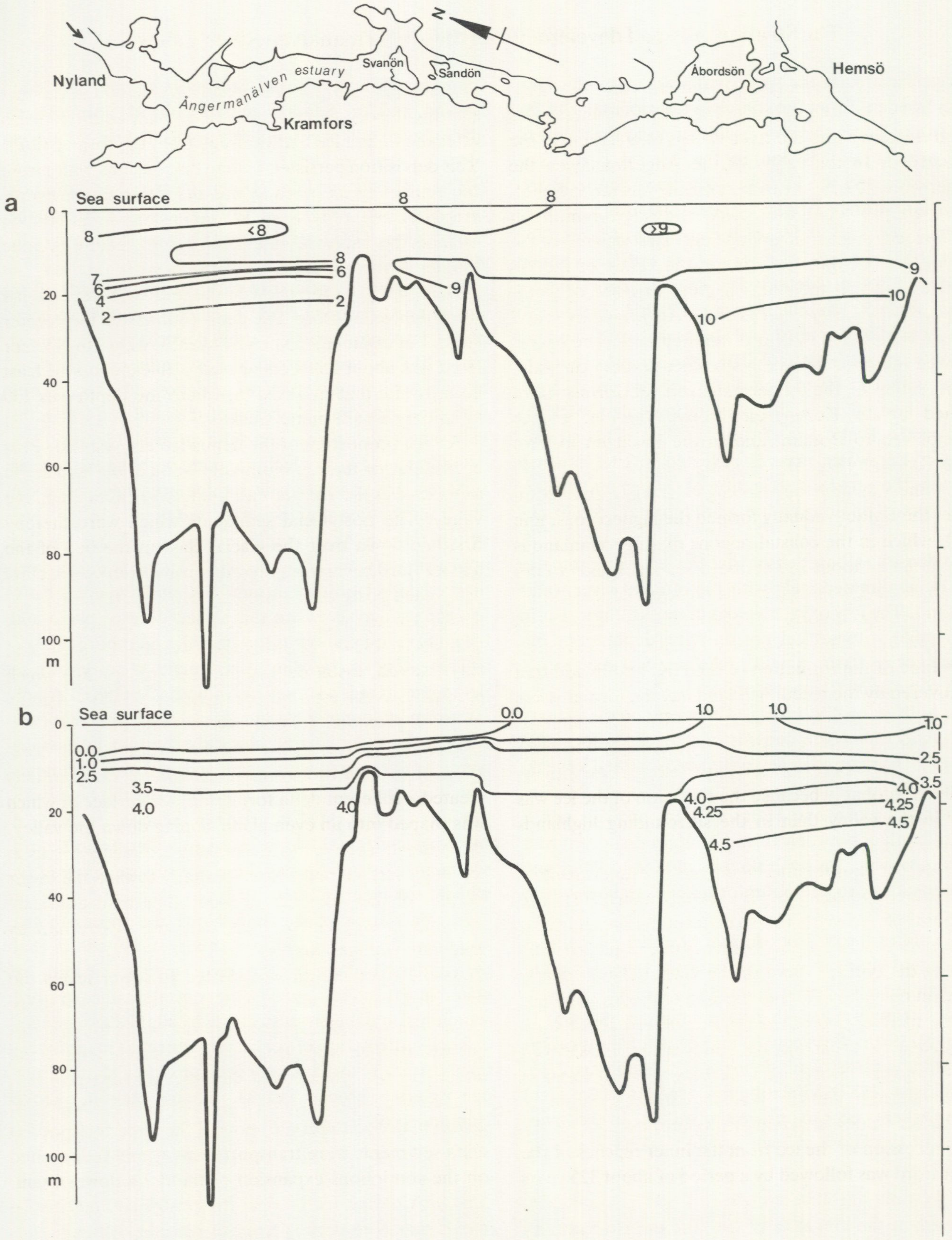


Fig. 4. Bottom profile chart of the Ångermanälven estuary showing the distribution of oxygen (mg/l) (a) and density (σ_t) (b) in the water mass on August 19th, 1952 (from Bruneau 1956).

The Stratigraphy and development of the Ångermanälven River Valley

Due to the deep depression of the land on the retreat of the inland ice, the waters of the former Bothnian Sea penetrated deep into the river valleys of Norrland as the ice receded. In the valley of the Ångermanälven the former fjord, 20–30 km wide, extended as far as Sollefteå, where projecting rock peaks and ridges ramified it and divided it into an archipelago landscape. To the west an arm of the fjord joined the valley of the Indalsälven, and to the north a great expanse of water extended between the valleys of the Ångermanälven and the Faxälven. Then the fjord ramified and more or less followed the river valleys in stretches several km wide. In the valley of the Ångermanälven the former fjord reached up to Kortingselet above Junsele, in the Fjällsjöälven to Bodum, and in the Faxälven to Flyn above Ramsele (Fig. 5).

In connection with the receding ice margin, mentioned above, the Baltic gradually formed the highest coast line (HK), which in the coastal regions of Ångermanland is to be found at about 280 m above sea level, only to decline to some 230 m in the inner reaches of the former fjord (*inter alios* Lidén 1913, Hörnsten 1964, Lindström 1973). Since the land was exposed to intensive elevation at the time of the formation of the HK, and in addition was covered by the receding inland ice, the former shore marks were created metachronously. The HK's metachronous isobases run more or less parallel with the coast (Fig. 5), but curve inward just along the Ångermanälven, probably because the recession of the ice was faster in the valley than in the surrounding highlands (Hörnsten op.cit.).

The deglaciation of the inland ice in Ångermanland covered a period of about 750 years (Lidén 1913). The ice front took 425 years to recede from the present coast to the inner reaches of the former fjord, as recorded by Lidén in the bottom varve of the glacial clay at nearly 30 sites in the valley. Within the area of the former fjord the rate of recession of the inland ice was 200–400 m/year (Lidén 1911), and in the valley of the Indalsälven 240–500 m/year (Borell & Offerberg 1955). Hörnsten (1964) and Lindström (1973) arrived at similar or somewhat higher values in neighbouring areas.

The recession of the ice from the inner reaches of the former fjord was followed by a period of about 325 years when the final deglaciation occurred supra-aquatically. By reason of the elevation of the land the river estuary was shifted during this period about 20 km along the valley to Gårelehöjden. The sediments in the upper parts of the valley are therefore purely glacial due to the fact that the deposition of varved glacial clay continued also after the inland ice had vanished from the former fjord. This deposition persisted so long that the melt water from the remaining ice residue was the determining hydrographical factor. Due to the diminishing accumulation of mud the varves of the glacial clay steadily became thinner in the upper layers of the deposits.

According to Lidén (1911) the thickest layers of clay were deposited along the deep channel of the former fjord. For instance, the clay at Multrå, where the former fjord was about 250 m deep, has a thickness of at least 10 m, while that at Tunsjön, where the depth was 130 m, is only a bare metre thick.

A high proportion of the deposited clay was however eroded during the continuous elevation of the land at the same time as the river mouth gradually shifted along the valley. The postglacial sediments which were thereby first laid down over the glacial clay on the bed of the former fjord became a grey-blue, usually unvarved clay, designated postglacial fjord clay by Lidén (op.cit. 1913) (equivalent to the "bottom sediment" in Caldenius' stratigraphy in 1924). This was then overlain by grey, fine silty, varved, distal delta sediments (see p. 20), which gradually, as the estuary approaches, yield to silty-sandy to gravel proximal delta sediments (Fig. 6).

Thus, at the river mouth which was shifted by the elevation of the land to lower levels, there was gradually created a coherent delta formation, the surface of which was shaped into an even plane sloping down the valley. Accordingly each varve in the delta sediments begins at the delta surface and plunges distally toward the lower reaches of the valley at the same time as it gradually becomes finer grained, thins out, and is overlain by gradually younger varves.

As the river mouth was shifted to lower levels the delta planes upstream were elevated above the sea. Insofar as the elevation proceeded the watercourses frequently cut their way through the loose sediments to the underlying till, glaciofluvial deposit, or bedrock.

In consequence of this erosion and the formation of gullies in the delta planes, most of the already deposited delta sediments were transported away and redeposited on the continuous expansion of the delta downstream. The bulk of the material in the postglacial delta sediments therefore derives from these redepositions.

Thus in their present form the alluvial sediments are only erosion residues of the original filling which was

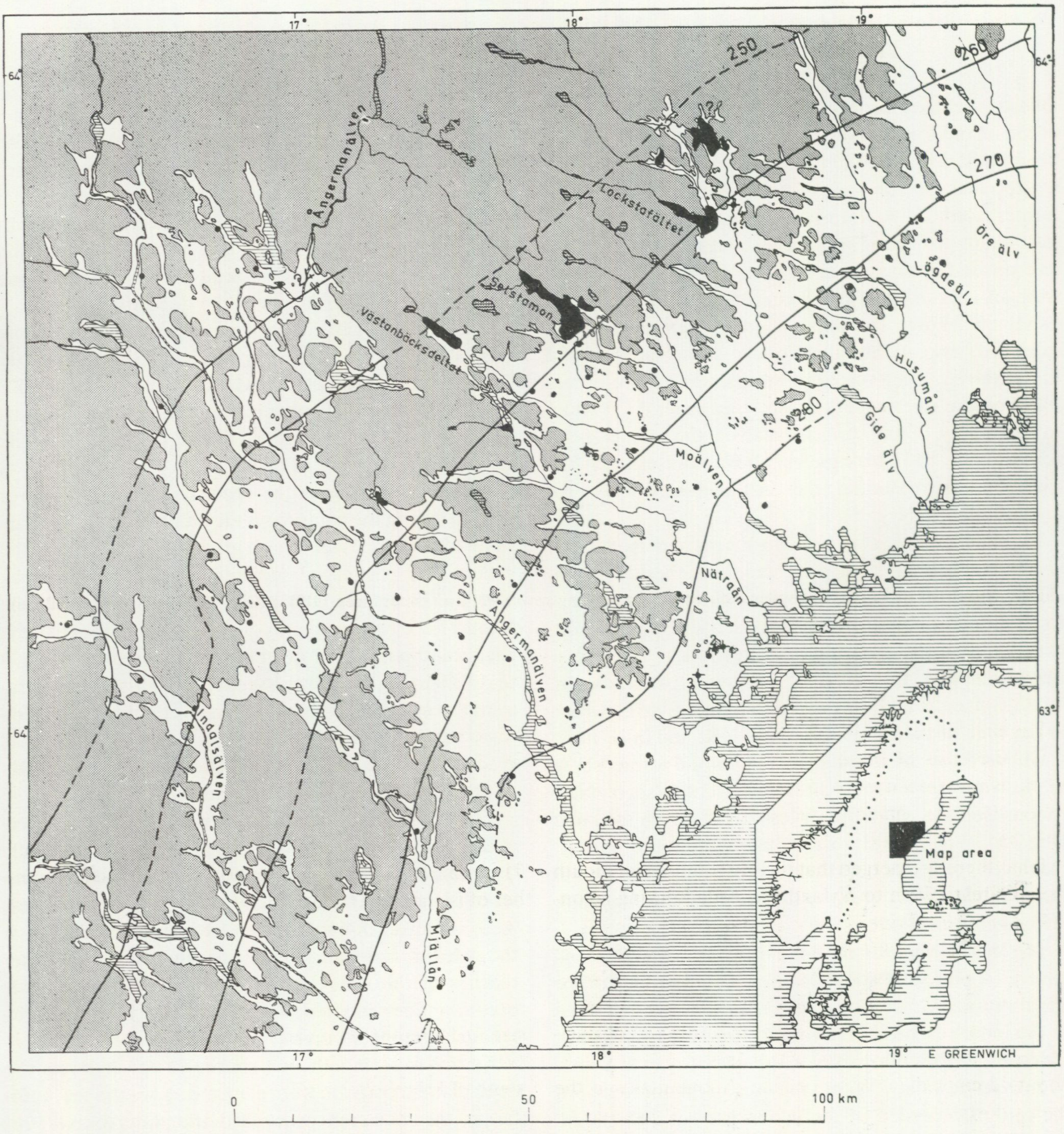


Fig. 5. The metachronous isobases of the highest coast line of the Bothnian Sea in Ångermanland, central Sweden. The grey areas represent land above the highest coast line and black areas ancient delta deposits (from Hörnsten 1964).

accumulated right across the valley. The original delta surface is as a rule preserved in the uppermost sediment plateaux and in the terrace ledges. The lower terraces are flood plain terraces since they were created when the river's flood plain sank through the sediments as the river bed shifted position. They are more or less deeply incised in the delta sediments and often enlarged by flood plain sediments. At the base of the unconformity to the delta sediment there is river gravel overlain by stratified sand which was deposited during the river's high water periods. In this way the upper, thick, postglacial sediment series of the Norrland rivers were and are formed.

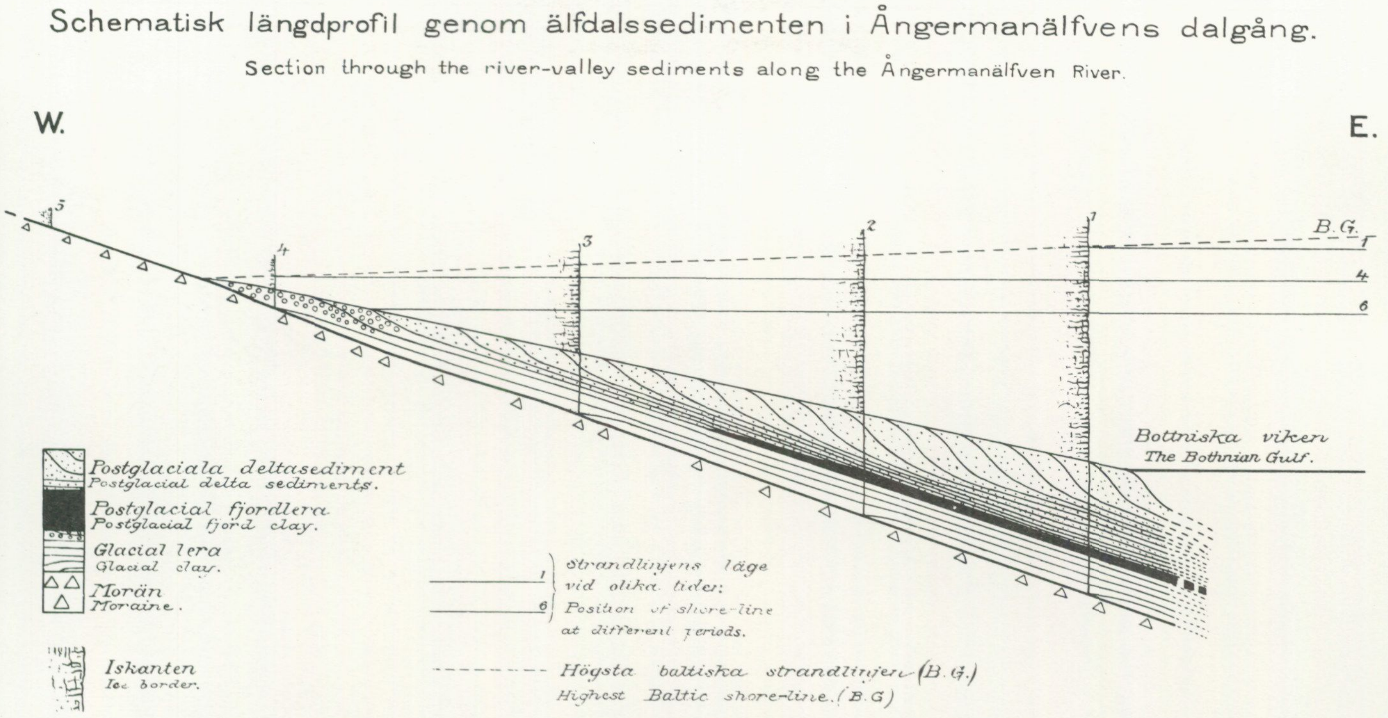


Fig. 6. Typical section through the valley sediments along the Ångermanälven river (from Lidén 1913). B.G. = HK (the highest coast line).

The glacial and postglacial layers thus form, up to the flood plain sediments, a continuous sequence of deposited annual varves.

On the basis of these varved sediments it was possible, as mentioned on p. 5, for Lidén (1913, 1938) to follow the development of the river and chronologically link the glacial period with the postglacial.

It has thereby emerged that the shift of the river mouth from Gårelehöjden to Nyland proceeded during a continuous land elevation during c. 8500 years (Lidén 1938). Throughout the 92 km long course of the river the shift was 11 m/year on an average in the postglacial period (Arnborg 1959).

The rate of elevation of the land during the deglaciation in Ångermanland was according to Lidén (1913) about 12 cm/year, only to decline exponentially in the river's postglacial period to approximately 1 cm/year in present time (Fig. 1 in Lidén 1938).

A calculation by Arnborg of the progress of the recent delta front before the regulation of the river (i.e. before 1950) can on the basis of soundings executed c. 1875 and 1950 be estimated to 3–8 m/year. Somewhat lower figures, 3–4 m/year, are mentioned by Caldenius (1924). The variation in the figures depends on the different rates of movement of different delta lobes.

Since only suspended material can be transported from one reservoir to another this has the consequence according to Arnborg (1959) that coarser material, which in an unregulated river would have reached the delta, will be accumulated in the reservoirs. The speed of advance of the delta front should therefore be slower today than before the regulations of the river in 1939–66.

The oldest, relatively accurate map of the investigation area is dated 1678 and drawn by Ch. J. Stenklyft (Fig. 7). A characteristic feature of the map is the large number of islands and tributaries which convey a very different picture of the delta morphology 300 years ago, compared with the wholly sub-aquatic delta plain of today (see Fig. 8). In 1678 there were 32 islands between Styrnäs and Nyland, 10 of them being of considerable size. At present there are only nine islands, of which Gistgårdsön, Fröksholmen, Lillholmen immediately south of Fröksholmen, the Lillholmarna islands just north of Styrnäs, Utnäsgrundet and Logrundet are natural formations, while Lilla Norge consists chiefly of ballast from boats. The island at Södra Sandslån has to some extent been changed by excavations in the sound between the island and the mainland.

The development of the area east of the present course of the river offers the most interesting aspects as regards its formation in connection with the advance of the delta and the process of the later elevation of the land. According to Stenklyft's map this specific area contained some 20 islands, the largest of which, called Hammarsön, was

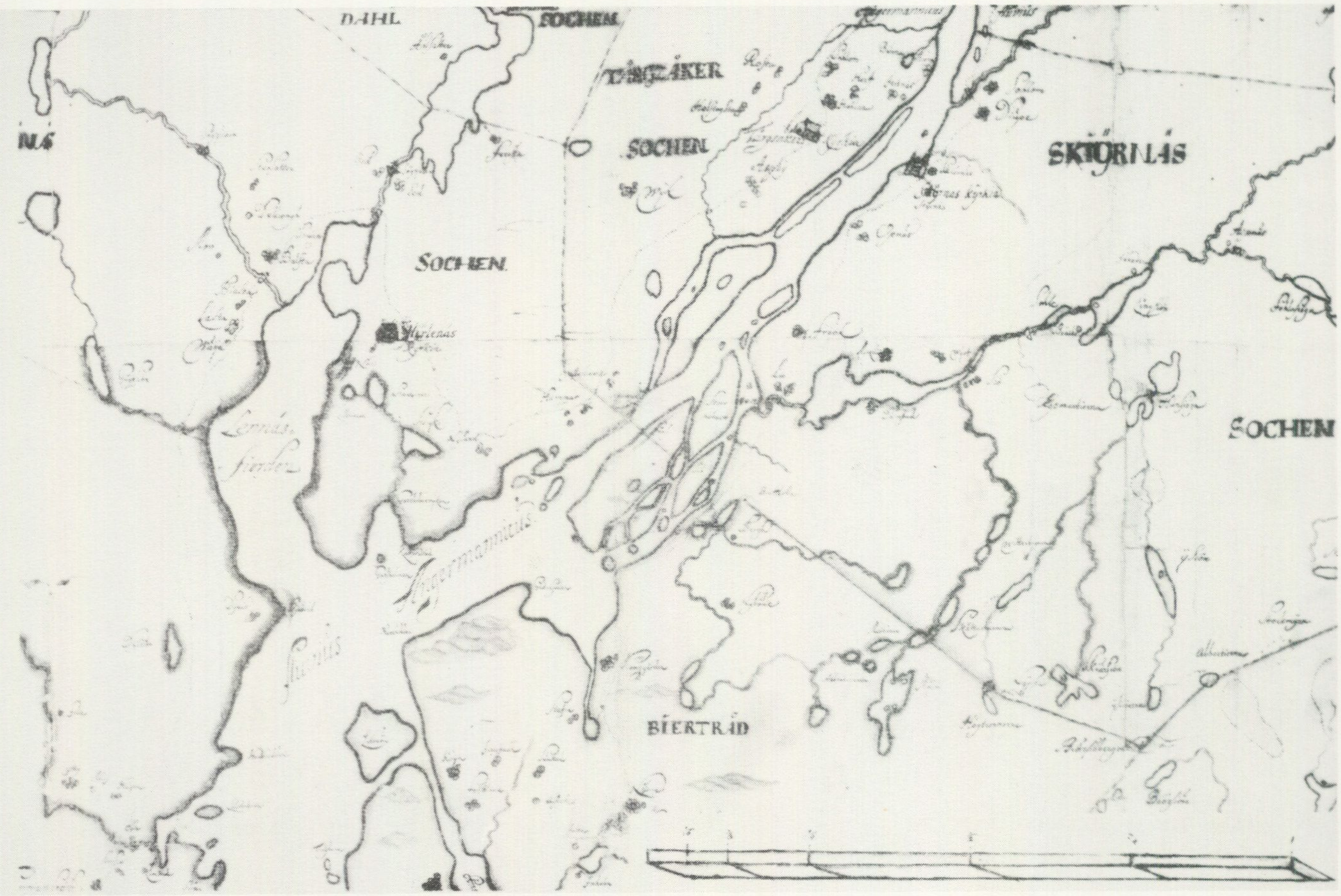


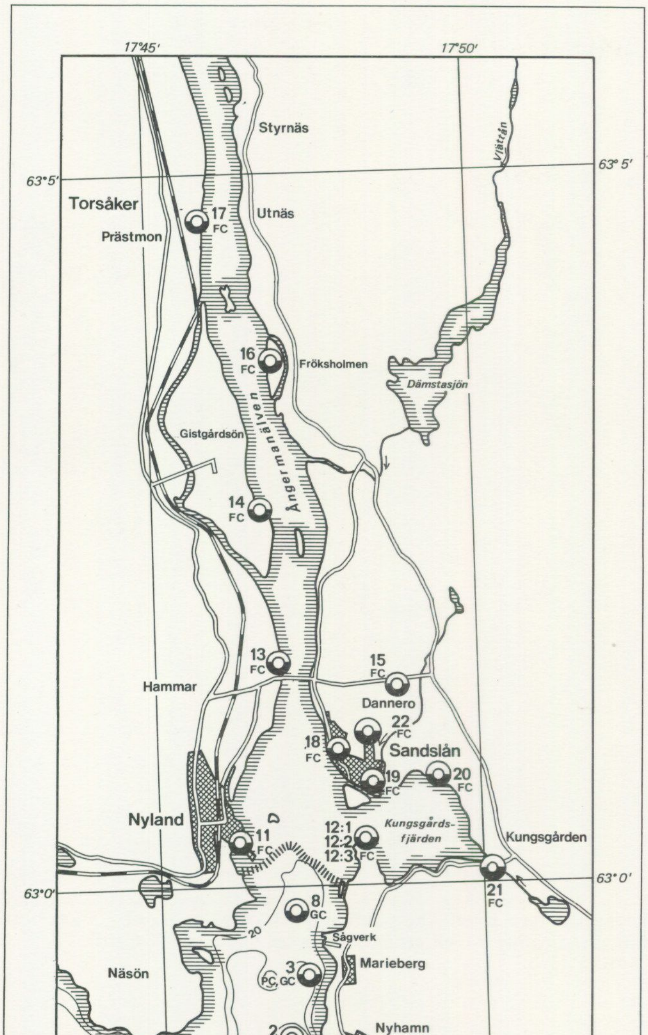
Fig. 7. Part of the C.J. Stenklyft's map of the lower Ångermanälven river from 1678.

