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SEISMIC REFLECTION MEASUREMENTS WITH A PNEUMATIC SOUND SOURCE IN THE RÍA DE AROSA (NW SPAIN)

BY

K. HINZ[1]

with a contribution by

A. J. PANNEKOEK[2]

ABSTRACT

In 1968 continuous seismic profiles with a total length of 150 km were made in the Ría de Arosa (Galicia, NW Spain). They were executed by the Bundesanstalt für Bodenforschung (Hannover) with the assistance of two members of the Department of Geology of the University of Leiden (The Netherlands). The pneuflex (airgun) system used for profiling is described. The transformation of travel-time profiles into depth profiles was done automatically with the aid of a computer program.

The profiles reveal the presence, below some 7—12 m of Holocene marine muds, of bedded deposits with a thickness of about 30 m (and in the outer part of the ria even more than 60 m), which are interpreted as being of fluvial origin. They are underlain by what is assumed to be colluvium and weathered granite. The bedded deposits must have been formed in times when the sea-level was low, presumably during the Riss and/or Würm glacials. They may originate in part from deposits of the Ulla River, but to a greater extent may represent fluvial fans of its tributaries.

SUMARIO

Mediciones sísmicas de reflexión con un sondeo neumático en la Ría de Arosa (Galicia)

por K. Hinz, con una contribución de A. J. Pannekoek

En 1968 fueron efectuados en la Ría de Arosa (Galicia) perfiles sísmicos continuos con una longitud total de 150 km. Fueron ejecutados por la Bundesanstalt für Bodenforschung (Hannover) con la asistencia de dos miembros del Departamento de Geología de la Universidad de Leiden (Holanda). Para el perfilaje se usó un sistema "Pneuflex" (airgun) descrito en este artículo. La transformación de perfiles de tiempo en perfiles de profundidad se hizo automáticamente con la ayuda de un programa de computador.

Los perfiles revelan, a una profundidad de 7—12 m por debajo de arcillas marinas del Holoceno, la presencia de depósitos estratificados con un espesor de cerca de 30 m (y hasta más de 60 m en la parte exterior de la ría), que son interpretados como depósitos de origen fluvial y que cubren lo que se presume es coluvio y granito alterado. Los depósitos estratificados tienen que haber sido formados durante un tiempo en que el nivel del mar fue bajo, probablemente durante las glaciaciones Riss y/o Würm. Estos depósitos pueden representar parcialmente deposiciones del Río Ulla, pero en su mayor parte son conos de deyección fluviales de sus tributarios.

1. INTRODUCTION

During the combined sedimentological, oceanographical, and biological investigations carried out by a group of students from The Netherlands in 1962—1964 (Brongersma & Pannekoek, 1966) in the Ría de Arosa, one of the deep embayments on the northwestern coast of Spain, no data could be obtained on the sediment thickness and the deeper sedimentary layers below the sea floor, because adequate equipment was not available at that time. It was only in 1968 that it became possible to obtain continuous profiles providing information about the sediments lying below the sea bottom and on the top of the granitic basement. In that year the Department of Geology of the University of Leiden (The Netherlands) requested the Geophysical Department of the Bundesanstalt für Bodenforschung (Geological Survey of the Federal Republic of Germany), Hannover, to make continuous seismic reflection measurements with a pneumatic sound source in the Ría de Arosa.

These measurements were carried out in July, 1968. Dr. W. J. Sluiter and Dr. W. S. Koldijk took part in the work on behalf of the Department of Geology of

[1] Bundesanstalt für Bodenforschung, Postfach 54, 3 Hannover-Buchholz, W. Germany.

[2] Department of Geology, University of Leiden, The Netherlands.

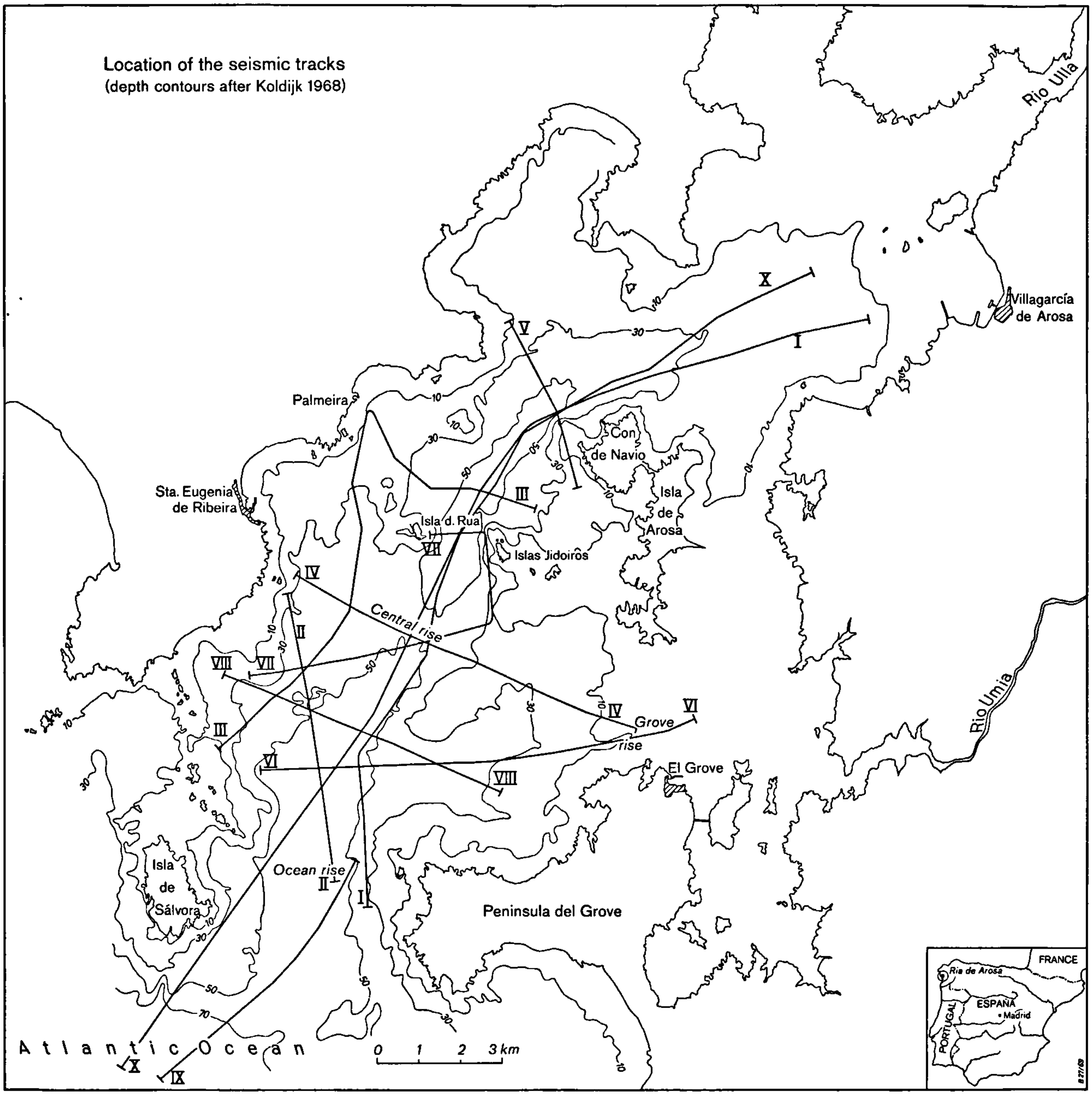

Fig. 1. Approximate positions of the seismic profiles. Scale 1:150,000.

the University of Leiden. They obtained a boat and were responsible for navigation and position finding. The Bundesanstalt für Bodenforschung provided the continuous profiling equipment (pneuflex system), which was operated by their technical staff consisting of Mr. B. Koslowski and Mr. D. Steinmann. The geophysical interpretation of the seismic recordings was entrusted to the author.

A total of about 150 km of profile was measured. The approximate positions of the reflection profiles are shown in Fig. 1.

Acknowledgements. – The author gratefully acknowledges the assistance of Miss I. Richter, Dipl.-Geophysicist, and Mr. S. Garde in interpreting the profiles.

The Department of Geology of the University of Leiden wishes to express its thanks to the President and to Prof. Dr. H. Closs and Mr. H. Bungenstock, Dipl.-Geophysicist, of the Bundesanstalt für Bodenforschung, for their share in the preparation of the investigation, and to Dr. W. S. Koldijk for critically reading the text.

The Netherlands Organization for Pure Research (Z.W.O.) is thanked for providing the necessary funds.

2. THE PNEUFLEX SYSTEM, METHOD OF MEASUREMENT, INSTRUMENT EQUIPMENT, AND INTERPRETATION

The pneuflex or airgun system belongs to the continuous seismic reflection systems. A ship equipped with the recording instruments (Fig. 2) tows the seismic sound source and the streamer cable at constant speed below the water surface, the energy source radiating acoustic energy at the chosen constant intervals.