3 km long and 1 km wide. It comprised *inter alia* what is now Sandslån and the glaciofluvially caused highlands to the north-east thereof. Above Sandslån Storholmen was situated, delimited to the north by the Loån. At the source of the latter there was a 50–100 m wide watercourse which was fed by the former Loån river. This branch of the river, known as Losundet, followed a wide curve down to Kungsgårdsfjärden (marked as Gädnäsviken on Stenklyft's map). Before it reached Kungsgårdsfjärden it increased in width east of Hammarsön into a 1.5 km wide river filled with islands of varying size. As late as 1787 Losundet still presented a network of watercourses but according to Arnborg (1959) it is not likely that the main river still flowed there. Instead the 200–300 m wide branch of the river west of Hammarsön was by then responsible for the flow of water.

Nowadays the landscape has changed (Fig. 9). The eastern branch on the 1678 map is dry, but in the terrain it is still possible to distinguish the channels which once separated the islands. The bottom of these former channels is now often overgrown with sedge vegetation (Fig. 10), which is indicated by the fact that the ground water is more or less visible there. Similar dried up channels are to be found at Prästmon, where Prästön and Holaön once lay. Today the islands have cohered to the land. Styresholm Fortress once stood on the northernmost part of the southern island (see p. 7).

The main features of Gistgårdsön were formed already in 1678. A major land formation has however occurred within the upper part, *inter alia* the former "Arpbyöhren" has merged with Gistgårdsön (Arnborg 1959). Similarly a land formation has taken place on the opposite bank of the river south of Fröksholmen. On the other hand a 100 m long island, "Svart Holmen", in the river outside the mouth of the Loån has disappeared completely by erosion.

Judging by Stenklyft's map an island formation also occurred askance from Hammars engineering workshop. This island is now eroded away, and according to Arnborg (1959) the area reveals sediment washed up from the bottom of the former fjord.



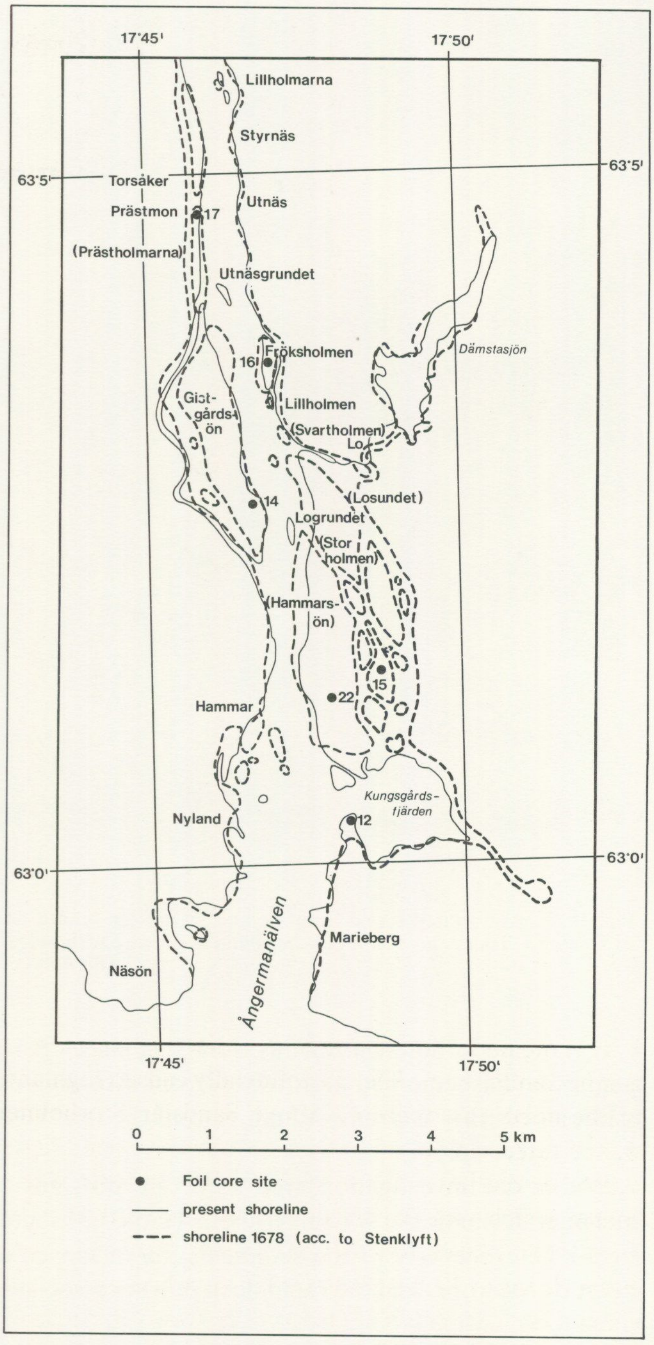


Fig. 9. Map showing the present and past (1678) shoreline in the river mouth area of the Ångermanälven. Important supra-aquatic coring sites are marked. Note the river branch Losundet in 1678, which nowadays is dried up.

Fig. 8. Bathymetric chart of the Ångermanälven estuary and the river mouth area showing the locations of both the sub-aquatic and the supra-aquatic coring sites. Contour interval 20 m.

Fig. 10. Part of a dried sound from the ancient eastern branch of the Ångermanälven river. The photograph was taken about 1.5 km north of Dannero. Today the bottom of the sound is covered with sedge vegetation indicating a high ground-water level (Photo: I. Cato).

It is of special interest for this work that since 1678 a peninsula has emerged northward from Kungsgårdsfjärden's south-westernmost limit toward the land (Fig. 9, see further p. 44).

Within the investigation area there are no signs of meander formations, which Arnborg (1959) attributes to the heterogeneity of the sediment, the incidence of bedrock outcrops, and the rapid deep erosion associated with the elevation of the land. All these circumstances have promoted the concentration of the currents to a few channels and the cohesion of island formations with the mainland. These conditions have contributed crucially to the very good preservation in such large measure of the original varved postglacial sediments, and thereby facilitated a continued expansion of Lidén's chronology.

The investigation area

The investigation area extends along both sides of the River from Kramfors in the south to Prästmon 20 km to the north (Figs. 1 and 8). The level conditions in the area have been measured photogrammetrically by Arnborg (with the reference level ±0 above sea level according to Sweden's precision levelling in 1900) and reported in a map with 2 m equidistance (Arnborg 1959, Pl. II).

Within the area the Ångermanälven presents a distinct curve at Styrnäs Church, caused by the mountain massif on the left bank. South of Utnäs the topography was such as to permit filling of the prehistoric fjord with delta sediment which reaches about 8 m above sea level. Channels, island formations and terrace planes of delta type are common in this area. The right bank, however, displays no delta forms but instead presents a series of islands of fluvial sediment (see Fig. 7) which gradually cohere ("Prestholmen" and "Holaön" at Prästmon) or are in process of being joined to the mainland (Gistgårdsön, Fröksholmen). The area on the left hand side of the River between Utnäs and Kungsgårdsfjärden, on the other hand, consists of a delta landscape with plane terraces built up of fluvial sediment. The area abounds in eroded deep channels (Fig. 10) which have been formed without visible primary connection to the bottom morphology of the former fjord.

Immediately west of Dannero there is a stretch of high land which reaches 18 m above sea level. Linked with this ridge there is a now in large measure extracted, thick glaciofluvial deposit, which in the proximal parts is overlain by about 0.5 m thick wave-washed sediment (gravel) (J. Lundqvist, 1987). In the distal parts at Sandslån there is almost only sand with current strata and unconformity surfaces.

The present delta plane is situated south of Hammarsbron between Nyland and Sandslån. Kungsgårdsfjärden, with a central maximum depth of about 26 m (Arnborg 1959, Pl. II), is more or less cut off from the estuary of the River by the extension of the delta.

The delta is delimited toward the estuary by a well marked rebound slope, outside which the depth rapidly increases from about one to five m at the edge of the precipice to between 15 and 25 m at its foot. Here begins the present estuary which consists of a greatly deepened fissure with a depth of 50–100 m (see above).

The recent delta plane is wholly sub-aquatic in consequence of the considerable depth of the original estuary and the rapid elevation of the land, 0.85 cm/year (Bergsten 1954), which, according to Fromm (1944), prevented the delta from being built up to project above the water surface. The thickness of the sediment at the delta amounts, according to Arnborg (1959), to an average of 50–100 m. It is composed of several separate sand lobes on a relatively even bottom beside the deep channel of the main current which attains a depth of 10 m.

Arnborg's (op. cit.) stratigraphical investigations of the bottom show that the active delta plane is built up of bottom transported, chiefly sandy, and even fine gravel material with inclusions of coarse gravel (nomenclature according to SGF's Laboratory Committee 1981, Karlsson & Hansbo 1982). The bulk of the suspended matter which was recently accumulated on the delta plane consists of fine silt. As a rule clay is not represented in the delta sediments but may in isolated cases amount to 1–2 %. The clay was deposited primarily below the delta in the estuary of the River.

The mobility of the delta has been greatest in connection with high water flow in the River. With a water discharge of less than 1000 m^3/sec practically all bottom transport is thought to cease (Arnborg op.cit.).

The lack of solid bottoms below Hammarsbron has had the result that the delta ramification normally caused by the current could continue in the area. Recently (after 1950), however, the accumulation of fine sediments, has changed markedly. The stable accumulation bottom, which was found in 1950 in the left-hand side of the delta area, had by 1958, according to Arnborg (op.cit.), spread over almost the whole delta plane. Arnborg considers that this results solely from reduced high water flow in consequence of the regulation of the River.

In Arnborg's opinion (op.cit.) the delta of the Ångermanälven is of a special type since it flows into a deep fjord. In all probability these special circumstances, coupled with the low salinity of the Baltic Sea (5‰ according to *inter alios* Pietikäinen *et al.* 1978), allowed a deposit of varved postglacial, and varved subrecent and recent sediments. This kind of sedimentation continues in the area even today (see p. 41).

Field work, coring and sampling

The current project was launched in August and September 1978 with field investigations around the mouth of the Ångermanälven. With the help of available drilling data from the Swedish State Railways, the National Road Administration, other investigations (by *inter alios* Arnborg in 1959) and SGU's own probings eight drill sites along the Ångermanälven were selected in consultation with Professor Jan Lundqvist and Dr. Åke Hörnsten. These sites were located on both sides of the river between Lidén's old site at Prästmon and the estuary of the Ångermanälven just below Nyland (Fig. 8; details are given in Table 1). The cores were drilled by means of a Swedish foil piston corer, FC, (Kjellman *et al.* 1950). The diameter of the drill is 38 mm, and its construction allows of the obtainment of intact cores of up to 11 m in length. This is possible because the friction between the drill core and the drill tube is reduced with the help of twelve 0.1 mm thick steel foils.

The collection of recent and subrecent sediment profiles was executed from the National Board of Fisheries'

Table 1. Data from the foil piston corestaken close to the Ångermanälven river-mouth.

Core No	Site	Position Lat.	Long	Date of coring	Ground surface[1] (Interval in m above sea level)	Penetration (m)	Coring start-end (m below ground surface)	Core length (m)	No of varves measured	Connected	Notes
11	Nyland	63°00′28″	17°46′10″	1978	0–2	>15	1.60–9.50	7.90	n.d.	No	No proximal varves, bioturbation
12:1	Kungsgårdsfjärden	63°00′20″	17°48′11″	1978	0–2	>20	1.40–11.10 11.10–16.00	14.60	367	Yes	
12:2		63°00′20″	17°48′11″	1982	0–2	>27	4.15–13.35	9.20	155	Yes	
12:3		63°00′20″	17°48′11″	1983	0–2	>27	10.00–17.30 17.30–20.60 20.45–23.05	13.05	786	Yes	
13	Hammar	63°01′34″	17°46′42″	1978	4–6	>14	2.30–11.70	9.40	n.d.	No	Indistinct varves
14	Gistgårdsön	63°02′38″	17°46′56″	1978	4–6	>14	1.70–11.50	9.80	874	Yes	
15	Dannero	63°01′22″	17°48′46″	1978	2–4	>15	1.80–11.50	9.70	949	Yes	
16	Fröksholmen	63°03′42″	17°49′00″	1978	8–10	>16	3.00–12.70	9.70	660	Yes	
17	Prästmon	63°04′37″	17°45′49″	1978	8–10	>16	3.30–12.80	9.50	181	Yes	
18	Sandslån	63°00′56″	17°47′42″	1978	2–4	>12	1.00–10.40	9.40	n.d.	No	Indistinct varves, bioturbation
19	Sursundet	63°00′48″	17°48′25″	1982	0–2	>13	2.05–12.20	10.15	48	Yes	
20	Edholmstorpet	63°00′43″	17°49′21″	1982	0–2	>15	1.30–3.70	2.40	–	No	Erosion
21	Kungsgården	63°00′07″	17°50′07″	1983	0–2	14.3	1.00–10.90	9.90	–	No	No proximal varves
22	Pershem	63°01′05″	17°48′14″	1983	2–4	>21	3.50–13.20	9.70	469	Yes	

[1] According to plate II in Arnborg (1959, Part II).

ship R/V Argos in the inner reaches of the River's estuary between Nyland and Kramfors (Fig. 8; details are given in Table 2).

The cores from the fjord bottom were taken by means of a piston corer, PC (constructed by Axel Jonasson and described by Kullenberg 1947) 10 m long with a diameter of 45 mm. All the sites (1–6) which were sampled with the piston corer, together with two further sites (8 and 9), were also sampled with a 1 m long gravity corer, GC (Jonasson & Olausson 1966). The latter in view of the fact that it is very difficult to set the release mechanism of the piston corer when sampling so that sodden and unconsolidated recent superficial sediment such as that of the Ångermanälven can be obtained intact. On the other hand this was possible with the help of a gravity corer. All the cores, with the exception of the gravity core samples, have been divided into 1 m sections, packed in plastic foil, and transferred to specially constructed sheet-metal boxes and wooden crates for further transport to a laboratory. The severely unconsolidated gravity cores, on the other hand, were transported in upright position in their plastic tubes.

In the laboratory the drill cores were divided longitudinally and the halves were turned sideways on, after which one half was allowed to air-dry for a while until its sediment assumed the degree of humidity at which the limits of the varves are most distinct. The measurement of the varve thickness and the construction of the varve diagram then followed the accepted principles and the method which was first devised and developed by G. De Geer (1912 and 1940). The measurement of the varves was executed on the drill cores as far down in the series of layers as the varves were discernible, or until a sufficiently large overlap with the adjoining profiles had been obtained.

Once the varve series from the 1978 collection were identified and connected with each other a gap proved to exist between core 12 (designated 12:1) beside Kungsgårdsfjärden and other profiles further upstream. This gap was not expected as the core reached a depth of 16 m as a result of two drillings.

An attempt was made to fill this gap in November 1982, when profiles 19 and 20 were drilled together with the deepening of site 12 (designated 12:2). The gap could not be filled this time either. Therefore a new attempt was made in June 1983, when profiles 21 and 22 were drilled and site 12 was deepened again (designed 12:3). The deepening to 23 m at this site proved to be successful.

In the present investigation sediment cores to a total length of about 200 m were collected and over 10 000 varves measured and counted. After rejection of sediment cores from certain sites (11 Nyland, 13 Hammar,

Table 2. Data from the piston and gravity cores taken in the Ångermanälven non-tidal estuarty.

Core No	Coring technique	Position Lat.	Long	Water depth (m)	Date of coring	Core length (cm)	No of varves measured	Connected	Notes
1	Piston Corer	62°58′37″	17°47′01″	97	1978	932	n.d.	no	Very few proximal varves
1	Gravity Corer	62°58′37″	17°47′01″	97	1978	54	n.d.	no	Indistinct upper part
2	Piston Corer	62°58′55″	17°47′00″	53	1978	966	767	yes	
2	Gravity Corer	62°58′55″	17°47′00″	53	1978	72	44	yes	
3	Piston Corer	62°59′21″	17°47′17″	47	1978	749	144	yes	
3	Gravity Corer	62°59′21″	17°47′17″	47	1978	53	29	yes	
4	Piston Corer	62°58′02″	17°47′08″	68	1978	604	n.d.	no	Very few proximal varves
4	Gravity Corer	62°58′02″	17°47′08″	68	1978	45	47	yes	Not connected, erosion (?)
5	Piston Corer	62°57′42″	17°47′32″	72	1978	816	n.d.	no	No proximal varves
5	Gravity Corer	62°57′42″	17°47′32″	72	1978	58	n.d.	no	Disturbed varves
6	Piston Corer	62°57′07″	17°48′17″	100	1978	791	720	yes	
8	Gravity Corer	62°59′50″	17°47′06″	19	1978	66	32	yes	
9	Gravity Corer	62°58′08″	17°47′18″	75	1978	76	35	yes	
491	Gravity Corer	62°59′10″	17°47′13″	42	1979	47	29	yes	X-ray, Axelsson (1983)

Table 3. Data from other investigations used in the present work.

Core no.	Site	Coring technique or other methods	Date of coring	No of varves	Reference
–	Prästmon	Measured in a bluff	c.1909–15	1091	Lidén in Lidén† & Cato, in press
I	Nyland	Piston Corer	1952	83	Granar 1956
II	Nyland	Piston Corer	1952	63	Granar 1956
IV	Nyland	Piston Corer	1952	99	Granar 1956
D	Nyland	Piston Corer	1945	432	Fromm unpubl.
E	Nyland	Piston Corer	1945	510	Fromm unpubl.
F	Nyland	Piston Corer	1945	516	Fromm unpubl.
2b	Nyland	Piston Corer	1943	16	Kullenberg & Fromm 1944

18 Sandslån, 19 Sursundet, 20 Edholmstorpet, 21 Kungsgården together with piston cores and gravity cores 1, 4, 5 from the estuary of the Ångermanälven) which for various reasons did not yield results in the form of measurable or intact varve series, more than 110 m sediment cores remained for further processing. Of these some 6 500 varves from 17 sediment cores have been measured, correlated to each other, and connected with eight series of a total of 2 800 varves from Kullenberg & Fromm (1944), Granar (1956), Fromm (unpublished) and Lidén (Lidén † & Cato, in press), see compilation Table 3.

The correlation work was carried out with the help of hand-drawn varve thickness diagrams and sketches of specific varves.

At a later stage the hand-drawn and correlated varve thickness diagrams were digitalized (with a precision of varve thickness of ±0.5 mm), stored and plotted in a system developed by J. Schedin on SGU's Prime/550 Computer in order to assume the form in which they are presented in this paper. The system, with the programme written in Fortran, signifies in brief that the digitalized clay varves are stored in a data base (Mimer, relation data base system) from which the points are plotted via a programme which automatically retrieves the desired data on varve thickness from the data base and processes them on a Calcomp plotter.

General description of the sediment profiles and varve diagrams

The appearance of all the drill cores in the present investigation agrees with Lidén's (1911, 1913 and 1938) observations of the postglacial sediments in the bluffs of the river valley, and with Kullenberg & Fromm's (1944) observations of the recent and subrecent sediments in the estuary of the Ångermanälven.

The stratigraphical structure of the fluvial sediment is illustrated in Fig. 6 and described on p. 11. In view of the terminology which will be used below there is reason to expound and clarify certain concepts once more since Lidén's figure (Fig. 6) verges on the summary.

The till or the coarse glaciofluvial material in the valleys of the Norrland rivers is overlain by glacial clay on which is superimposed the grey-blue, rarely varved postglacial estuarine clay. On this rests first postglacial, chiefly fine silty, varved, distal delta sediment, which gradually gives way to silty, sandy, varved, proximal delta sediment. In certain cases unvarved flood plane sediment such as recent fluvial sand or gravel is to be found unconformable to proximal delta sediments.

The corings FC 11, 13, 20 and 21 penetrate the glacial clay while the others terminate in the postglacial sediments. At drill site FC 20 (Fig. 8) almost all the postglacial sequence of layers are eroded, presumably by the former eastern branch of the River (Losundet), which flowed here until the mid 18th century (see p. 14).

Sandy flood plane sediments several metres thick occur on top of the postglacial varved sediments at coring sites FC 19 and FC 22. These corings and a dozen probings demonstrated that the greater part of the varved delta sediments on southern Sandslån are covered by flood plane sediments.

The grain size (nomenclature according to SGF Laboratory Committee 1981, Karlsson & Hansbo 1982) of all the cores drilled on land within the investigation area varies primarily between fine silt and fine sand but layers of medium sand occur. The fine silt predominates in the deeper, distal deposits of sediment while fine and medium sand appear in certain proximally deposited layers in the upper parts of the sequence.

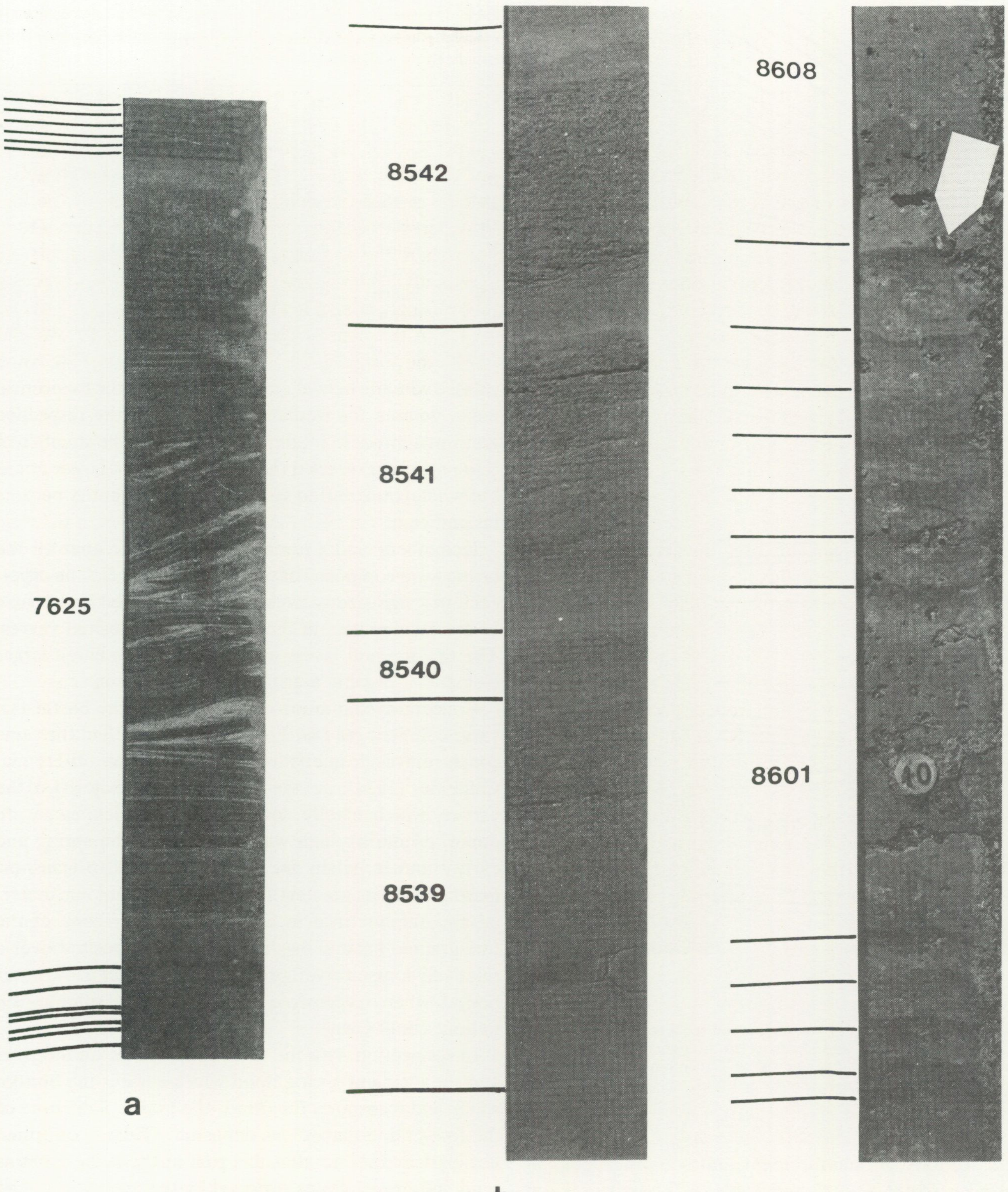
The recent sediments in the estuary of the Ångermanälven display similar variations. The sediment profiles GC 8, GC 3 and PC 3 nearest the delta (Fig. 8) are predominantly of coarse silt to fine sand, the profiles GC 2, PC 2 and GC 9 are medium to coarse silt, and in the most distal profile PC 6 – in relation to the delta – the sediments are of fine silt. The expected trend with declining grain size with increased distance from the delta front in the recent sediment layers is also valid if the perspective goes from the recent sediments in the upper part of the profiles to the lower, subrecent parts of the same profile. The reason for the latter state of affairs is that the delta, via the elevation of the land, wandered down the River and thereby eventually approached the sampling sites with the result that the gradually accumulated and overlain sediments became increasingly coarse in character.

As in the case of the glacial clay (e.g. G. De Geer 1940) the postglacial sediments in the valley of the Ångermanälven are varved (Fig. 11 a–e). Each varve consists of two zones, a lower with relatively coarse-grained, and an upper with fine-grained material. In contrast to the often distinct, black glossy, so-called winter layer of the upper sections of the glacial clay, the upper zone of the delta sediments consists of a thinner, grey to dark grey clayey to fine silty layer. This layer is frequently composed of a lower, thicker, dark part and an upper, thinner, light grey part, which occasionally contains sand and gravel particles (Fig. 11c) (cf. Kullenberg & Fromm 1944). The lower, coarse-grained part of the postglacial varves is usually much thicker than the upper zone. As an extreme example we may mention the 88 cm thick varve 8894 in profile PC 3 Nyland (Fig. 13 c), the lower layer of which is about 85 cm thick. The difference is rarely so great, however, as the conditions at 1:3–1:5 are more representative. But the variations are considerable, primarily in the proximally formed varves.

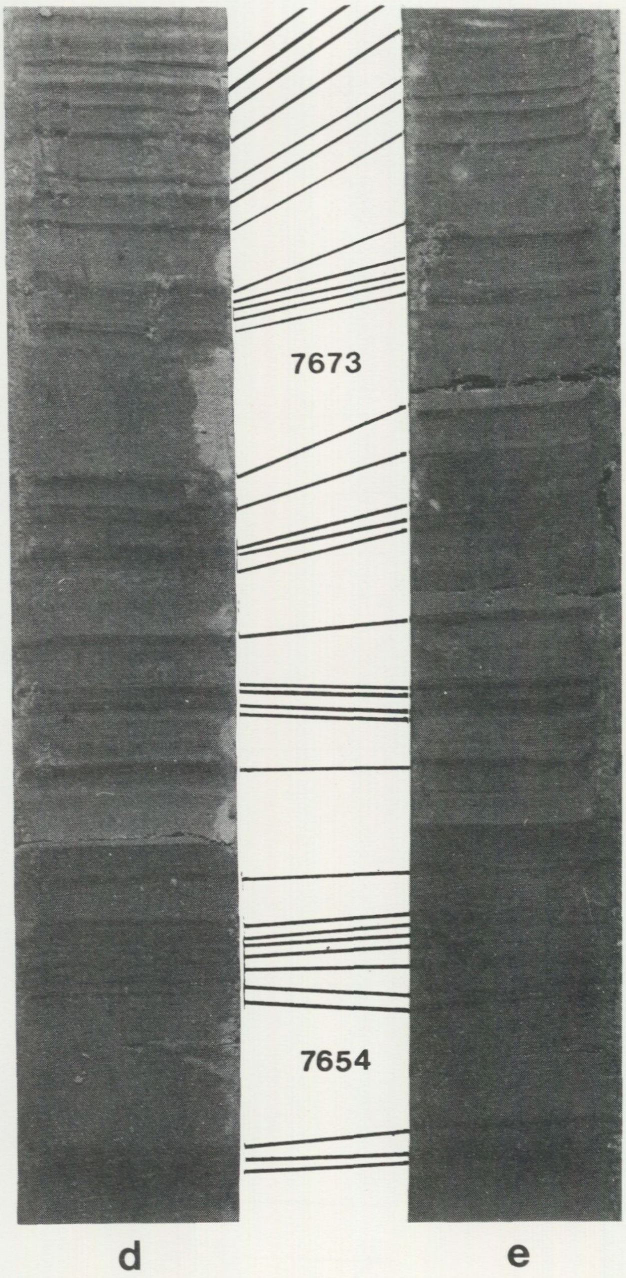
By and large the more coarse-grained, thicker part of the varves has few prominent internal layers (Fig. 11b). Where these occur they comprise sedimentary structures marked by different degrees of rust colour, indicating periods of bed load transport (Fig. 11a, varve no. 7625 cf. Caldenius 1924 p. 41 and Bergström 1968 p. 38). Turbidites have also been observed.

The above account of the sediments outlines the general trend displayed by the stratification. But variations and deviations are common so that the sequences of layers may be described as variegated. There is no point in reporting these changes in grain size and colour in detail. In general, however, it may be said that thick varves are lighter and consist of coarser grain sizes than thin varves.

In order to illustrate the structure of the recent varves in the estuary of the Ångermanälven Kullenberg and Fromm carried out a number of approximative determinations of the grain size composition of the different



Figs. 11a–c. Photographs of parts of varved sequences in cores from Gistgårdsön (*a*), Kungsgårdsfjärden (*b*) and Nyland (*c*). The numbering of the varves constitutes a direct continuation of Lidén's postglacial chronology, where varve 1 corresponds to the first postglacial varve in the valley of the Ångermanälven. The arrow marks a sand grain. (Photo: I. Cato).



Figs. 11d–e. Photographs of parts of varved sequences in cores from Gistgårdsön (to the left) and Dannero (to the right). Note the good agreement between the individual varves. Concerning the numbering of the varves, see Fig. 11a–c. (Photo: I. Cato).

Table 4. Grain-size distribution expressed in volume percentages in different parts of varves from recent sediments of the Ångermanälven estuary (from Kullenberg & Fromm 1944).

Sample	Unit	Clay	Fine silt	Medium silt	Coarse silt	Fine sand
2A	Summer	Traces	0.2	4	40	55
2B	Winter	0.5	2	18	63	16
3A	Summer	Traces	0.5	7	48	44
3B	Winter	0.4	3	19	54	23
3C	Summer	0.1	0.6	8	50	41
3D	Spring	0.8	4	29	59	8
4A	Winter	1.4	5	35	58	1
4B	Summer	0.4	4	39	55	2

varve sections by measurement and counting under a light microscope (Fig. 12 and Table 4). The grains were thereby divided into magnitudes between 0.6 and 20 μm, while grains larger than 20 μm were combined in two subgroups for each grain size class according to Atterberg (1903). Six to 12 hundred grains were counted per analysis. The proportion of the different grain categories in the total, expressed in volume per cent, were calculated with the help of grain numbers and the theoretical mean volume for isodiametric grains in the respective grain magnitudes. In almost all samples the number of clay particles exceeded the total number of larger grains but when converted to volume the clay quantity became insignificant.

Kullenberg and Fromm (op.cit.) found that all the layers were composed of well sorted material. The difference in grain size between the fine-grained and coarse layers was greatest in the proximally deposited varves. The fine-grained layers also proved to contain a larger element of organic detritus and sulphur iron.

Concerning the mode of formation of the postglacial varves Kullenberg and Fromm (1944) reached the same conclusion as formerly reported by Lidén (1911) and Caldenius (1924): i.e. the coarse-grained majority of the varves, which wholly determine their thickness, were deposited during high water periods in the spring and early summer, when the River's capacity to transport material is at its greatest. The content of organic material and sulphur iron in the lower, darker zone of the fine-grained layer shows that this was deposited over a relatively long interval, probably throughout a low water period, when oxygen-free bottom water and sulphur iron fall-out could ensue.

In connection with the melting of the ice on the river and the incipient spring flood which aerates the bottom water and transports fine mud, the upper, light zone of the fine-grained layer was deposited. This is confirmed not least by the fact that this part of the layer contains sand and gravel grains dropped by the ice.

The thickness measurements performed in the current investigation are reported together with Lidén's original measurements (Lidén† & Cato, in press) of the 500 uppermost varves from his classic site at Prästmon in Figs. 13a–k. The varve thickness diagrams bear the varve number at the bottom and at the top two time scales

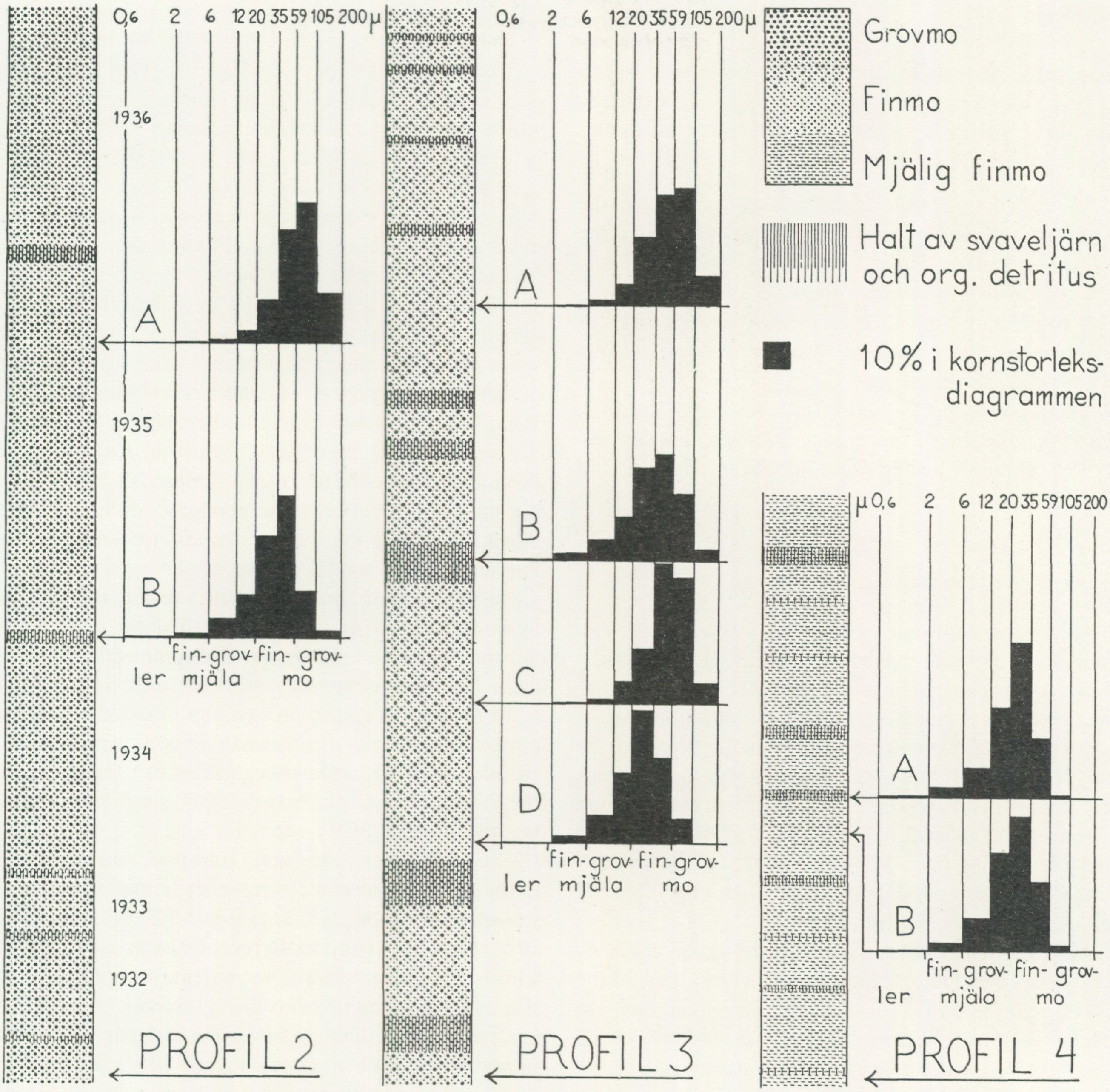


Fig. 12. Grain-size distribution at different levels in three varved cores from Nyland in 1943 (from Kullenberg & Fromm 1944).

exactly connected with the present. The one states the age of the varve before and after the present (B.P.) and the other before (B.C.) and after (A.D.) the Birth of Christ. The numbering of the varves (in Figs. 11a–e, 13a – 13l and 25a–25b stated as PG varve no.) constitutes a direct continuation of Lidén's postglacial chronology for the valley of the Ångermanälven, where varve 1 or year 1 corresponds to the deposition of the first postglacial varve (Lidén 1938).

The varve thickness diagrams for the profiles GC 2, GC 3, GC 8, GC 9, PC 2, PC 3 and PC 6 comprise the total length of the profiles included (with the exception of the lower, disturbed parts of PC 6). In the other profiles the measurements and reports are confined to such a depth that a sufficient number of varves overlapping and connected to adjacent profiles (in general 300–500) were obtained.

Remarks on varve connections and varve diagrams

In order to obtain an exact connection between the present and Lidén's postglacial geochronology, and thereby with the Swedish Time Scale it was essential in this project to achieve to following:

1. An exact dating of the uppermost recent varves in the bottom sediments from the non-tidal estuary of the Ångermanälven River, and proof that varve formation is still in progress there.
2. A connection with Lidén's youngest varve series at Prästmon and specific verification of varves 7061–7522 in this series.
3. A link between the varve profiles in points 1 and 2, and completion of the expected difficult passage between sub-aquatic and supra-aquatic sediments in the Nyland area.

Dating of recent sediments

The first important phase of the work thus involves an attempt to confirm the calendar year affinity of the youngest varves since it is not feasible without further ado to assume that the uppermost varves in the bottom sediment really were formed continually prior to the year of sampling. In order to clarify this, correlations were sougth with *inter alia* the water discharge of the Ångermanälven. Such hydrographical observations are available, having been kept since 1909 by the Swedish Meteorological and Hydrological Institute (SMHI) (Melin 1954 and unpublished).

This means that discharge data are extant for a 40 year period both before and after the regulations of the River's natural flow. The first of the regulations was effected in 1939 and this was later followed by others. Today the River has a degree of regulation of 41 % at its mouth. The maximum mean daily discharge in the Ångermanälven is reported for the period 1909–78 in Fig. 13 a–c. The water discharge measurements for 1946 onwards derive from Sollefteå. The total discharge for the preceding period was obtained by combination of the discharge data from Forsmo (the Fjällsjöälven and the Åseleälven) and Långsele (the Faxälven) (see Fig. 1).

The successive changes in the River consequent upon the storage reservoirs and the hydro-electric plants can clearly be discerned in the discharge diagrams from Sollefteå for the years 1946 to 1958 (Arnborg 1959) and in Fig. 13 a–c. A comparison between the regulated and the reconstructed discharge (Arnborg 1959) demonstrates that the spring flood peaks have been curtailed to an increasing extent (see e.g. Fig. 14). That this change occurred primarily after 1950 is indicated by Fig. 13 a–c, which show that the maximum mean daily discharge before 1950 could amount to about 3 200 m^3/s while since 1950 it has never exceeded 2 000 m^3/s.

Since the snow melting proceeds at a more or less uniform pace within the precipitation area the spring maxima tend to take place around June 5th (Arnborg 1959). In connection with heavy rainfall in the late summer the discharge can reach a new peak which has on some occasions meant that such a high water has exceeded the spring flood, as happened at Forsmo in 1909, 1918, 1921, 1954 and 1957 (Arnborg op.cit.).

As previously mentioned by both Kullenberg & Fromm (1944) and Granar (1956) there is a direct, obvious correlation between the maximum daily mean discharge in the spring and early summer floods in the Ångermanälven and the thickness of the corresponding varve. This correlation is also proven in the present investigation (Figs. 15, 16 and Table 5). The correlation with the mean value of the spring flood, or with the mean value for the total annual discharge, on the other hand, is far less clear or in some cases non-existent. This was not the case at e.g. Lovatnet in Norway where a good correlation was found between the varve thickness and the monthly mean discharge during the period May to October (Olsen 1978).

The recent fluvial erosion, transport and deposition in the lower Ångermanälven was examined in extensive studies by Arnborg (1958, 1959) and B. Nilsson (1971, 1972, 1974, 1976) and more recently by Axelsson (1980, 1983). B. Nilsson's work shows that the transport of suspended matter before the regulations of the River amounted to an average of 85 000 tons per year in the period 1951–57. During the intensive development stage (1962–66) the transport reached an average of 116 000 tons, and after the expansion it diminished by 53 000 tons to an average of 32 000 tons per year (see Fig. 17). Thus the regulation involved a major interference with the natural condition of the River. By and large the transport of suspended inorganic material to the delta was reduced by 60 % after the latest regulation. It is also probable that the bottom transport out to the delta has declined (B. Nilsson 1974). The changes in the water level after the regulations, however, brought new points of attack for the erosion both in the storage reservoirs and along the River. According to B. Nilsson the erosion below the Sollefteå dam may have increased by more than 30 %. Since the adjustment of the landscape to the

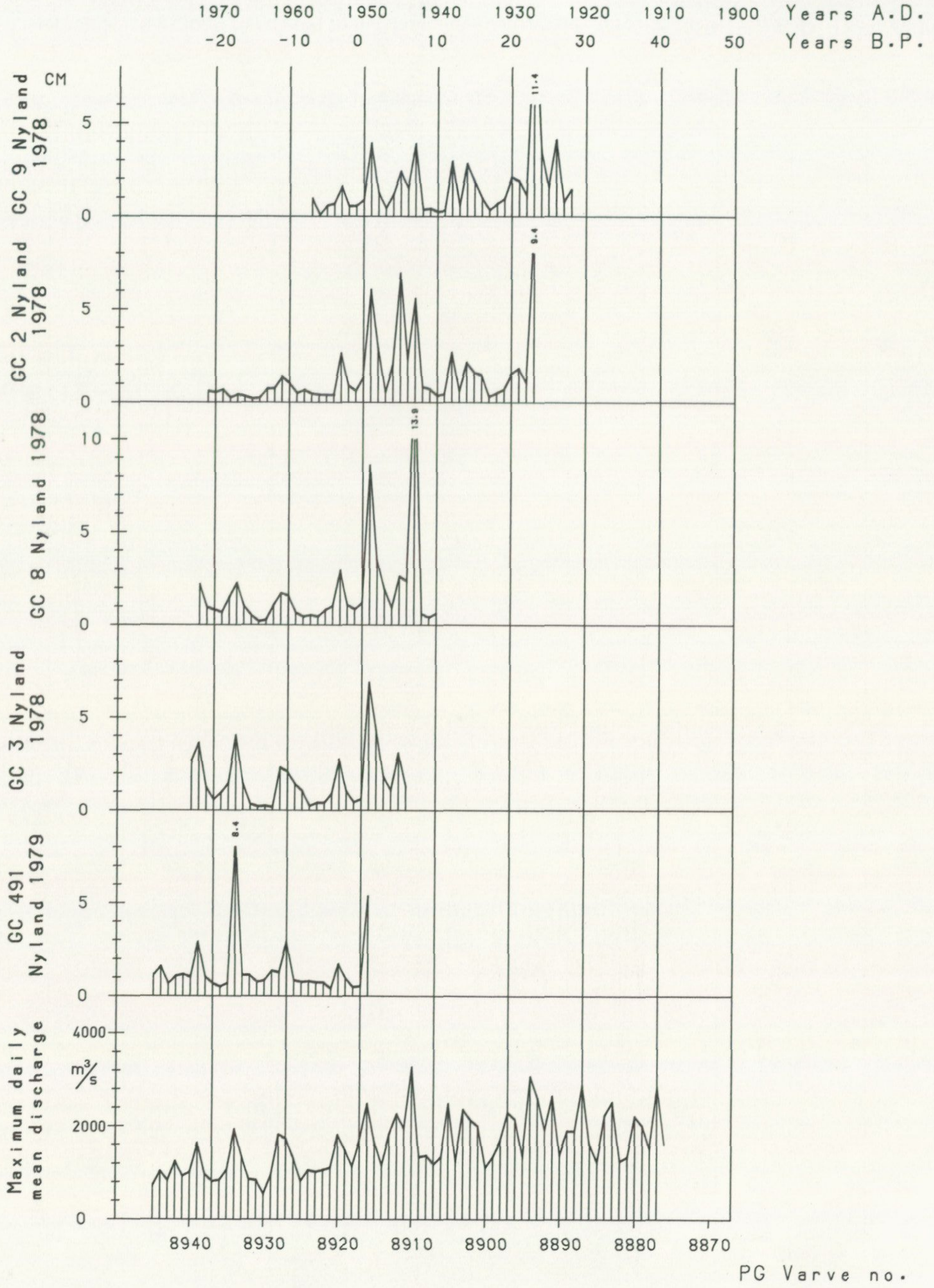


Fig. 13a. Varve diagrams from the Ångermanälven estuary, correlated to maximum daily mean discharge A.D. 1909–1978. The varve numbers below follow and extend the postglacial chronology of R. Lidén. PC = Piston Corer, GC = Gravity Corer.