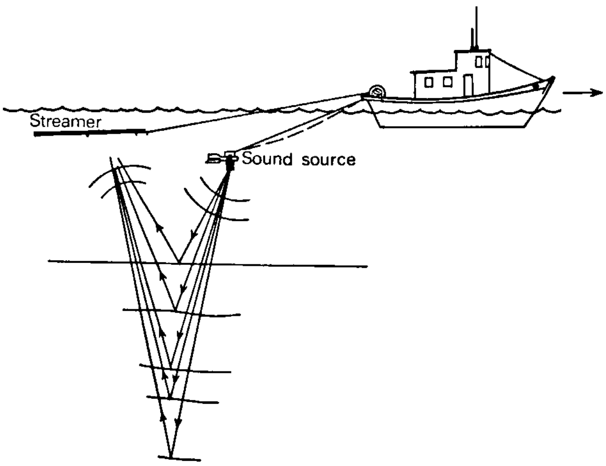

Fig. 2.

Owing to the shallowness of the water the distance between the cable and the sound source in the present investigations amounted to about 5 m. The shooting rate was approximately 3 seconds, which at a speed of 4 knots corresponds to a point spacing of about 6 m.

2.1. The pneumatic sound source

To produce an acoustic impulse, we used a pneumatic sound source (Fig. 3) consisting of a control chamber A, a storage chamber B, a mobile shuttle, and a rapidly reacting solenoid valve S.

From a compressor compressed air (150 kg/cm²) is conducted into chamber A and depresses a shuttle, so that both chambers are closed (Fig. 3). The pressure balance with respect to the storage chamber B is established through an orifice in the shuttle.

Excitation of the solenoid valve S by a short electrical impulse discharges a shot, in the process of which a conductor is opened (shown by dotted line in Fig. 3) through which the compressed air is forced under the upper shuttle plate. In this way the pressure under the upper shuttle plate is suddenly increased. The shuttle rapidly moves upwards, opening discharge points through which the compressed air of chamber B escapes in an explosive manner.

In the present investigations, a pneumatic sound source, type BOLT PAR Model 600, with a chamber volume of 1 cm³ was used.

2.2. Equipment, acoustic signal, and noise effects

The shots are discharged at determined intervals via an R-C generator which triggers an ignition device and the recording unit simultaneously.

The seismic signal reflected at the ocean floor or at a seismic interface of the subsoil is recorded by a streamer (BOLT Hydrophone Array 1010) and transformed into an electrical signal, which, after having passed a pre-amplifier and the filter and final amplifier stages, is made visible on an Elac recorder (type LAZ 32) provided with electrosensitive dry paper operating according to the start-stop principle.

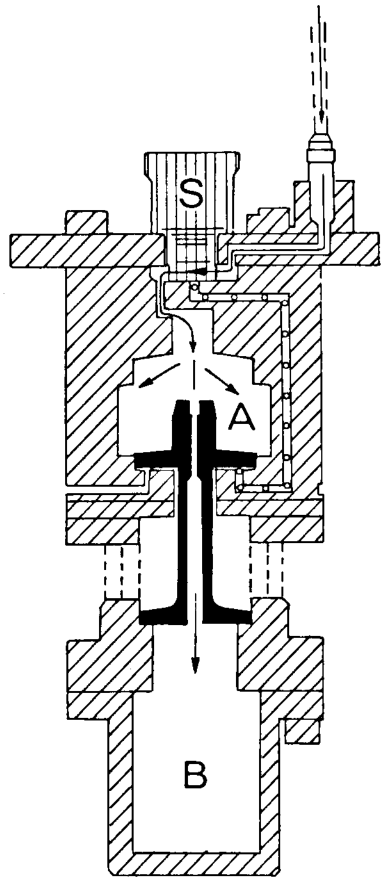

Fig. 3. Pneumatic sound source.

In the investigations in the region of the Ría de Arosa, the gun was moved in a water depth of 1 to 2 m.

The penetration and resolution are determined by the main frequency and the pulse length of the acoustic signal produced by the pneumatic sound source and radiated into the subsoil; maxima in the frequency spectrum of the signal lie between 20—500 Hz (Bungenstock, 1969).

In general, the resolution can be given by the equation d=v.t/2, in which v=rock velocity in m/sec, t=pulse length of the first full oscillation in seconds, and d=resolvable zone in metres. With a pulse length of

6 m/sec and a rock velocity of 1,700 m/sec, it is still possible to determine layers of a thickness of 5.5 m.