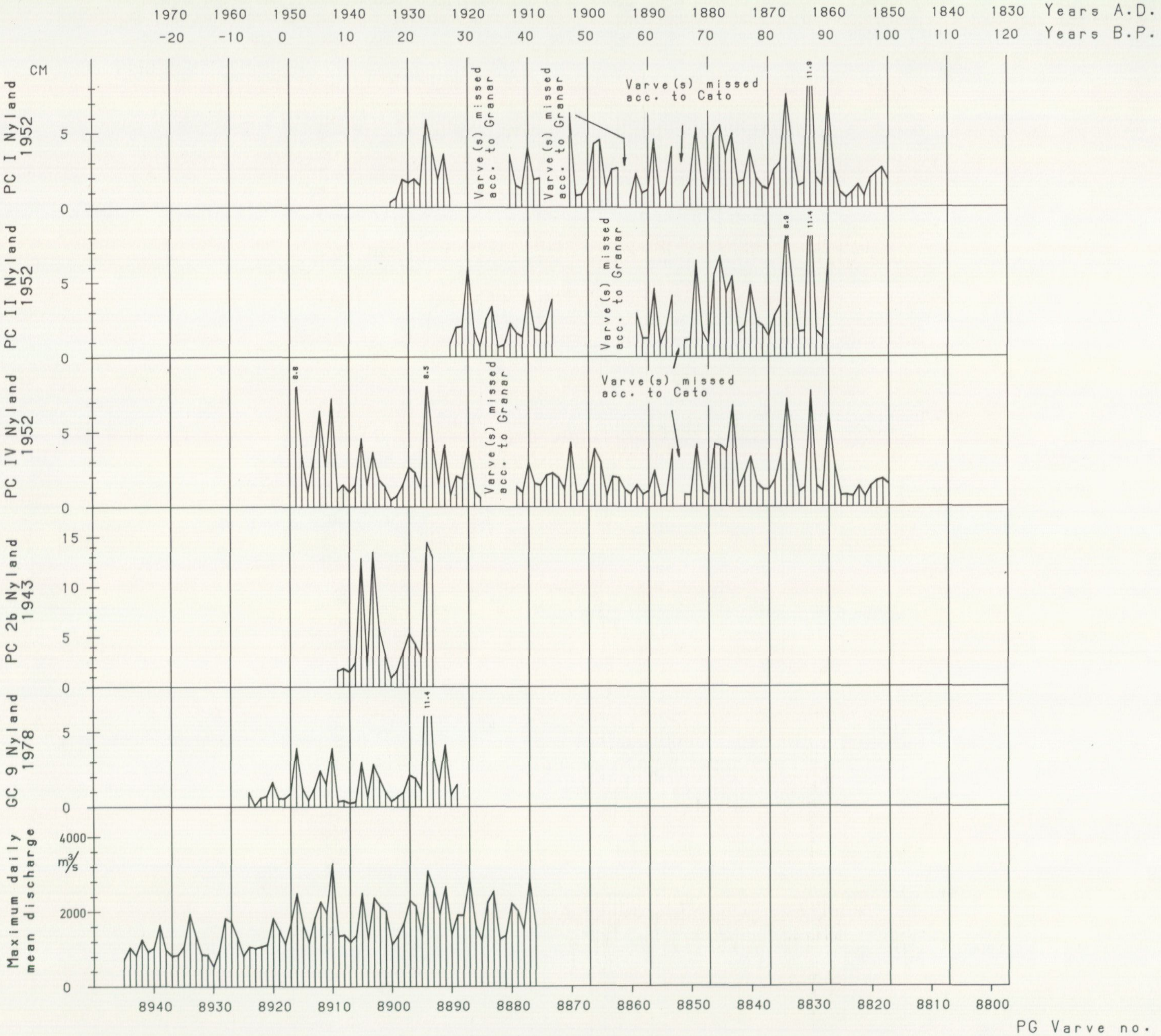


Fig. 13b. Varve diagrams from the Ångermanälven estuary correlated to maximum daily mean discharge in 1850–1978 A.D. The core PC 2*b* is from Kullenberg & Fromm (1944) and the cores PC I–PC IV are from Granar (1956).

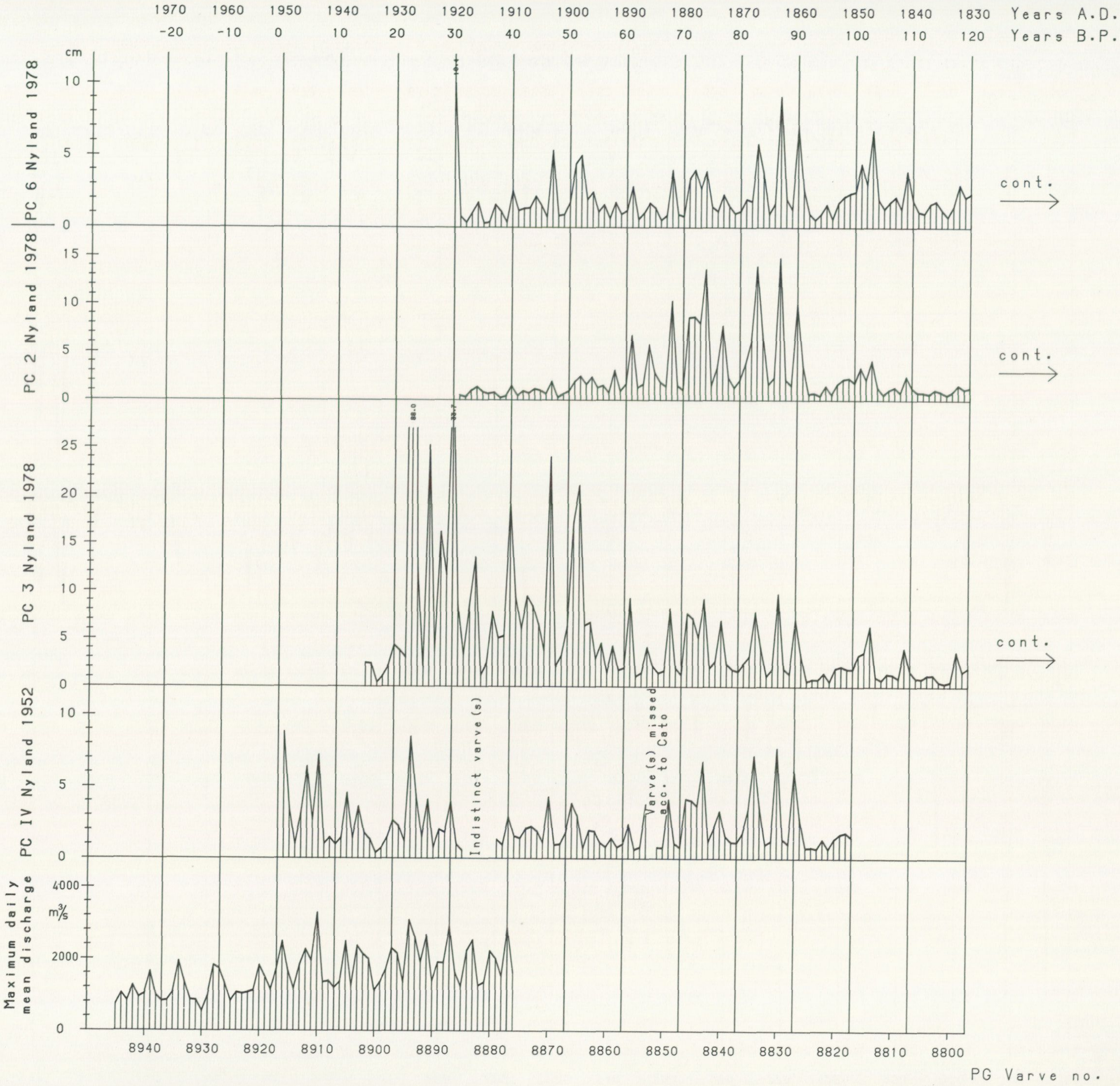


Fig. 13c. Upper parts of varve diagrams from the Ångermanälven estuary correlated to maximum daily mean discharge in 1830–1978 A.D. The core PC IV is from Granar (1956).

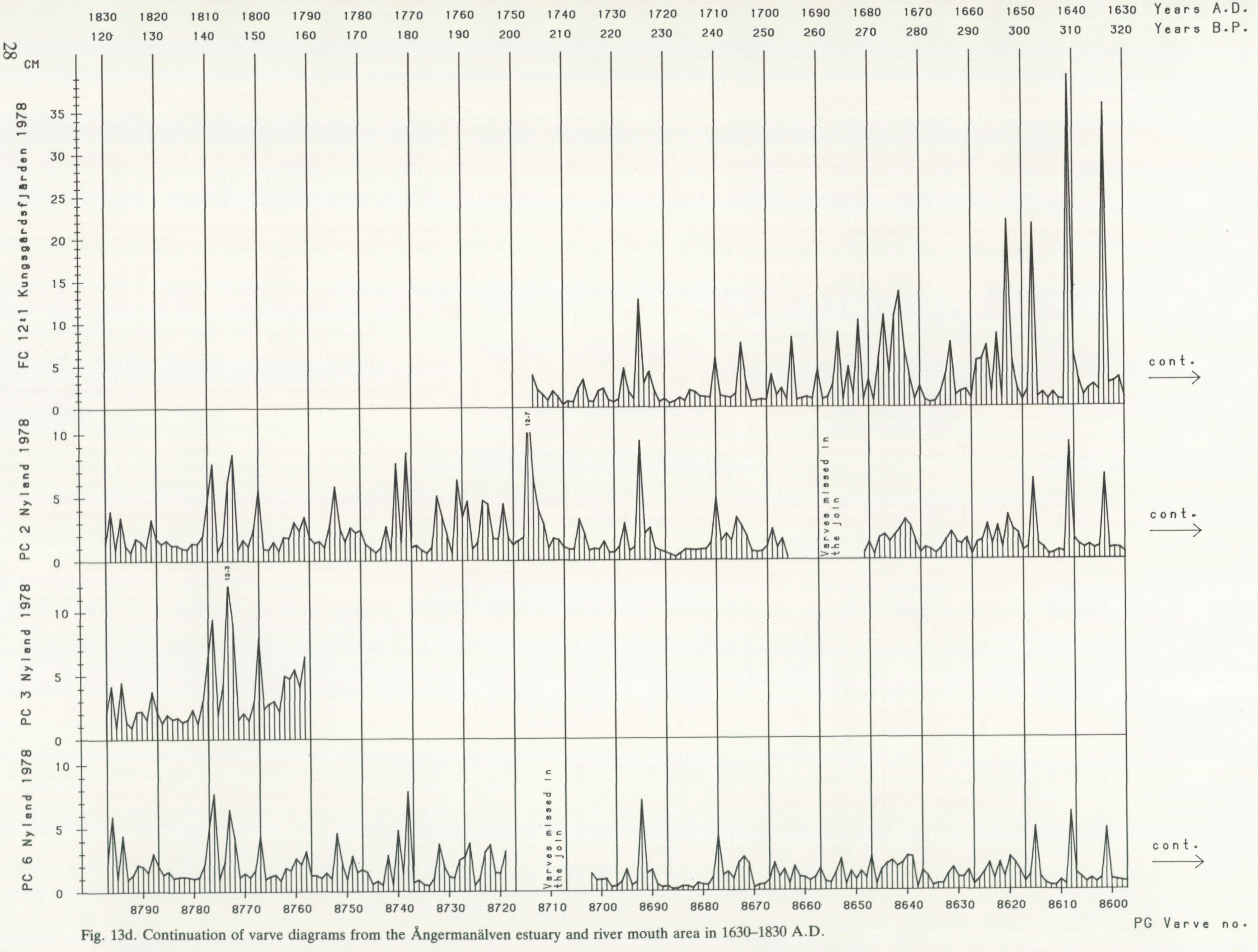


Fig. 13d. Continuation of varve diagrams from the Ångermanälven estuary and river mouth area in 1630–1830 A.D.

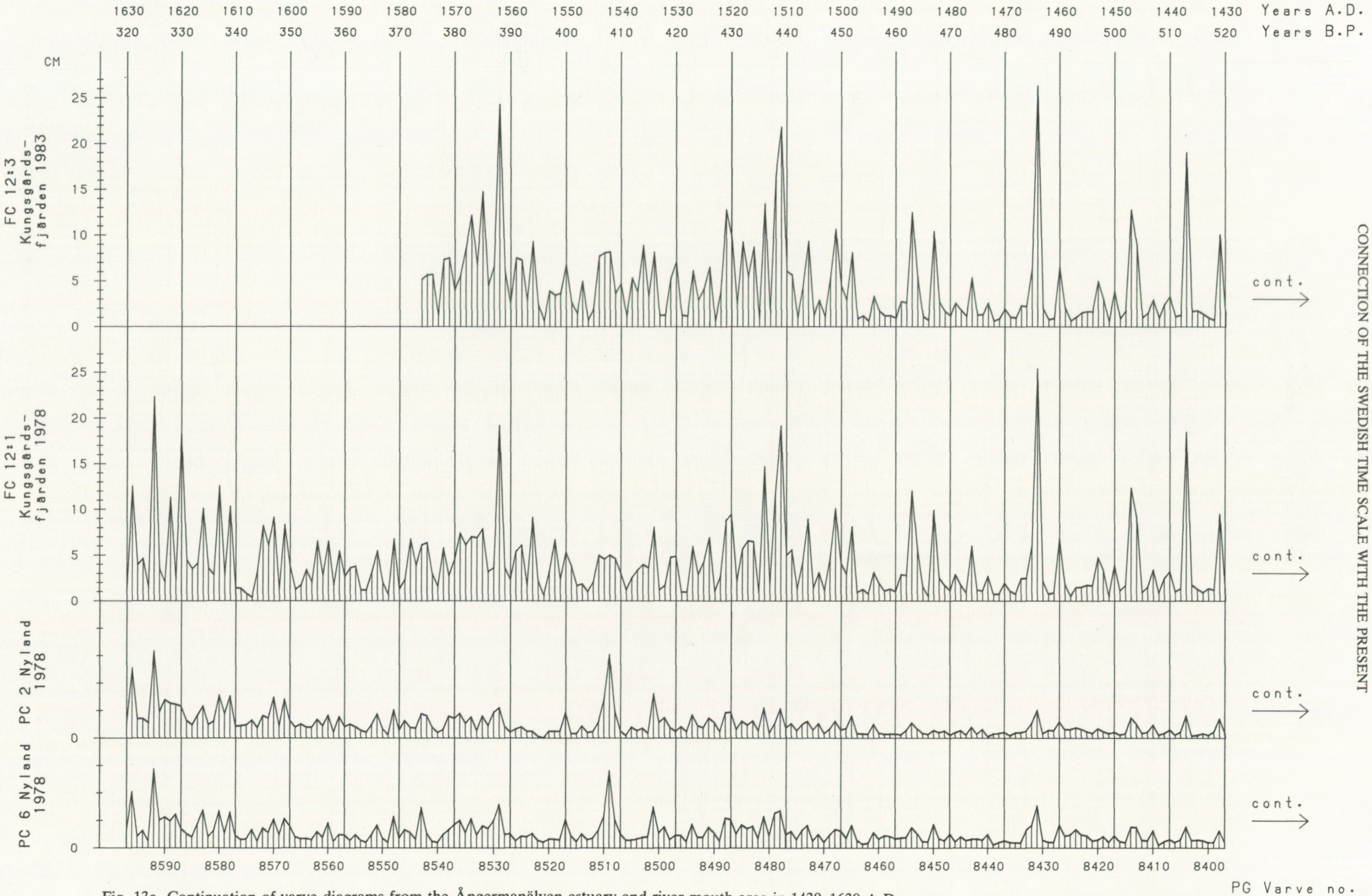


Fig. 13e. Continuation of varve diagrams from the Ångermanälven estuary and river mouth area in 1430–1630 A.D.

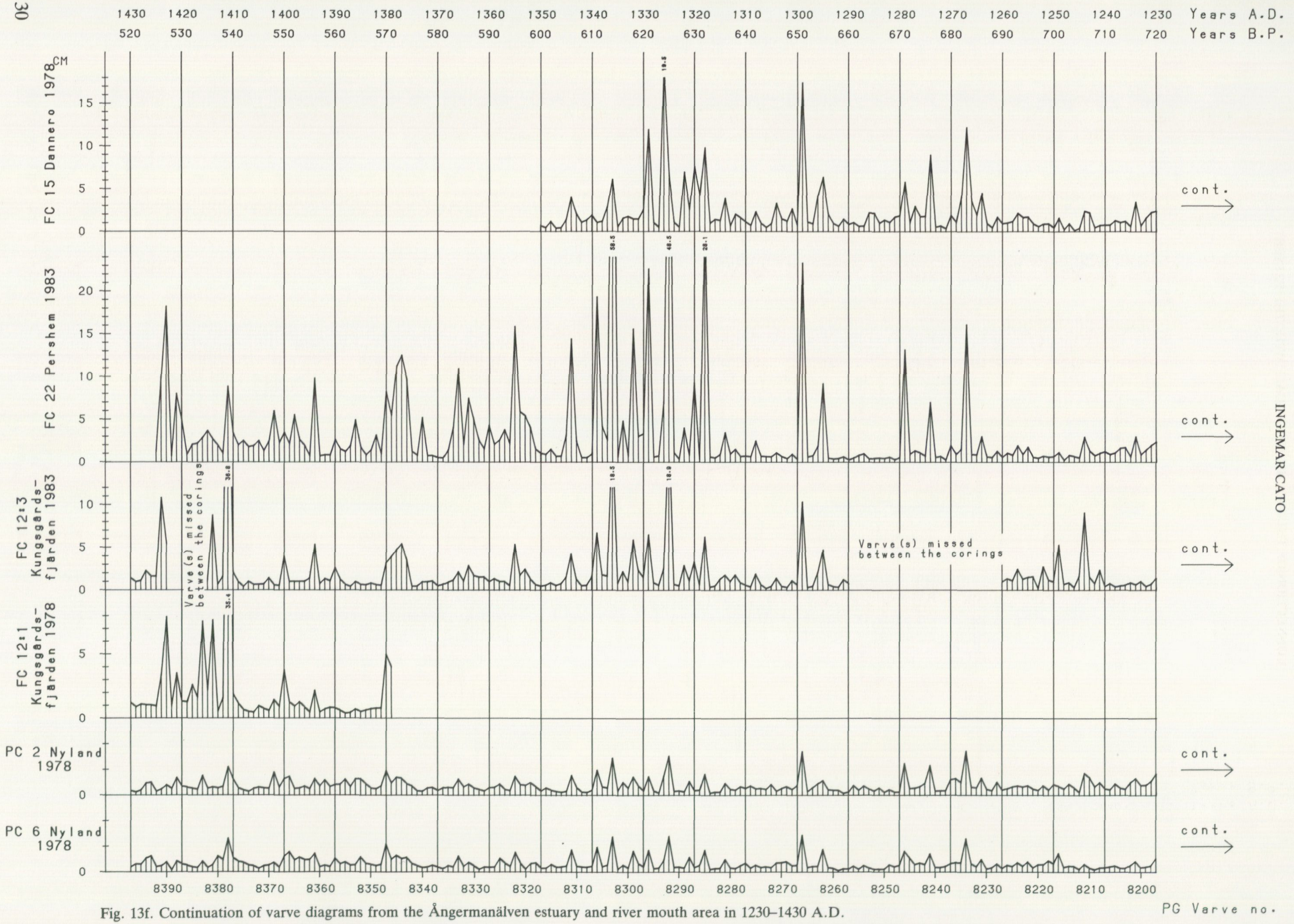


Fig. 13f. Continuation of varve diagrams from the Ångermanälven estuary and river mouth area in 1230–1430 A.D.

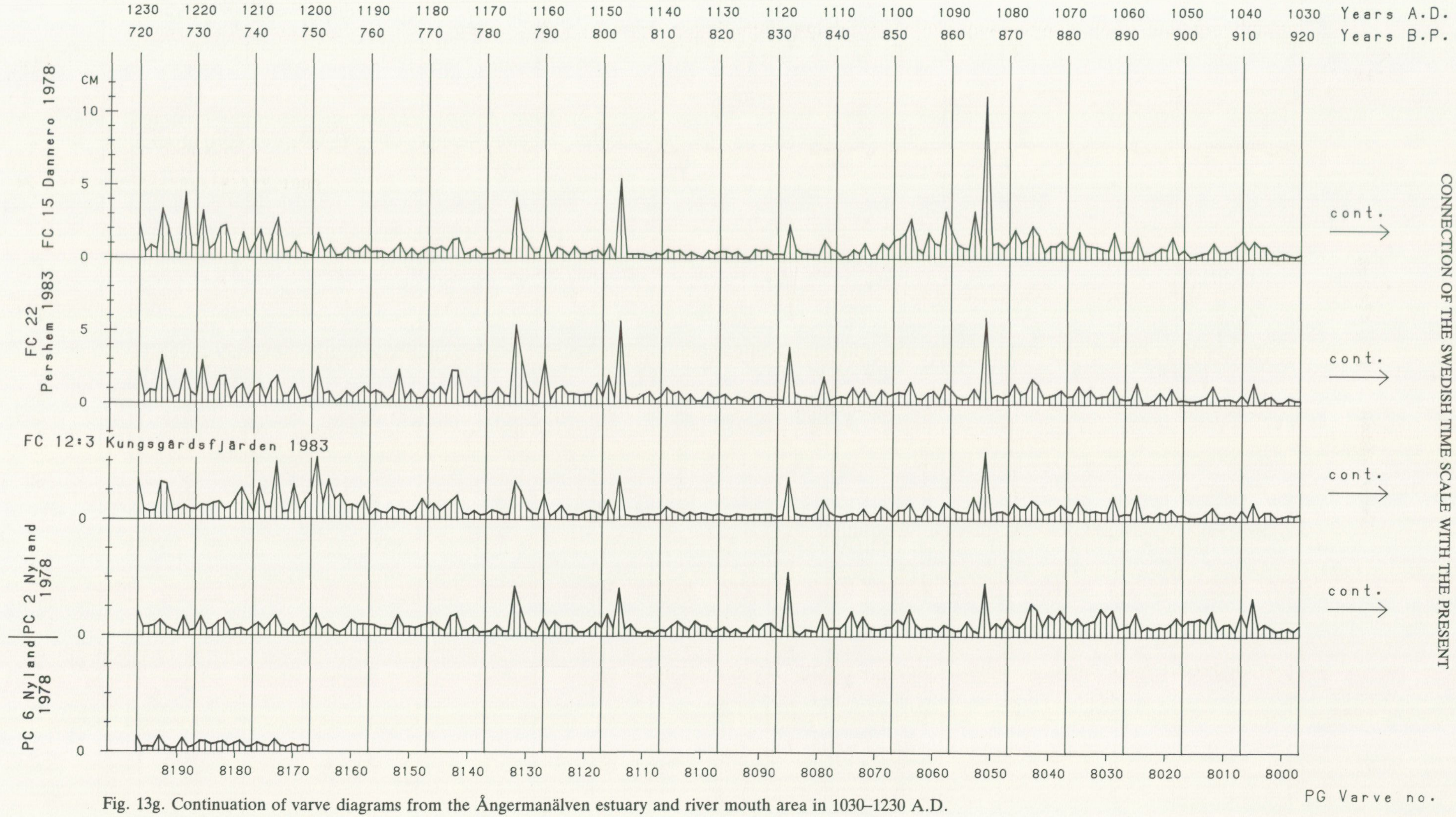


Fig. 13g. Continuation of varve diagrams from the Ångermanälven estuary and river mouth area in 1030–1230 A.D.