2.3. *Geophysical interpretation and representation of the results*

The seismic impulse produced by a pneumatic sound source in the water and radiated into the subsoil is reflected at the interfaces between various layers, the reflected part of the amplitudes being dependent on relation of the acoustic impedances, i.e. $w=v.\rho$. The more strongly the acoustic impedances differ from one another, the more strongly the lithological boundary plane reflects. Interfaces which reflect well are marked by an increase in amplitudes (in the pneuflex recordings high density) and by equal phases.

In the Ría de Arosa the sea floor consists to a large extent of muddy sediments of Holocene age (Koldijk, 1968). The pneuflex recordings, however, also revealed hitherto unknown deposits of presumably Pleistocene age, which appear as strong reflection horizons. The basis of the sedimentary complex is composed of crystalline rocks, predominantly granite, which is "deeply weathered and displays typical features such as spheroidal weathering and tors" (Pannekoek, 1966). Seismically, it appears as weak horizons with a rugged relief which cannot be traced continuously.

In all the pneuflex records reproduced in this paper, only the 0.1 second time mark has been indicated. The vertical distance between two time marks amounts to 0.01 seconds.

In the course of the interpretation, all prominent reflection horizons were digitized in the process of which, in the pneuflex recordings, the travel times of a reflection were read at horizontal spacings of 1 mm (40—60 m, depending on the speed of the ship).

With the aid of a computer programme developed for this particular purpose, the depth coordinates read for each travel-time value of a reflection were calculated on an IBM 1620 according to the Tuchel formulas (Reich & Zwerger, 1943); these values were then punched on tape, and the depth profiles automatically drawn on a plotter (type ZUSE Z 64).

In all these profiles the granitic basement is shown by oblique hatching.

Since data on the transmission velocity of longitudinal waves in the sediment were not available, a velocity of 1,700 m/sec was assumed for the Holocene to Pleistocene sediments in the depth calculation. For the water layer, a velocity of 1,500 m/sec was assumed in the calculations.

3. RESULTS

3.1. *General features*

In the central parts of most of the profiles, where the water depth is greatest and the top of the granitic basement deepest, a distinction can be made between (from top to bottom):

(c) an almost continuous upper layer, which in the shallower areas directly overlies layer (a) or even the granite;

(b) a layered complex, displaying various, often somewhat convex, reflection horizons;

(a) a seismically transparent zone, filling up depressions between granitic residual hills and also occurring at shallower depths where zone (b) is absent.

The upper layer (c) may be correlated with the Holocene marine muds and sandy muds which cover most of the ria bottom (Koldijk, 1968) and have been deposited since the post-glacial rise of the sea-level.

The layered complex (b) is assumed to be of fluvial origin and, because of the somewhat convex reflection horizons, to represent flat alluvial fans. The seismically transparent zone (a) may be considered as mainly consisting of weathering debris of the granite, which on the land often reaches a thickness of 10 m and more, and of colluvium.

Some profiles show, in addition, series of sediments marked by numerous reflections traceable over short distances only, and which, at their outer end, have a distinct dip, parallel to a pronounced slope of the sea floor. They have been interpreted as delta deposits. Sediments accumulated on the slopes of the crystalline basement and showing reflections parallel to this slope have been classified as slope deposits (colluvium).

The distribution of most of these deposits is shown schematically in Fig. 4.

These units will now be discussed for the individual profiles. When comparing the profiles it should be kept in mind (1) that the velocity and direction of the boat may have varied without this having been recorded; this means that the horizontal scales are only approximate and that the tracks of the profiles in Fig. 1 and the intersection points may have to be shifted; (2) that the streamer may have varied in depth and that no correction has been applied for the tides, so that the vertical distances too are approximate.

3.2. *Discussion of the seismic profiles*

The profiles in the central part of the ria will be considered first[1].

Profile IIIA runs from SSW to NNE (near Palmeira), parallel to, and to the W of, the central channel of the ria. In a central section, between two residual granitic hills, a seismically transparent zone, directly overlying the granite, is followed by sediments with closely spaced, slightly convex reflections. These closely spaced reflections are indicative of an alternation of different deposits; the bedding suggests an alluvial fan, probably overlying deeply weathered granite or colluvium.

In the two zones north and south of this central section, the surface of the granite lies at a level with the top of the assumed fan of the central section. Apparently, these two zones, probably covered by weathering debris and colluvium, were drowned after the fan had been formed. Subsequently all three sections were covered by a uniform layer of marine mud.

[1] Profile II, being of bad quality, is not reproduced or discussed.

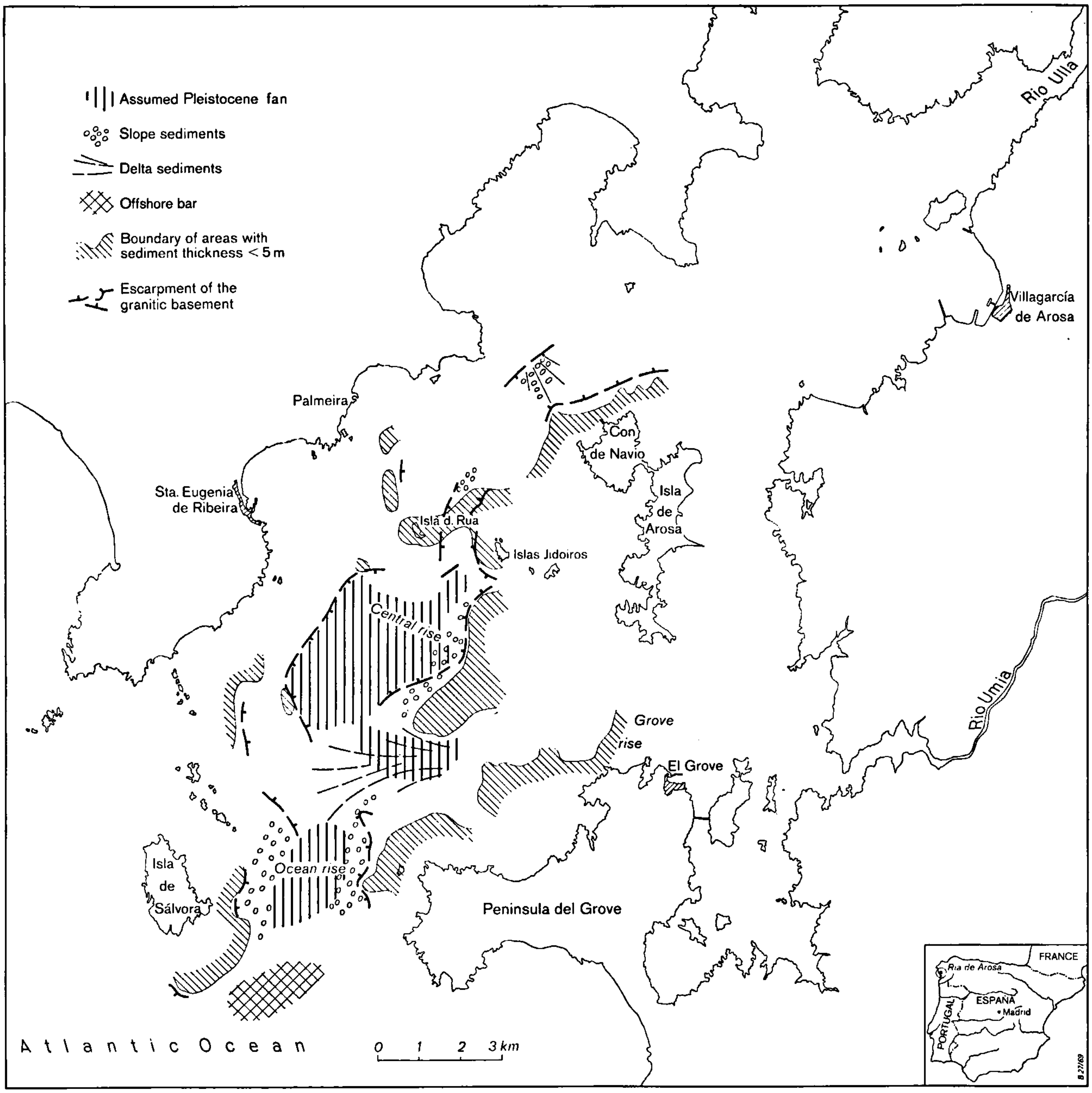

Fig. 4. Distribution of the deposits below the Holocene bottom sediments of the Ría de Arosa (schematic). Scale 1:150,000.