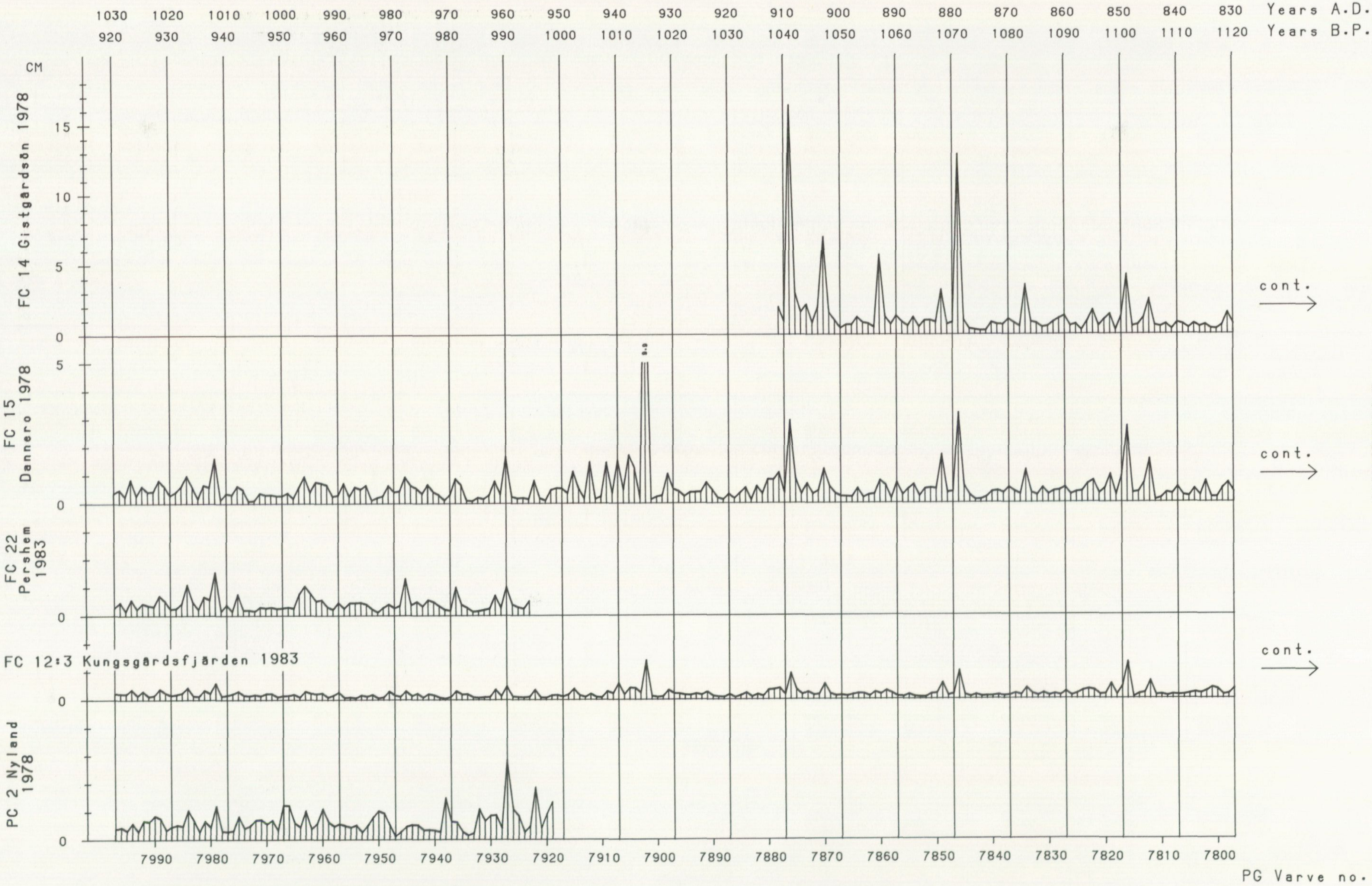


Fig. 13h. Continuation of varve diagrams from the Ångermanälven estuary and river mouth area in 830–1030 A.D.

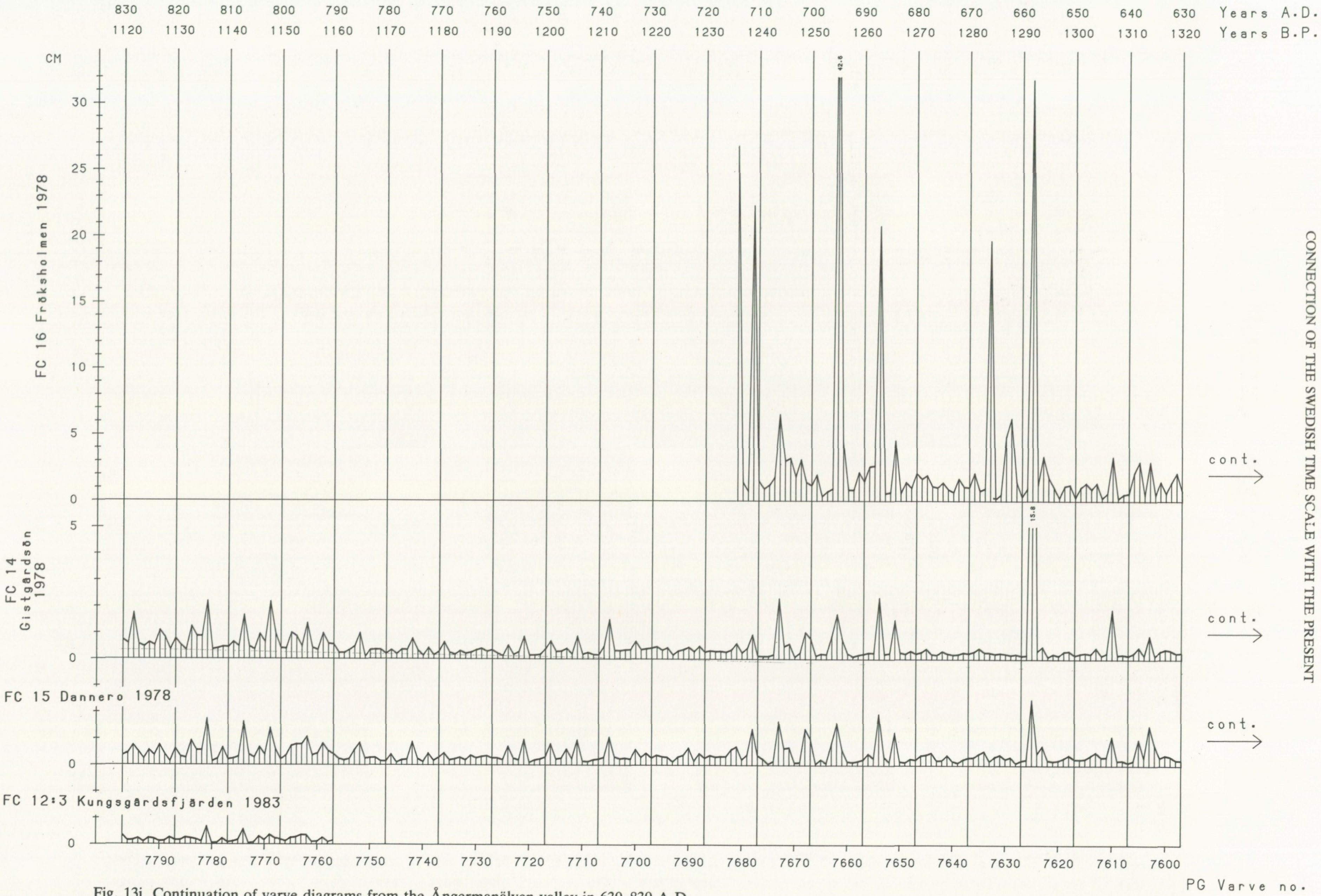


Fig. 13i. Continuation of varve diagrams from the Ångermanälven valley in 630–830 A.D.

Fig. 13j. Continuation of varve diagrams from the Ångermanälven valley in 430–630 A.D., correlated to the original Prästmon varve diagram (19. Prästmon) of R. Lidén (Liden† & Cato, in press).

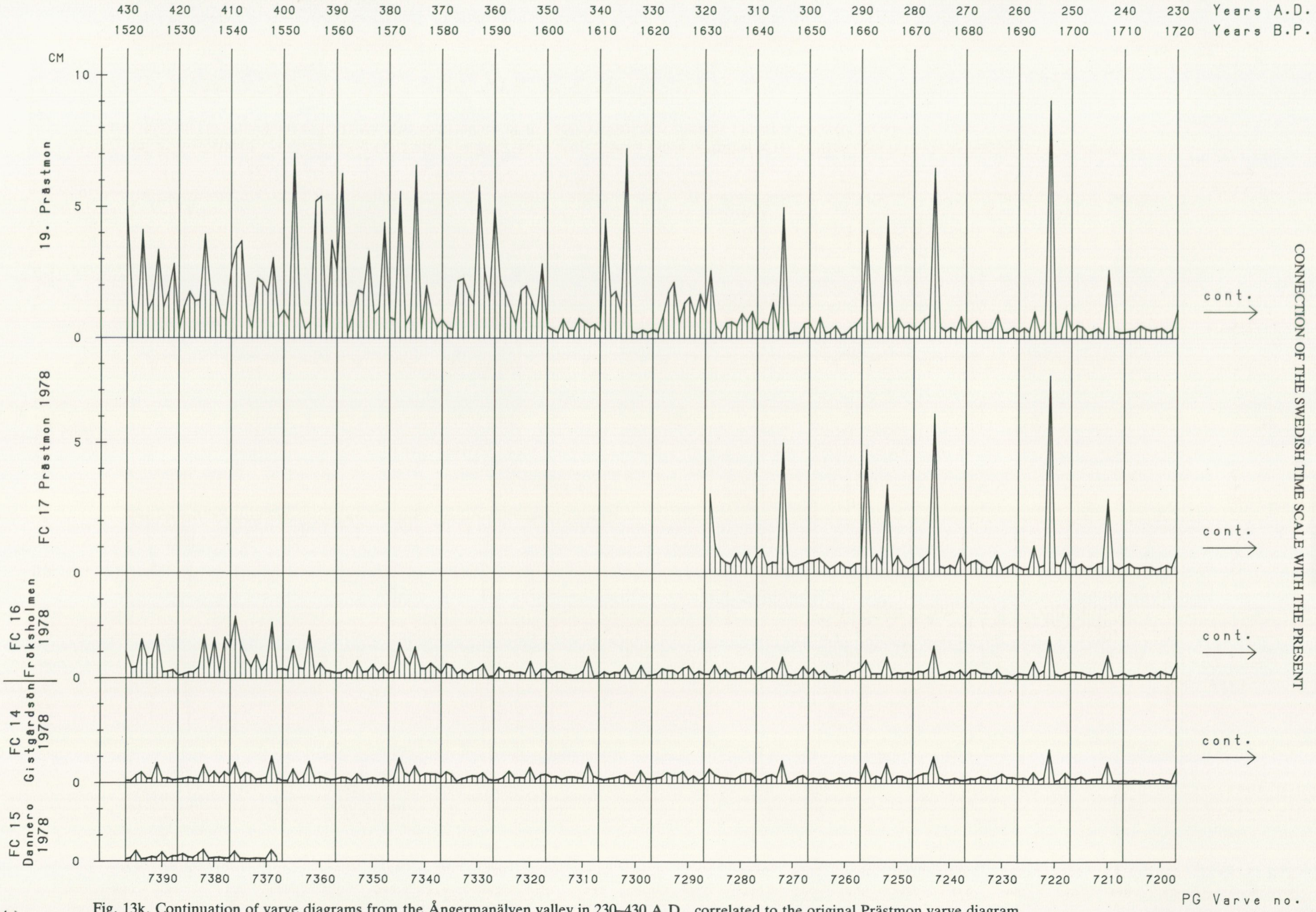


Fig. 13k. Continuation of varve diagrams from the Ångermanälven valley in 230–430 A.D., correlated to the original Prästmon varve diagram (19. Prästmon) of R. Lidén (Lidén† & Cato In press).

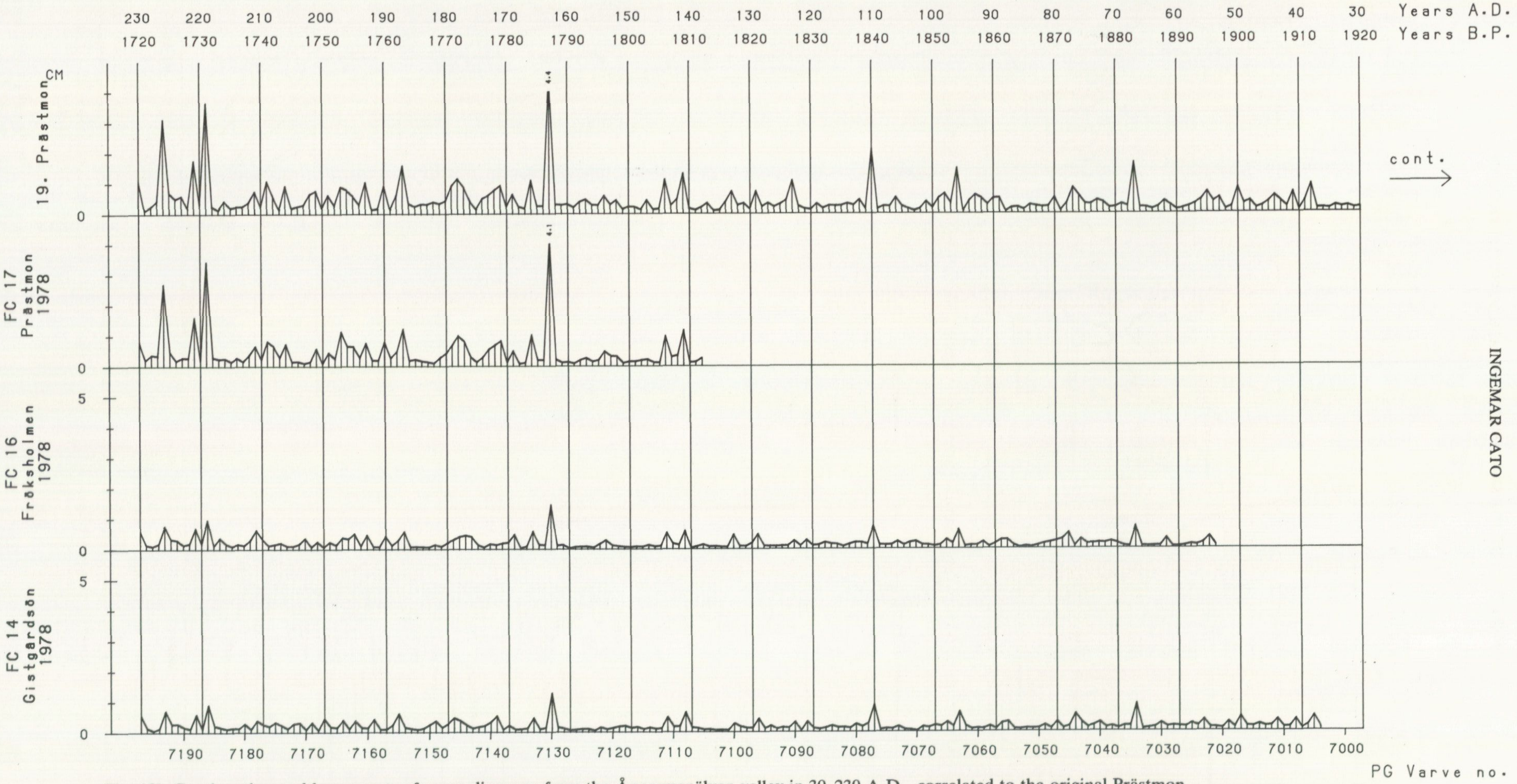


Fig. 13l. Continuation and lower parts of varve diagrams from the Ångermanälven valley in 30–230 A.D., correlated to the original Prästmon varve diagram (19. Prästmon) of R. Lidén. The continuation of R. Lidén's diagram is given by Lidén† & Cato (in press).

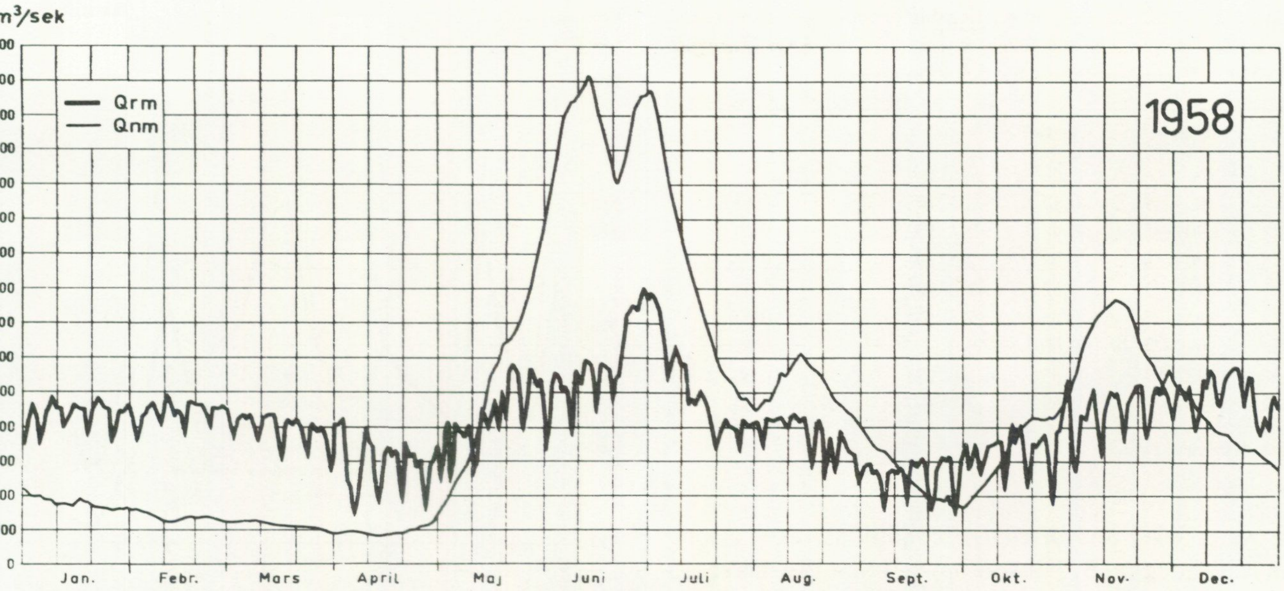


Fig. 14. Regulated (Qrm) and unregulated (Qnm) daily mean discharge in the Ångermanälven river in 1958 at Sollefteå (from Arnborg 1959).

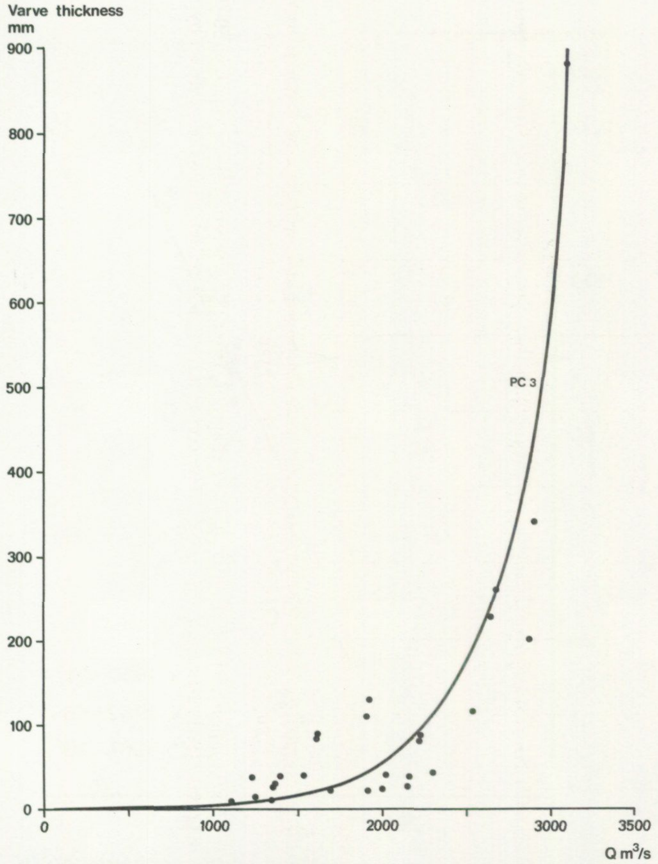


Fig. 15. The varve thickness of core PC 3 versus maximum daily mean discharge during the period 1909–35 in the Ångermanälven estuary. The correlation coefficient, *r*, is 0.68. For further details, see Table 5.

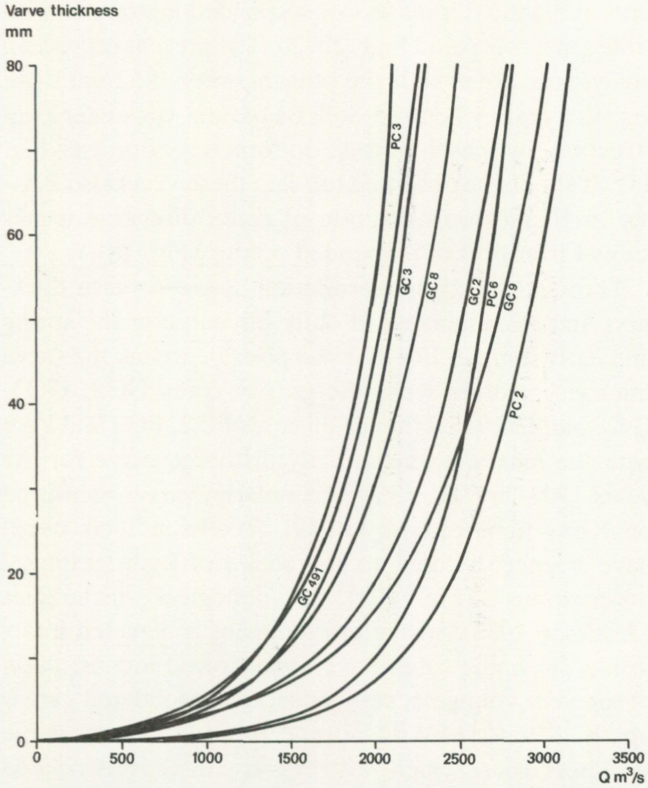


Fig. 16. Regressions of varve thickness of different cores versus maximum daily mean discharge during periods between 1909–78 in the Ångermanälven estuary. The correlation coefficient, *r*, varies between 0.50–0.80. For further details, see Table 5.

Table 5. The regressions of the relationship between varve thickness, y, (mm) and daily mean discharge, x, (m^3/s) in the Ångermanälven river. The relationships follow the equation $y=ae^{bx}$.

Core	Years	$y=ae^{bx}$			
		a	b	n	r
PC2	1909–19	0.11	$2.1\ 10^{-3}$	11	0.65
PC3	1909–35	0.44	$2.4\ 10^{-3}$	27	0.68
PC6	1909–19	0.07	$2.5\ 10^{-3}$	11	0.80
GC2	1927–71	0.53	$1.8\ 10^{3}$	45	0.52
GC3	1944–73	0.36	$2.3\ 10^{-3}$	30	0.57
GC8	1940–72	0.60	$2.0\ 10^{-3}$	33	0.63
GC9	1922–57	0.65	$1.6\ 10^{-3}$	35	0.80
GC491[1]	1949–78	0.69	$2.1\ 10^{-3}$	29	0.50

[1] from Axelsson (1983)

new water level and discharge conditions takes a long time it is thought (B. Nilsson op.cit.) that the increased erosion will continue for several years to come until a new equilibrium is attained.

In his work from 1976 B. Nilsson demonstrated the strong logarithmic correlation which prevails between the annual mean discharge and the annual transport of suspended matter in the Ångermanälven (Fig. 18). There is also a distinct linear correlation between varve thickness and annual transport of suspended matter, as illustrated in Table 6 and Figs. 19–20. The present regression analyses do not include the years between 1962 and 1966, viz. the years when the Sollefteå Dam was under construction, by reason of their uniform deviation (see Fig. 17). It should be observed too that these years also deviate in B. Nilsson's diagram of mean discharge versus annual transport of suspended matter (Fig. 18).

Through the strong correlation between varve thickness and maximum mean daily discharge in the spring and early summer floods it was possible to link the varve thickness profiles from the gravity cores GC2, GC3, GC8 and GC9 and the piston cores PC2, PC3 and PC6 with the maximum mean daily discharge curve for the years 1909–78 (Fig. 13 a–c). Similarly, varves measured on X-ray films of core GC491 (Axelsson 1980, 1983) have been correlated to the series of hydrographical observations (Fig. 21). Radiological techniques (Axelsson 1972), where the sediment is depicted intact inside the lining tube, have also allowed identification of the very youngest, very loose, unconsolidated varves up to 1979 A.D. With normal procedures, viz. varve thickness measurement with the strip directly associated with the extracted core, such an identification is impossible because the sediment flows out into a structureless mass too diffuse for varve measurements. The somewhat more consolidated sediments under this uppermost,

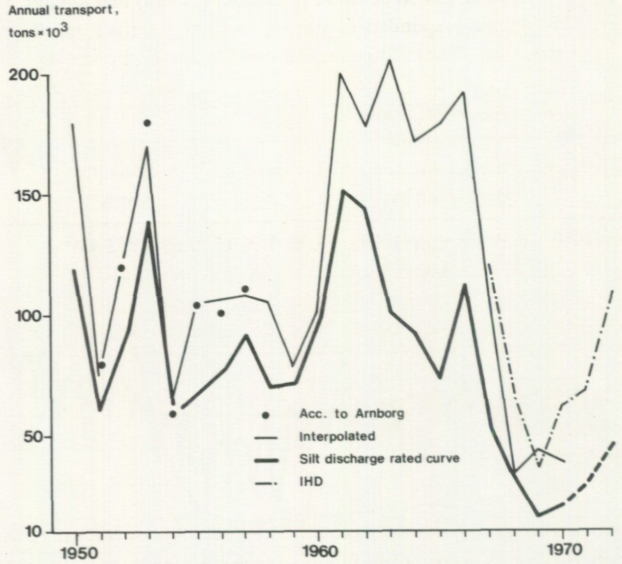


Fig. 17. The annual transport of suspended matter in 1000 tons at the bridge over the Ångermanälven river close to Hammar. The values were calculated with different methods (after B. Nilsson 1974).

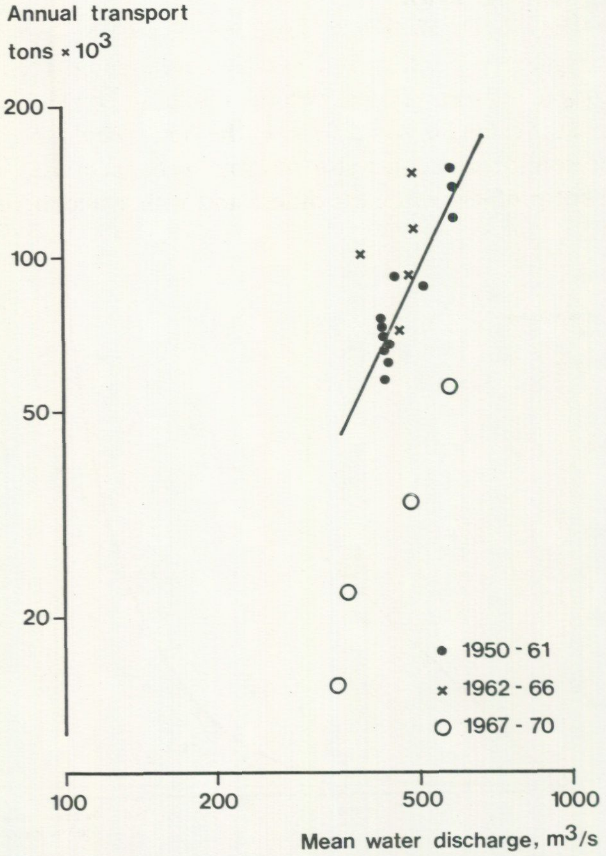


Fig. 18. The annual transport of suspended matter in 1000 tons versus the annual mean discharge in the Ångermanälven river in 1950–61 (solid circles), during (crosses) and after (open circles) the period of power plant building (after B. Nilsson 1976).

Table 6. The linear regression of varve thickness, y, (mm) and annual transport of inorganic suspended matter, x, (ton) at the river mouth of the Ångermanälven. The relationship follows the equation y=ax+b.

Core	Years	Annual transport of suspended matter acc. to data given by	Y=ax+b		n	r	Except years
			a	b			
GC 2	1950–70	B. Nilsson (1974)	0.06	1.91	15	0.60	1962–66[1]
GC 9	1950–57	Hydrokonsult in B. Nilsson (1974)	0.10	–0.05	7	0.67	–
GC 491[3]	1951–70	B. Nilsson (1974)	0.06	2.71	13	0.63	1962–66[1], 1967[2]

1. period of power plant building
2. subaquatic slide
3. from Axelsson (1983)

loose layers are also disturbed in some cases, albeit to a much lesser extent. This is illustrated by the uppermost varves (younger than 1960 A.D.) in gravity core GC2. The disturbance by compaction in the collection of this core has had the result that the varve thicknesses measured are misleading for the years 1960–71 A.D. It was nevertheless possible to establish the number of varves (Fig. 13 a).

The varve thickness diagrams from the profiles sampled with piston and gravity corers could thus be convincingly correlated with the discharge in the River, and the calendar year affinity of the varves could thereby be confirmed. It was also possible to connect the sediment profiles with each other, and with Kullenberg & Fromm's (1944) profiles from 1943 (the cores 1a, 1b, 2a and 2b, comprising varves from 1926–42 A.D.) and with Granar's (1956) profiles from 1952 (the cores PC I, PC II and PC IV, covering varves from the period 1850–1950 A.D.). Kullenberg & Fromm's profile 2b and Granar's profiles are reported in Fig. 13 b–c. Yet in comparison with the profiles PC2, PC3 and PC6 it seems as if Granar lacks the varve for 1885 A.D., and that he has

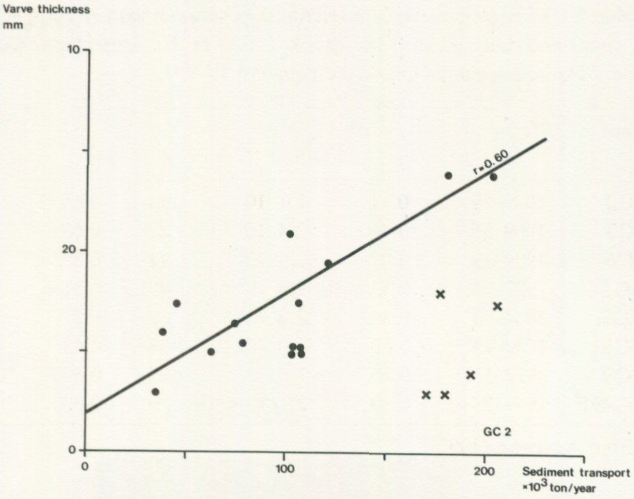


Fig. 20. Varve thickness of core GC2 versus the annual transport of suspended sediment during the period 1950–70 in the Ångermanälven river. The regression analysis does not include the years 1962–66 (crosses). During this period the power plant at Sollefteå was built, which obviously influenced the sediment transport in such a way as to disturb the illustrated relationship. The data on the annual sediment transport are from B. Nilsson (1974).

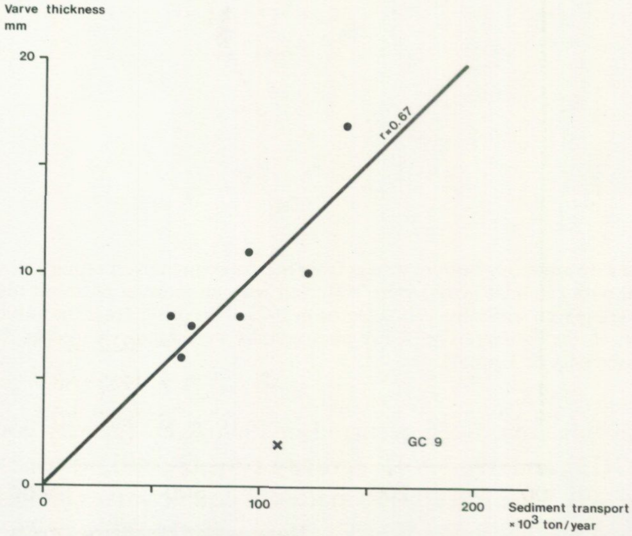


Fig. 19. Varve thickness of core GC9 versus the annual transport of suspended sediment during the period 1950–57 in the Ångermanälven river. The regression analysis does not include the year 1956 (cross). The data on the annual sediment transport are from B. Nilsson (1974).

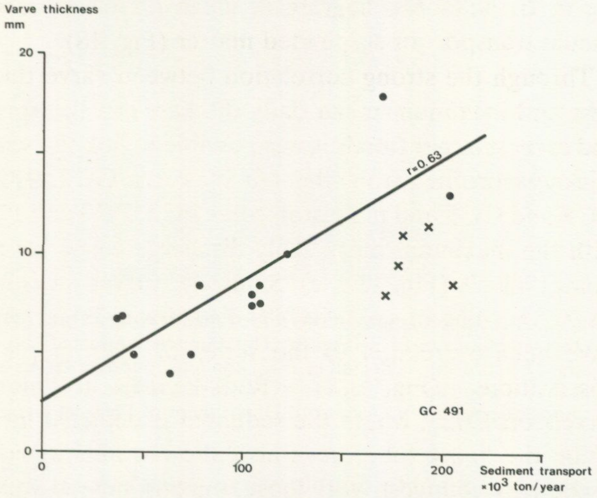


Fig. 21. Varve thickness of core GC491 (data from Axelsson 1983) versus the annual transport of suspended sediment (data from B. Nilsson 1974) during the period 1951–70 in the Ångermanälven river. The regression analysis does not include the years 1962–67 (crosses). During this period the power plant at Sollefteå was built and in 1967 a sub-aquatic slide occurred from the delta front. Events which obviously influenced the sediment transport in such a way as to disturb the illustrated relationship.

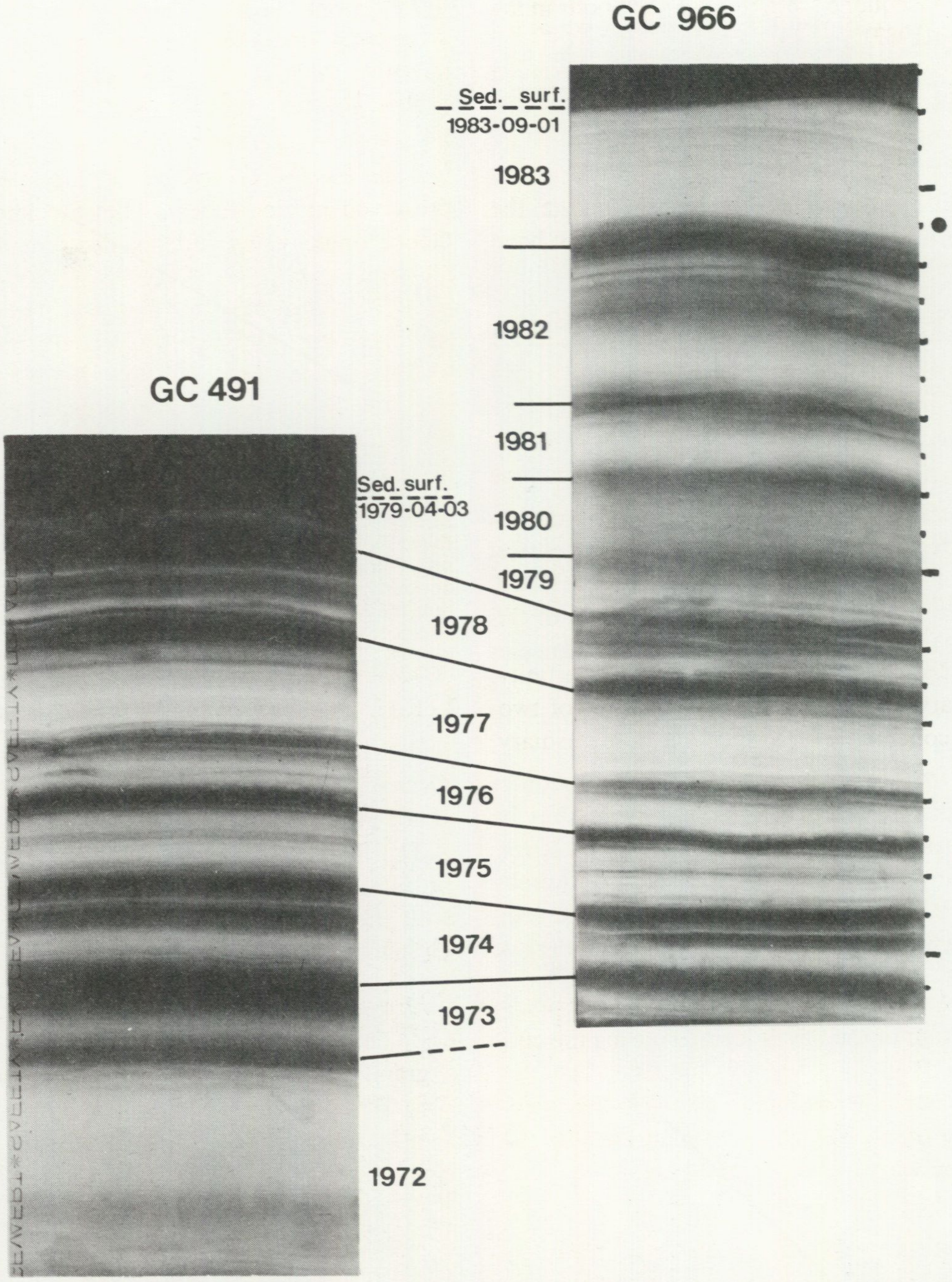


Fig. 22. X-ray photographs of two unextruded sediment cores (491 and 966) with adjoining bottom waters from the Ångermanälven estuary close to the sampling site PC3 (Fig. 8). The annually laminated cores (marked with calendar years) were collected with an interval of about four years. The core 966, collected in 1983, contains four new varves on the top compared with core 491 collected in 1979. This proves that the varves are annual and that the deposition of varved sediments is still in progress in the estuary. The X-ray photographs were kindly placed at the author's disposal by V. Axelsson. Department of Physical Geography, University of Uppsala.

counted a possible double varve 1894/5 A.D. as two varves. This assumption is also strengthened when Granar's profiles are compared with Fromm's previously unpublished varve measurements from 1945 (Figs. 25 a–b). For this reason the presumptive errors in Figs. 13 b–c have been corrected.

Formation of double varves is obviously not unusual in this area. Such occurred in 1945 A.D. (gravity core GC2) and 1967 A.D. (gravity core GC 491) (see also p. 49). That it really is a matter of double varves in these two profiles and not lack of varves in the other profiles emerges from the comparison of the covariation between the varve thickness and the water discharge (Fig. 13 a). It is also known that underwater slides occurred in both these years in consequence of severe spring floods in the River (Axelsson 1983).

The above indicates that the calendar year affinity of the recent varves could be established in the cores studied with the help of discharge data from the River. The very close agreement with coincident peaks, valleys and groups in the diagrams covers a 70 year period, viz. the entire period in which discharge measurements have been made in the River. Furthermore the good agreement is reinforced by the demonstrated mathematical correlation between both the maximum mean daily discharge and the varve thickness (Figs. 15 and 16), and between the annual sediment transport and the varve thickness (Figs. 19–21). Moreover the calendar year affinity of the varves is confirmed by certain extreme varves formed partly by turbidities originating in underwater slides (see e.g. Axelsson 1980) and partly because the regulations of the River from primarily 1950 onwards have reduced the varve thickness due to diminished spring flood peaks in the discharge.

In order further to verify the calendar year affinity of the recent varves Fig. 22 shows X-ray films of two sediment cores collected by V. Axelsson in the estuary of the Ångermanälven (Nylandsfjärden) in 1979 and 1983, i.e. with a four year interval. A comparison of the appearance of the varves clearly indicates that in the latter core (GC 966) four more varves were created during the four years which had elapsed since the collection of the former core (GC 491). This shows that the varves are annual, and that the sedimentation and varve formation is still in progress in the area, i.e. the uppermost varve at the bottom of the bay is formed during the current year.

These studies made it possible to establish the calendar year affinity of the recent varves and thereby the connection of the varve series to the present.

The link with Lidén's profile from Prästmon

The second phase of the project comprised a new study of Lidén's southernmost site at Prästmon. The purposes of this drilling were the production of a new profile from the classic site and the verification with a new profile of Lidén's previously unpublished diagram from Prästmon. This diagram pertains to Lidén's own version (which is now partly reported in this paper and in its entirety in Lidén† & Cato, in press), and differs from a diagram of Lidén from Prästmon published after modification by E.H. De Geer (1933).

The youngest varves (7061–7522) in Lidén's postglacial time series were before the present paper represented only in his Prästmon profile, which naturally involved some uncertainty since these varves could not be verified by other profiles. All other profiles of varves earlier than 7061 of Lidén have indeed been verified by his own varve series (see Lidén† & Cato, in press).

Ebba H. De Geer checked Lidén's varve profiles, preserved in zinc tubes at the Stockholm Institute of Geochronology, by Lidén's varve measurement slips. She states (E.H. De Geer 1933 pp. 206–7) that a couple of varve limits were doubtful in Lidén's measurement, and that she added one varve each at three places in Lidén's profile. According to E.H. De Geer this applies to the years 715, 720 and 754 A.D., following her correlation with the annual rings of the sequoia tree. Yet a check of Lidén's unpublished diagram from Prästmon against the diagrams which E.H. De Geer includes in her publication from 1933 indicates that:

1. E.H. De Geer's varves 715 and 754 A.D. are missing in Lidén's diagram. These two varves would have lain between varves 7221 and 7222, and 7258 and 7259 respectively in Lidén's postglacial chronology.
2. E.H. De Geer's varve 720 A.D., on the other hand, is not missing in Lidén's diagram (as E.H. De Geer alleges). The varve therefore corresponds to Lidén's varve 7226.
3. E.H. De Geer also reports Lidén's varves 7523–7526 in her diagram. These varves are not to be found in Lidén's diagram. According to Fromm (verbal communication) Lidén omitted varves formed later than 7522 from the Prästmon profile. The reason for this is unknown.
4. Lidén's varve 7266 is missing in E.H. De Geer's diagram. The varve would have lain between varves 761 and 762 A.D. according to E.H. De Geer's chronology.
5. E.H. De Geer's varve sections 779–818 A.D. and 901–2 A.D. do not resemble the corresponding varve sections (7285–7323 and 7405–74066 respectively) in Lidén's diagram.
6. E.H. De Geer's varve 880 A.D. is missing in Lidén's diagram. The varve would have lain between Lidén's varves 7384 and 7385.

Thus there are considerably more discrepancies between E.H. De Geer's reported profile and Lidén's unpublished profile from Prästmon than can be deduced from the text of E.H. De Geer's paper from 1933.

Another remarkable detail is that in this paper from 1938 Lidén states that the surface varve 7522 at Prästmon corresponds to the year 1018 A.D. according to the annual ring series of the sequoia tree. A scrutiny of E.H. De Geer's diagram (1933 p. 209) indicates that varve

7522 at Prästmon instead corresponds to the year 1013 A.D. E.H. De Geer states in the text (1933 p. 207) that Lidén's varve 7530 corresponds to the year 1020 A.D. There is an error here; 1020 A.D. corresponds to varve 7529. The odd thing is, however, that the profile in E.H. De Geer's book does not show any varves after 7527 (Lidén's chronology) or 1017 A.D. (E.H. De Geer's chronology) notwithstanding that in the text she mentions varves which were formed later.

The discrepancies are not important for the present work, but they are reported in order to avoid misunderstandings arising from the existence of an erroneous version or a version wrongly re-interpreted by E.H. De Geer of Lidén's original digram from Prästmon.

Lidén's postglacial chronology and the displacement of the shoreline in the valley of the Ångermanälven published in 1938 is based *inter alia* on his original diagram, designated "19 Prästmon", which is reproduced in its entirety by Lidén† & Cato (in press), and deals with the uppermost 530 varves also in this paper (Fig. 13 j–l). The same figure also illustrates the varve thickness diagram FC 17 Prästmon from the current study.

Lidén carried out his varve measurement on bluff sections, while the new measurements at Prästmon were made on a foil piston core. For practical reasons the core could not be taken at the site's highest point, with the result that the uppermost (youngest) varves 7287–7522 in Lidén's chronology are missing in the foil piston corer profile. The latter comprises the varves 7105–7286 and, judging by Fig. 13 j–k, presents the same appearance as Lidén's varve thickness diagram. The deviations are very slight and can probably be attributed to the facts that the varve series were not located in exactly the same spot, and that two different people executed the measurements.

By means of the new varve measurements, Lidén's varve diagram profile 19 Prästmon has been verified, with the exception of varves 7287–7522 and 7061–7105. The latter varve section has however been verified by the sediment profiles from Fröksholmen and Gistgårdsön (the foil piston cores FC 14 and FC 16) (Fig. 13 i–j). Here, too, the agreement is obvious in view of the fact that the varves at these sites were at the time of their formation deposited in a more distal position compared with the same varves at Prästmon.

The profiles from Fröksholmen, Gistgårdsön and Dannero (the foil piston cores FC 14–16) also comprise *inter alia* the varves 7287–7522 in Lidén's Prästmon diagram. In these cases the agreement with Lidén's series is not always that good, although several groups of varves display close resemblances, e.g. varves 7499–7517, 7480–88, 7431–7437, 7391–7405. This is presumably because the upper varves in Lidén's series were formed in a very proximal position, where the varve formation is to a great extent controlled by local factors, with the result that their thickness is a very local feature. This applies consistently to all the profiles in both Lidén's original material (Lidén† & Cato, in press) and the material of the current study. Thus it seems to be a characteristic of the fluvial sediments in Norrland, so that correlations should generally be sought in more distally formed varves, viz. further down in the varve series.

There is also a possibility that errors may occur in Lidén's measurements of the proximal varves from Prästmon. One reason is that he had no opportunity to check his measurements by a more distally situated bluff section. On the other hand he was able to confirm the lower part of the varve series at Prästmon by bluff sections further upstream at Undrom and Björkå Bruk (see Lidén† & Cato, in press).

It must be added, however, that the accuracy of Lidén's measurements of the most proximal varves at Prästmon now lacks significance since a complete, bridging connection and verification of Lidén's varves older than 7286 at Prästmon, and thereby a definite connection backwards in time, has been obtained.

This investigation has thereby linked the varve series both with the present and with about 500 of Lidén's youngest postglacial varves. In addition the discrepancies in E.H. De Geer's (1933) presentation of Lidén's varve series from Prästmon vis-à-vis Lidén's original diagram could be verified in Lidén's favour.

The link between the recent sediments and Lidén's profile from Prästmon

The third phase of the project signifies the linkage of the recent varve profiles from the estuary of the Ångermanälven with the varve series associated with Lidén's chronology, primarily FC 17 Prästmon. This was effected by the gradual expansion of the chronology toward present time with the help of the varve profiles FC 16 Fröksholmen, FC 14 Gistgårdsön, FC 15 Dannero, FC 22 Pershem and FC 12 Kungsgårdsfjärden (Fig. 13 d–i), which are situated in the said order downstream of Prästmon at 1–3 km intervals.

The whole of the measured profile from Fröksholmen, comprising some 650 varves from 7021–7681 (Lidén's chronology), is covered by, and has been correlated with the varve series from Gistgårdsön (Figs. 13 h–k). The similarities between these two series are very close. The agreement is particularly strong in the case of the varves between 7020 and 7330 (Lidén's chronology), which are almost identical as regards appearance and thickness. The uppermost 60 or so varves in the profile from Fröksholmen have been formed in proximal position, so that they manifest distinctly local features. Nevertheless several of the sturdy peaks recur in profiles with a more distal position.

The uppermost 325 varves in the series from Fröksholmen are represented also by the varve series from Dannero. Here, too, the similarities between the graphs are strong (Fig. 13 h–j) and more or less follow the pattern described above as regards the agreement between the profiles from Fröksholmen and Gistgårdsön.

Gistgårdsön and Dannero overlap each other with more than 500 varves between varves 7368 and 7878 (Lidén's chronology). The agreement is very good here as well (Fig. 13 g–j), being most accentuated for the varves between 7580 and 7850 (Lidén's chronology). A section from this part of the varve series is illustrated in Fig. 11. The very close resemblance between the varves from these two sites as regards both appearance and thickness is evidence that the water discharge was equally strong at both places during the years from c. 600–850 A.D. This is interesting as Dannero is situated about 3 km below Gistgårdsön (Fig. 8) in the now dry Losundet branch of the river (Fig. 9 and p. 14). If the discharge was the same at both coring sites during this period then the flow must have been heavier in Losundet than in the other branch of the river due to the distance involved. Judging by the clay thickness diagram the flow was presumably even stronger in Losundet at least in the century before c. 600 A.D.

The uppermost 300 varves in the series from Dannero are also represented in the series from Pershem, situated a bare km below Dannero. The pattern recurs here too, with very strong similarities between the varves, with the exception of the uppermost 50 varves formed proximally at Dannero. The difference in varve thickness between these two sites is almost non-existent if only the proximally formed varves are excepted.

The varve series FC 12:3 from Kungsgårdsfjärden, about 2 km below Dannero, comprises some 800 varves. Gistgårdsön is overlapped by 120 of these and Dannero by about 550, while the entire series of almost 500 varves from Pershem is represented. The lower 200 varves at Kungsgårdsfjärden are very thin, so that the correlation emerges most distinctly in the coincident peaks in this section (Fig. 13 g–h). Between varves 8000 and 8200 the similarities are very great between Kungsgårdsfjärden on the one hand and Dannero and Pershem on the other. The varve thickness is, however, more than double in the case of the latter series.

From varves 8230–70 (Fig. 13 f) onwards in time the varves in these three series are of the proximal type. Nevertheless the similarities are occasionally very great between Kungsgårdsfjärden and Pershem, so that there were no difficulties involved in correctly correlating the

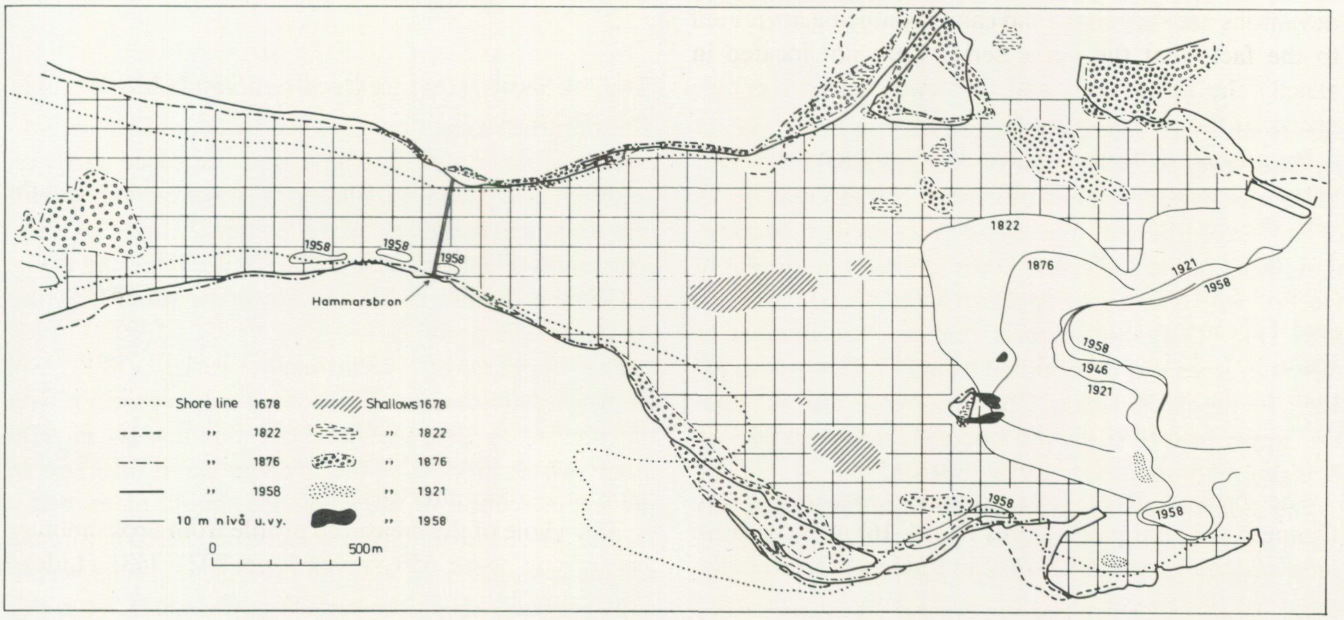


Fig. 23. Map showing shorelines and shallows 1678–1958 and the contour at 10 m water depth according to soundings between 1822 and 1958 (after Arnborg 1959).

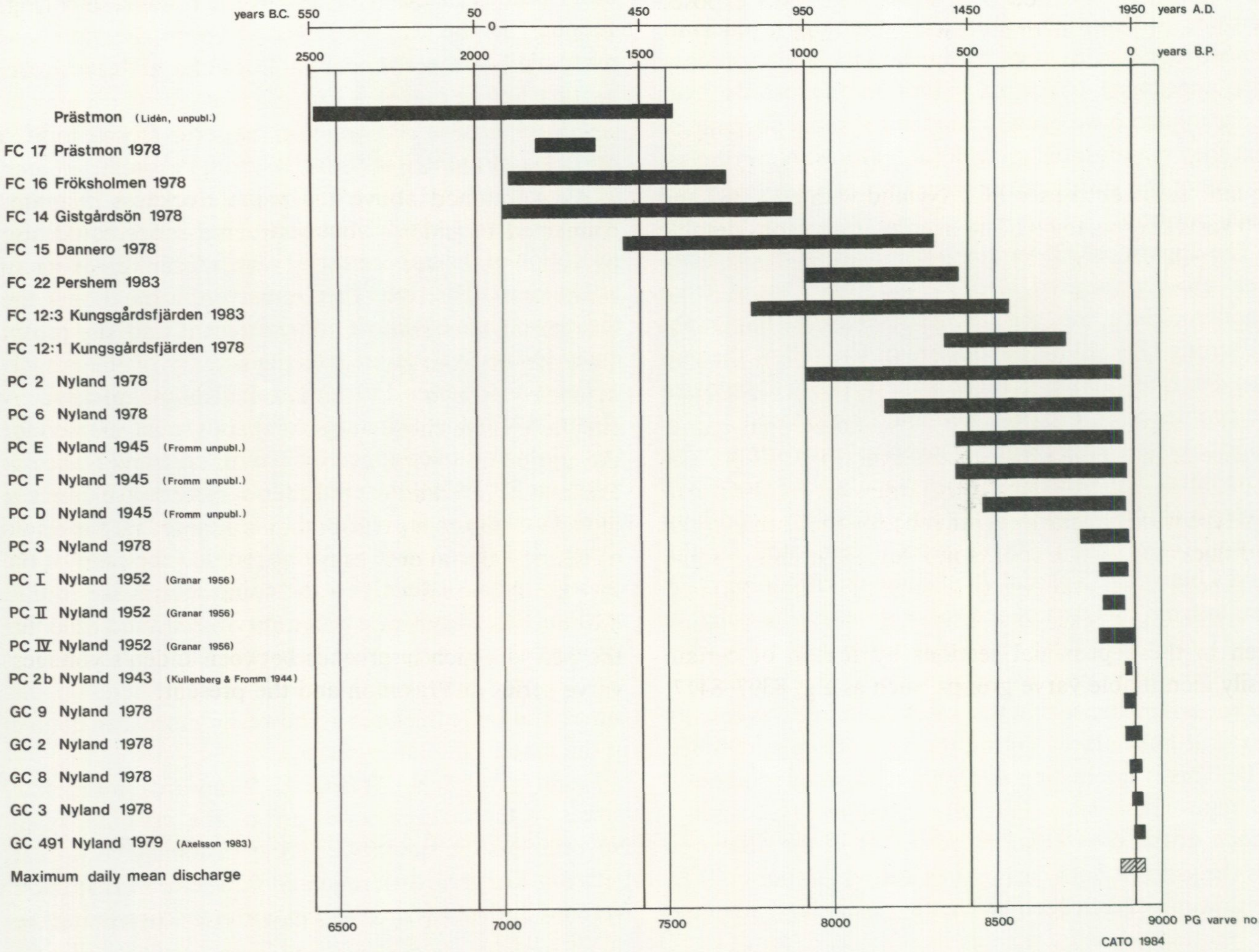


Fig. 24. Outline diagram showing the mutual connections between the studied varve series in the Ångermanälven valley as well as the connection with the original Prästmon varve series of R. Lidén.

varves which lie above the section 8227 to 8257 (Fig. 13 f). The latter varve section of Kungsgårdsfjärden (FC 12:3) was ruined, in that by reason of the great depth of soil, the cores had to be taken in stages with intermittent lifting of the foil piston corer at *inter alia* this depth (see p. 18). The same applies to the section 8383 to 8389 (Fig. 13 f), but in the latter case the number of missing varves was determined from Foil Piston core FC 12:1, Kungsgårdsfjärden. The latter core also includes the uppermost 170 varves under "the dry crust" at Kungsgårdsfjärden, viz. varves 8544–8713.

The sediment profile at Kungsgårdsfjärden, which was compiled from two foil piston cores (FC 12:1 and FC 12:3), comprises some 1 000 varves althogether down to a soil depth of 23 m. The uppermost 400 varves were formed in a proximal position until the sedimentation ceased and the area emerged by the elevation of the land. This occurred some time between 1678 and 1876, as indicated by Figs. 9 and 23. The figures are based partly on Stenklyft's map from 1678 (see p. 13), and on later soundings and measurements by the National Board of Shipping and Navigation (1822), The Civil Egineering Corps (1876) and the Swedish State Power Board (1958) (see Arnborg 1959 p. 44).

The uppermost identifiable varve (8713) in Kungsgårdsfjärden has been dated via connection with the present to 1746 A.D. Above this lies 1.4 m sediment, which in view of the average varve thickness in the upper section of the sequence should mean that a further 30–50 varves may have been deposited before the sedimentation ceased and the present peninsula was finally elevated above the surface of the water. That this probably took place at the end of the 18th century is also confirmed by the 1822 soundings which show that the area then consisted of a shoal which was exposed at low water but at times covered at high water (Fig. 23). Under such circumstances no complete varve formation can have occurred.

The sediment profiles from Kungsgårdsfjärden, Pershem and Dannero are overlapped by the subaquatic sediment series PC2 Nyland with 800, 380 and 320 varves respectively. The overlap is also considerable as regards the profile PC6 Nyland. This profile is, however, shorter since the lower part of the sequence was severely damaged at the sampling. The covariations between the profiles from Nyland and the other three sites mentioned above are very distinct in the varve section around 8000 to 8300 (Lidén's chronology) in consequence of the varve's distal formation (Fig. 13 f–g). The younger varves at Kungsgårdsfjärden are of the proximal type with a strong local influence on their appearance and thickness, which results in a less clear and in some cases poor covariation vis-à-vis the profiles from Nyland. Nevertheless it was possible to verify the connection even in these proximal sections by reason of certain easily identifiable varve groups, such as e.g. 8397–8417, 8427–8434, 8449–8455, 8575–8617 and 8687–8699 (Fig. 13 d–e).

The piston core profiles PC2, PC3 and PC6 display an excellent covariation with each other, which may be worthy of note as the distances from the former to PC6 are 4 and 5 km respectively.

As mentioned above the varve thickness diagrams connected to Lidén's youngest varve series could also be correlated (step by step) with a number of varve series down the river. This made it possible to link the postglacial time series with the recent and sub-recent varve series from Nyland in the estuary of the Ångermanälven, which are connected with the present. A complete varve chronology has thereby been created for the period following Lidén's youngest varve series at Prästmon. In addition, if Lidén's older varve series is included, a complete chronology is attained for the whole of the postglacial era regarding the development of the Ångermanälven river. Figure 24 summarizes how the 24 different varve thickness diagrams overlap each other for the period which intervenes between Lidén's youngest varve series at Prästmon and the present.

Comparison between recent/subrecent profiles and Fromm's unpublished diagrams

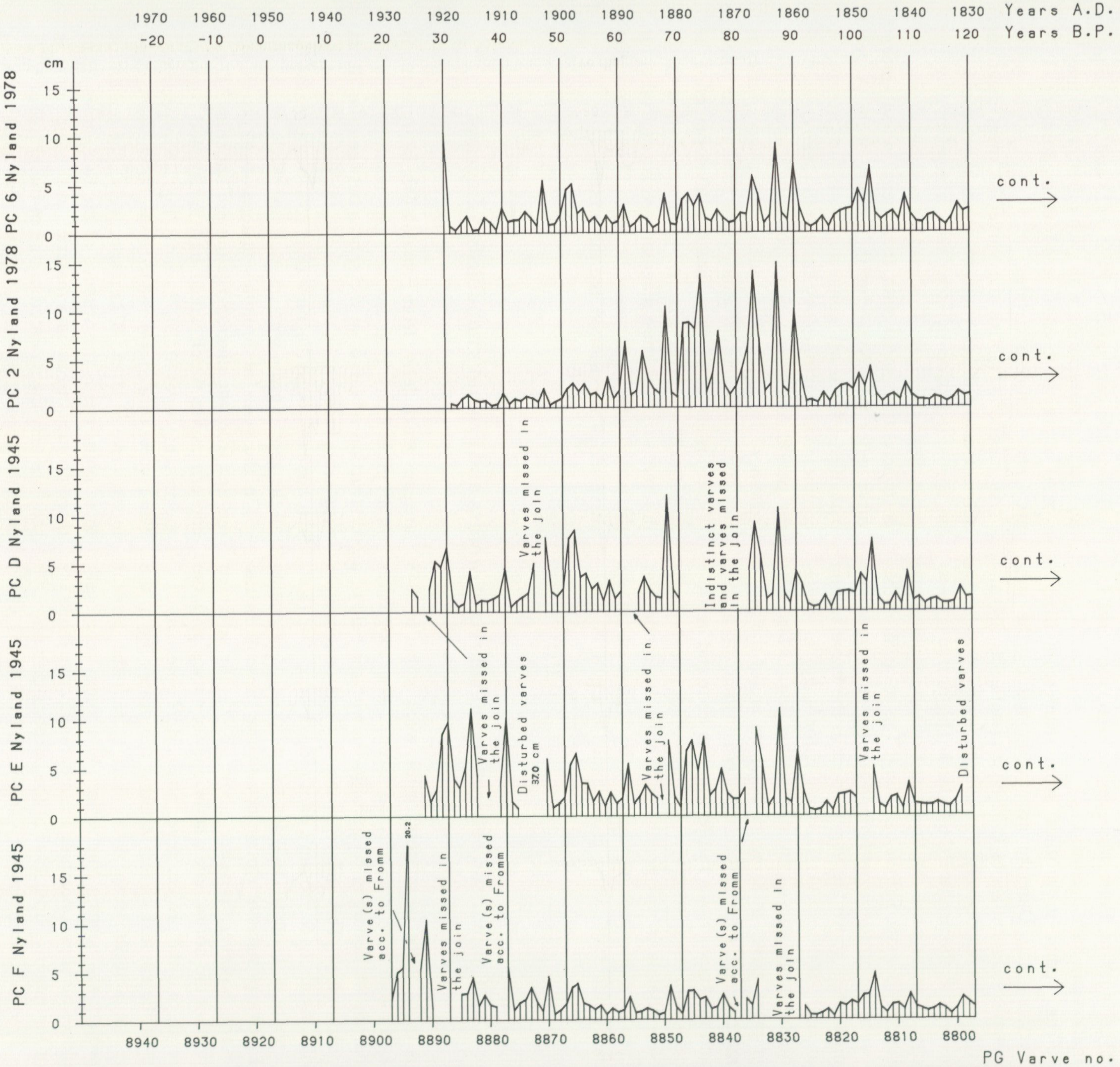
A point of special interest for this work is that in 1945 E. Fromm *inter alia* collected seven, 5–9 m long cores outside Marieberg in Nylandsfjärden with the help of a piston corer. This collection was a direct continuation of Kullenberg & Fromm's pilot project from 1943 (Kullenberg & Fromm 1944) for the purpose of extending Lidén's postglacial chronology to the present. In the event, however, as stated above (p. 8), the sediment profiles did not include a sufficiency of varves, with the result that the project never attained its objective.

In the context of the fact that the processing of the recent and subrecent varve series from the present project was nearing completion, E. Fromm generously placed his slips concerning the measured varve thickness of the material from 1945 at the author's disposal.

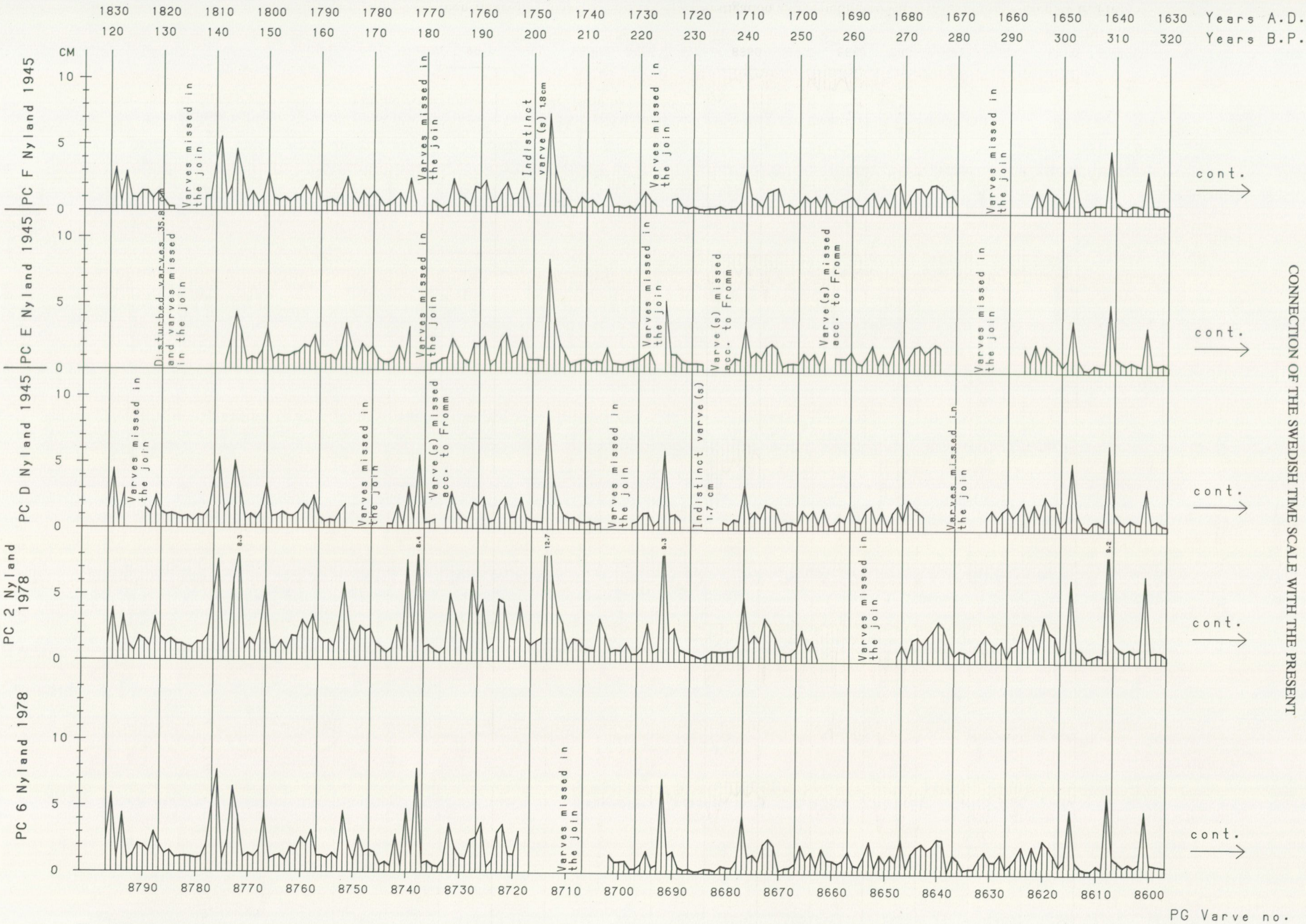
Fromm's three longest varve series (PCD-F Nyland 1945) are reported in detail with the exception of the lowermost highly uncertain parts in Fig. 25 a–b, together with the present project's varve series (PC2 and PC6) from Nyland. In relation to the report on the efforts at connection it was necessary to open gaps in Fromm's material insofar as varves are lacking vis-à-vis the profiles included in the present project. In addition there are gaps which derive from Fromm's own interpretations in his preliminary diagrams, and gaps resulting from the destruction of varves in the splices between the 70 cm long brass inner tubes then used in the piston corer. In the varve thickness diagrams (Fig. 25 a–b) the reason for all the gaps is given with inserted text.

On the basis of Fromm's material two varves are omitted from the diagrams in the present study. These concern varves which would have intervened between the present varves 8712/8713 and 8715/8716 respectively. These varves are considered to be double varves belonging to varve 8713 and 8715 respectively. The reason for these omissions is the absence of the two varves in all three profiles in Fromm's material, at the same time as they are only documented in one of the profiles (PC2) from the present project since the other profile (PC6) has a gap of barely 20 varves in just this section because of a splice between the drill tubes.

A comparative study of the varve thickness diagrams from Fromm's and this investigation showed that 14 varves were missing in Fromm's material and 13 in the present study. The latter varves could be rediscovered in a control of the sediment profiles. In almost all cases



Figs. 25a. Comparison between varve diagrams from the present investigation and unpublished varve diagrams measured by E. Fromm in 1945. The diagrams are from piston cores taken in the Ångermanälven estuary, close to Nyland.



Figs. 25b. Comparison between varve diagrams from the present investigation and unpublished varve diagrams measured by E. Fromm in 1945. The diagrams are from piston cores taken in the Ångermanälven estuary, close to Nyland.

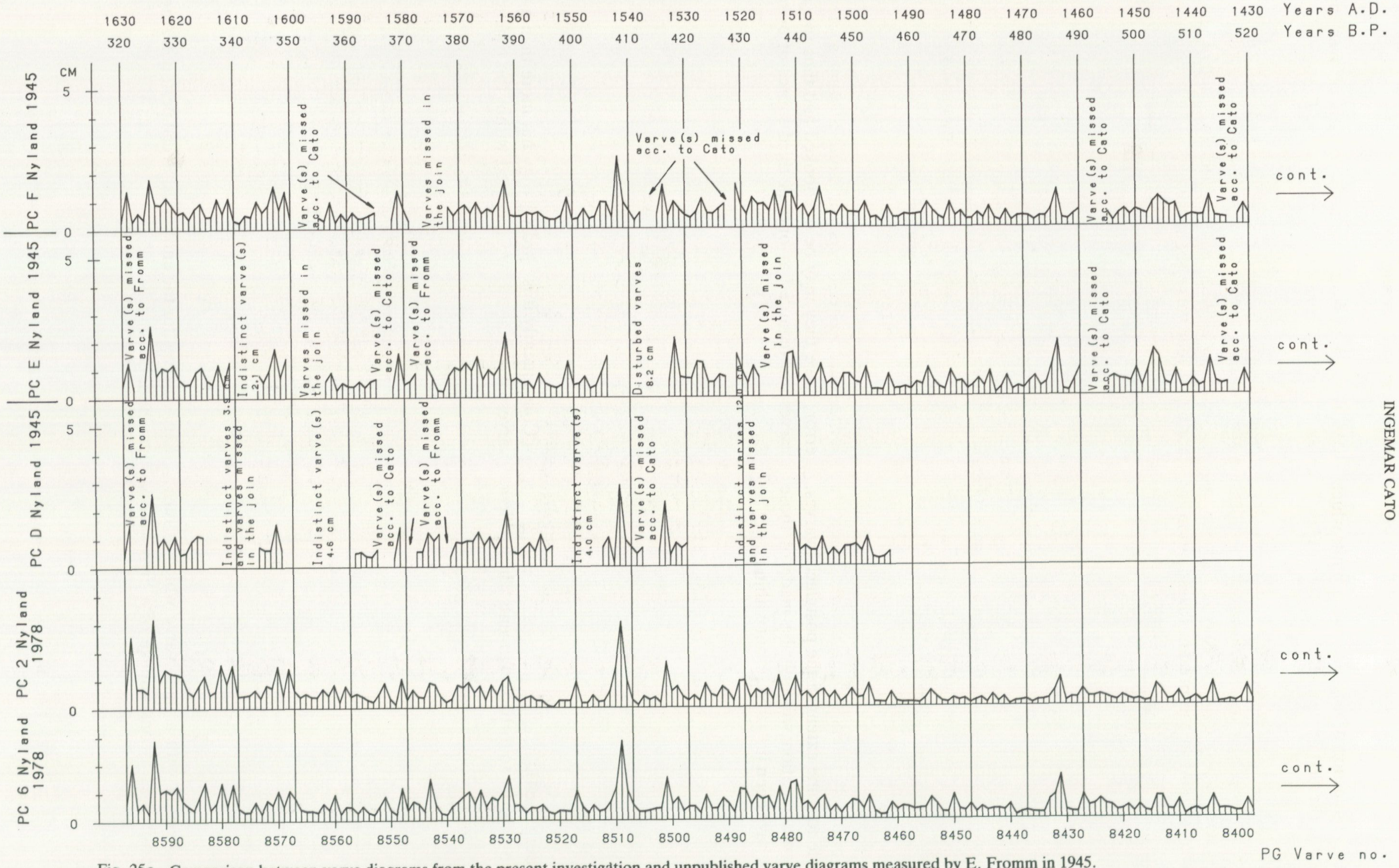


Fig. 25c. Comparison between varve diagrams from the present investigation and unpublished varve diagrams measured by E. Fromm in 1945. The diagrams are from piston cores taken in the Ångermanälven estuary, close to Nyland.

it proved to be a question of indistinct varve limits which were omitted at the first examination of the profiles. In some cases the varves were lost.

The result of this comparative study indicates how important it is to verify the number of varves in a given section via several sediment profiles. An effort was indeed made to this end in the present investigation, as can be seen in from the large number of overlapping profiles studied (see Fig. 24). The results also demonstrate that the accuracy of the varve thickness studies is very high, since measurements on different sediment profiles from the same area, made by two individuals 35 years apart, differ only by 14 minus 13, viz. one varve for a 500 year varve sequence.

Margin of error

A correct geochronological time scale, of course, requires that the varve limits have been correctly marked on the measuring paper-strips. But even if this requirement is fulfilled, several uncertainties may still remain as a consequence of primary and secondary sedimentological processes. The most important sources of error were compiled by G. De Geer (1940). Although this compilation primarily refers to glacial varves they are also applicable to some extent to the postglacial varves. In what follows, mention will only be made of those errors, which have been judged relevant within the frame of this project.

Sliding of sediments may occur in a dynamic area such as a river valley, especially where the slopes are steep as e.g. at the delta front and along the river sides. The predisposition to slides increases when the sediment becomes elevated above the sea-level and its counterpressure is thereby neutralized or when the river-mouth area is flooded during heavy spring thaws (see Wenner 1951 and Viberg 1984).

Slides often give rise to turbidity currents which follow the bottom slopes and rush into deeper levels, where they accumulate with a graded bedding structure. The appearance of these turbidities is sometimes very similar to that of annual varves and they then create a "double varve", which during varve measurements might be counted as two varves.

Double varves may also ensue from heavy autumn rains which increase the water discharge to a level close to that of the spring flood. Often, but not always, it is possible to distinguish these "internal", deceptive laminae, which apparently subdivide one varve into two varves, from the true annual varves; since they mainly appear in connection with a thick varve which in turn has been deposited as a consequence of a high water-discharge, e.g. periods of snow melt or heavy rainfall with a high frequency of slides. For this reason the varves 8934 (core GC491), 8912 (GC2), 8877 (PCF), 8862 (PC IV), 8713, 8715 (PC2), 8608 (PCF and PCD) and 8509 (PCF) have been interpreted as double varves only representing one year each (see Figs 13 a–e, 25 a–b). Otherwise a corresponding number of varves are lacking in the other cores.

Indistinct winter-layers constitute another source of error, since they may be overlooked and thus two real varves are regarded as one. A third source of error is the compaction of sequences of thin varves, as this causes difficulties in the resolution of the correct number of varves. Varves may also be missed in the joins between core sections.

In most cases in the present investigation the problems arising from these sources of error could be solved by verifying the number of varves in a given core section via several sediment profiles taken outside the area in question (see Figs. 13 b–d, 13 f and 25 a–b).

Consequently it is hardly likely that more than a few varves, if any at all, were missed within the time-span of nearly 2000 years which has been investigated.

As mentioned above eight double varves were detected between 1542 and 1967 A.D., i.e. during a time span of about 400 years. This gives a frequency of two double varves per century on average. Before the varve 8509 (1542 A.D.) no double varves have been recorded. The question then rises whether undetected double varves still exist also in this material, and if they have been counted as two annual varves each. If the latter is true for this project as well as for R. Lidén's part of the Postglacial Time Scale, another 170 double varves at most may be included before 1542 A.D. This yields about 180 double varves for the entire postglacial period in Ångermanland.

Conclusions and the dating of the zero years in the Swedish Time Scale

On p. 7 an account is given of how Lidén (1938), by means of certain historical data, deduced the course of the shift in the shoreline during the last 600 years in the valley of the Ångermanälven, and how he approximated the interval between the formation of the delta surface at Prästmon and the year 1300 A.D. as c. 380 years. Lidén concluded that the 7522 years which his chronology comprises should be supplemented by a further 980 to extend the Time Scale to 1900 A.D.

In the present investigation Lidén's chronology has been expanded to the present (1978) by new varve series. The results show that since Lidén's youngest varve 7522 was deposited until 1978 A.D. 1423 varves were formed in the valley of the Ångermanälven. This means that instead of Lidén's 980 years 1345 years must be added to Lidén's chronology in order to link it with 1900 A.D.

The fact that Lidén's figure of 980 years must be increased by 365 years can hardly be regarded as surprising, since several authors, in view of *inter alia* the current land elevation in the area, have maintained that a further 0–500 years must probably be added to Lidén's figure (Wenner 1968, Tauber 1970 and Fromm 1970).

R. Lidén's old unpublished measurements of postglacial varve series from the valley have also been checked by the author (Lidén† & Cato, in press). This revision verified Lidén's (1938) data, and no change is needed in this part of the Swedish Time Scale. Thus the combination of the varve series in the present study with those of Lidén yields a complete varve chronology embracing 8917 varves/calendar years for the entire postglacial period up to 1950 A.D., or 8945 varves/calendar years up to the present (1978 A.D.) in Ångermanland. According to the discussion of the occurrence of double varves in the previous chapter the theoretical margin of error for this period can be estimated to a maximum of $^{+10}_{-180}$ calendar years.

The consequences of the present study are far-reaching, however, not only for the Swedish Geochronological Time Scale (see Strömberg 1985) but also for all the geological and archaeological events which are temporally suspended from it. In view of all the intercalibrations between chemical dating methods and the Swedish Time Scale, between palaeofloristic and palaeofaunistic successions linked with datings suspended from the Swedish Time Scale etc., the consequences reach even further. Yet it is beyond the scope of this paper to scrutinize all these consequences. Only the effects of the results with regard to the dating of Borell & Offerberg's and G. De Geer's zero years respectively, will be recounted.

Earlier in this paper mention was made of the difference between the two zero years, the one from Vikbäcken and the other from Döviken in the valley of the Indalsälven (see p. 6). These were at first assumed by G. De Geer (1940) to have been formed at the same time, but Borell & Offerberg (1955) showed that the Döviken varve was at least 80 years older than the Vikbäcken varve. The difference in time was later fixed by E. Nilsson (1960) as 84 years. In accordance with G. De Geer's original opinion the 98 cm thick varve from Döviken (the bipartation varve) marks the dividing line between finiglacial and postglacial time in the Swedish Time Scale. Starting from Lidén's calculated connection of the Swedish Time Scale with the year 1900 A.D. (Lidén 1938) E. Nilsson (1960) could date this conventional zero year to 6923 B.C. His chronological calculations were recently checked and confirmed by Fromm (1985). In consequence of the result from the present study, however, the age of the zero year (of the Döviken varve) must be amended to the year 7288 B.C. or 9238 B.P. Thus the total length of the postglacial period up to the present (1986) in the Swedish Time Scale can be set at 9273 $^{+10}_{-180}$ varves/years if the zeroyear is excluded. However, the margin of error is probably much less.

Figure 26 demonstrates more clearly how the different time scales in the valleys of the Indalsälven and the Ångermanälven are related to each other, and how they are affected by the current study's exact connection of the Swedish clay varve chronology with the present. The figure is a further development of that presented by E. Nilsson in 1960.

It is obvious from the figure that the postglacial period is 321 years shorter in the Ångermanälven valley than in the Indalsälven valley. Here it must be stressed that the change from glacial to postglacial sedimentation is not synchronous between different valleys, which implies that the age relation must be determined by varve correlations and not by varve numbers since different local time scales exist in different valleys.

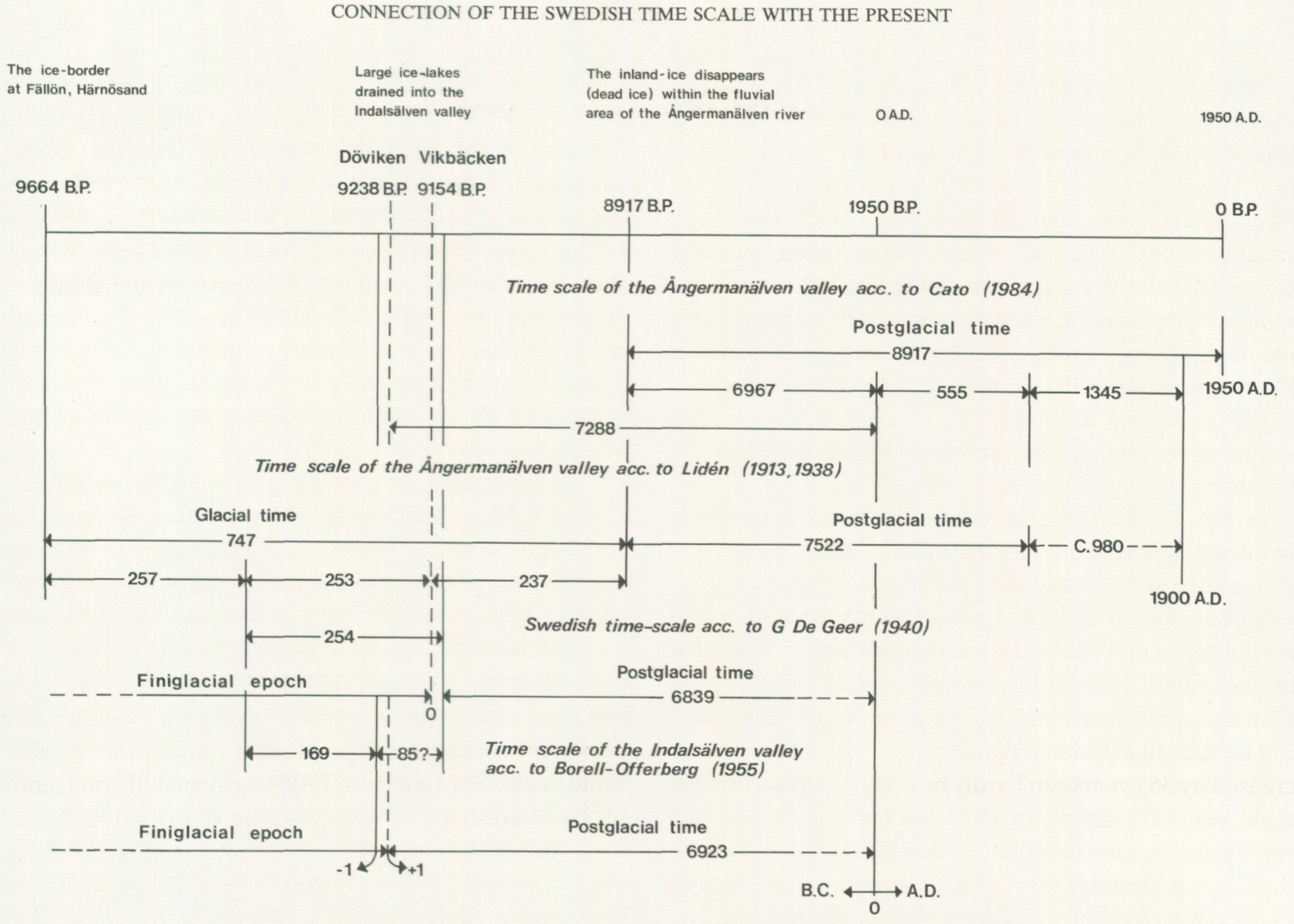

CONNECTION OF THE SWEDISH TIME SCALE WITH THE PRESENT

Fig. 26. Time scales of the Ångermanälven and the Indalsälven valleys. The commonly used zero year (Borell & Offerberg 1955) in the Swedish Time Scale can now be dated by the exact extension of the Postglacial Time Scale in the Ångermanälven valley to 7288 B.C. or 9238 B.P. (partly after E. Nilsson 1960).

Summary

The exact connection between the Swedish Geochronogical Time Scale and the present has been a matter for not merely Swedish but also international geology for almost 75 years. Despite several attempts during the 20th century no researchers progressed further than R. Lidén, with his provisional connection based on the isostatic land upheaval in the Ångermanälven river valley in northern Sweden. This connection was achieved by interpolation of the interval between the formation of Lidén's youngest varve 7522 on the delta surface at Prästmon and two historically datable shore levels in the valley of the Ångermanälven river. The interpolation indicated that varve 7522 was probably formed c. 980 years before 1900 A.D. According to several authors the recent land elevation of Ångermanland implies that the uncertainty of Lidén's calculated interval might be between 0 and 500 years.

Against the fact that the largest single error in the Swedish Time Scale could be concealed in just Lidén's provisional connection with the historical year 1900 A.D., the present project was launched within the framework of the IGCP Project 24 at the Geological Survey of Sweden.

In order to supplement Lidén's chronology with new varve series which extend to our own time, and thereby establish a definitive link between the Swedish Time Scale and historical time, 25 sediment cores amounting to a total length of 200 m were collected between 1978 and 1983 in the Ångermanälven valley. The corings were carried out both in the uplifted delta sediments within the barely 15 km long stretch of the lower part of the river and in the bottom sediments of its non-tidal estuary. Over 10 000 varves were measured and counted before all the correlations were clear and R. Lidén's chronology from 1938 was thereby expanded to the present.

To confirm the calendar year affinity of the youngest varves, since it was not feasible to assume without further ado that the uppermost layers from the bottom of the Ångermanälven's estuary really were formed continually until the year of sampling, correlations were sought over a 70-year period between the youngest varve series and the river's water discharge. The strongest correlation was found to exist between the maximum daily mean discharge during the spring and early summer floods (generally in May and June) and the corresponding varve thickness.

The documented links were also strengthened by the following facts.

1. The thickness of the varves diminished, relatively speaking, at the same rate as the regulation of the river proceeded during the 1950s and 1960s.

2. The construction of a power station dam at Sollefteå in the year 1962 to 1966 led to a marked deviation of the linear correlation between annual transport of suspended matter and the thickness of the varves belonging to this period.

3. The occurrence of a double varve 1967, was explained when one of the two varves was identified as a turbidity due to a subaquatic slide that year.

4. X-ray photographs, by V. Axelsson of Uppsala University, of two cores taken with a four year interval in the estuary of the river allowed confirmation that the most recent core contained another four distinct varves. This proved that the varves are annual and that the current sedimentation and unique varve formation are still in progress in the area. The calendar year affinity of the recent varves was thus clearly documented by several independent methods.

The recent and subrecent varve series were then linked and extended to Lidén's unpublished varve series from Prästmon with the help of five varve series derived from Fröksholmen, Gistgårdsön, Dannero, Pershem and Kungsgårdsfjärden respectively. Lidén's unpublished varve diagram from Prästmon was also verified by a new varve series from this locality. Altogether the verification and connection could be achieved with Lidén's 500 youngest postglacial varves.

The extension of Lidén's chronology to the present (1978 A.D.) by new varve series shows that his previously calculated gap of 980 years between his youngest varve 7522 found at the delta surface at Prästmon and the historical year 1900 A.D. should be extended with 365 years. This means that instead of his 980 years, 1345 years must be added to Lidén's chronology in order to link it with 1900 A.D.

In another project the author has checked Lidén's old unpublished varve diagrams from the valley (Lidén† & Cato, in press) and found that no change is needed in this part of the Swedish Time Scale. Thus the combination of the varve series in the present study with those of Lidén yielded a complete varve chronology embracing 8917 varves/calendar years for the entire postglacial period up to 1950 A.D. or 8945 varves/calendar years up to the present (1978 A.D.) in Ångermanland. According to the discussion given in this paper about *inter alia* the occurrence of double varves, the theoretical margin of error for this period has been estimated to a maximum of $^{+10}_{-180}$ calendar years.

The uppermost identifiable varve at the coring site Kungsgårdsfjärden close to the present delta front has also been checked. The varve was dated to 1746 A.D. by means of its connection with the present. The plausibility of the age of this varve is of special interest since it could support the investigation results. This was indeed the case, as is clear from a comparison of the shore line displacement at the site. According to Stenklyft's map from 1678 the drill site was still well below the surface of the river, while according to another map from 1876 it was situated on a peninsula which had emerged from the river. This indicates that the sedimentation at the site must have been interrupted some time between these years, which is in good agreement with the age of the uppermost indentifiable varve (1746 A.D.).

The unpublished varve thickness measurements carried out by E. Fromm on three cores taken by him in the Ångermanälven estuary in 1945 were compared with those of this investigation, in order to demonstrate the accuracy of varve measurements. The results showed that measurements on different sediment profiles from the same area, made by two individuals 35 years appart, differ only by one varve for a studied 500 year varve sequence.

The consequences of the present connection of varve series to the present are far-reaching not only for the Swedish Geochronological Time Scale but also for all the geological and archeological events, intercalibrations etc. which are temporally or otherwise based on it. Yet it was beyond the scope of this paper to scrutinize all these consequences save one, viz. Borell and Offerberg's zero year (the Döviken varve) in the valley of the Indalsälven river some 50 km south-west of the Ångermanälven river. The zero year, which denotes the boundary between finiglacial and postglacial time in the Swedish Time Scale, was previously dated by E. Nilsson, on the basis of Lidén's provisional connection, to 6923 B.C. In consequence of the present study the exact date of the zero year can now be set at the year 7288 B.C.

or 9238 B.P. Thus the total length of the postglacial period up to the present (1986) in the Swedish Time Scale can be set at 9273 $^{+10}_{-180}$ varves/calendar year if the zero year is excluded. Here it must be stressed that the change from glacial to postglacial sedimentation is not synchronous between different valleys. In e.g. the Ångermanälven valley the period was found to be 321 years shorter than in the Indalsälven valley.

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