Profile IV runs across the ria at the site of the transverse "central rise" separating the deeper inner and outer parts of the ria; the profile then continues in the shallow-water area south of the Islas de Jidoiros. Below the central rise the granite has been deeply eroded and the depression has been filled up by sediments of considerable thickness (see also the longitudinal profiles I and X). Apart from a lower seismically transparent zone, these sediments are again characterized by flat, slightly convex reflections. In analogy with profile III, this sedimentary complex may be interpreted as an alluvial fan which has filled up the original erosion valley. Afterwards, the top level of the fan, marked A in the profile, was eroded, as indicated by the gully in the reflection horizon A. Subsequently, the NW part, and still later the shallow-water area south of the Islas de Jidoiros, were inundated, after which marine muds were deposited on the granite or on the weathering debris and colluvium that had collected between the granitic residual hills.

The left part of *profile VII* again crosses, in a more oblique direction, the deeply eroded and wide central valley (maximum depth of the granitic basement about 95 m) filled up with sediments having a total thickness of 30—45 m (see also profiles I and X). They can again be subdivided into three zones. The weakly reflecting granite surface is overlain first by seismically transparent material (probably weathering debris or colluvium) and then by a complex characterized by reflections showing a concentric, convex pattern with a strong top reflection (horizon A). Here too, they may be interpreted as part of the drowned alluvial fan encountered in the foregoing profiles. This complex is disconformably covered by what are probably Holocene marine muds and sandy muds.

Profile VI runs from the so-called Grove-rise in the east towards the central channel of the outer ria in the west. Within the shallow-water region, seismically transparent material (presumably weathering debris) is mainly confined to pockets in the unweathered granite. The deeply eroded central valley (western half of the profile) is filled by sediments with a total thickness of 30—50 m. They show numerous reflections that can be correlated over short distances only. Where the sea bottom slopes strongly to the west, the deeper reflections also dip westwards. On the basis of these bedding properties, the latter sediments may be tentatively considered as a delta of the Umia River, deposited in front of the shallow-water region of the Peninsula del Grove.
In the eastern half of *profile VIII*, conditions are similar to those in the righthand part of profile VI. The deltaic deposits seem to be underlain by an old fan deposit in the deeper part of the central valley, as indicated by concentric,convex reflections (dotted on profileVIII).
The greatest sediment thickness (70 m) found by the seismic-reflection method in the Ría de Arosa was encountered in *profile IX*, running from the area west of the Peninsula del Grove towards the southwest into the Atlantic Ocean. In the few places where the surface of the crystalline basement is discernable as a reflection horizon, it shows a rugged relief. It is overlain by a thick seismically transparent zone upon which follows a series of bedded, presumably fluviatile sediments in the northeastern part of the profile, corresponding approximately to the "ocean rise". The centre of the profile shows a distinct off-shore bar.

The inner half of the ria is crossed by three seismic profiles.
Profile V shows the narrow central erosion valley, partially filled up by sediments. The deepest part contains horizontally layered sediments, which along the northwestern valley slope are overlain by finely bedded deposits dipping towards the centre of the valley. The latter sediments may represent slope deposits, or perhaps part of a delta. The surface layers are in any case composed of Holocene marine muds.
More to the south, the inner part of the ria is crossed by *profile III B*. This profile shows a wide erosion valley which is partially filled up, presumably by weathering debris or colluvium, but the Ulla River seems to have later eroded a narrower valley not only into this material, which now stands out as a terrace, but also into the underlying granite; the bottom of this valley has a thin sedimentary veneer, probably representing Recent marine muds.
The righthand part of *profile VII* crosses the same narrow erosion valley between the islands of Rua and Jidoiros. Here too, the bottom is probably veneered by a thin layer of marine mud.

3.3. Thickness contour map of the sediments

The calculated depth profiles were used to compile a thickness contour map (Fig. 5) of the presumably Holocene and Pleistocene sediments.
The greatest thicknesses, viz. more than 60 m, of the sediments have been demonstrated in the outer part of the Ría de Arosa southeast of the Isla de Salvora. In the central part of the Ría de Arosa, in the area between the Isla de Rua in the north, and the Isla de Salvora and the Peninsula del Grove in the south, there is a wide sedimentary basin in which the average thickness of the sediments amounts to about 30 m. The western and eastern borders of this basin approximately coincide with the present 30 m water depth contour (see Fig. 1). The "central rise" and the "ocean rise", two slight ridges on the sea floor, are, according to the seismic records, of sedimentary origin.
For the northern part of the Ría de Arosa there is only a small number of useful seismic data available. They too, however, indicate a thickness of sediments amounting to 30 m north of Con de Navio.

4. PLEISTOCENE HISTORY OF THE RIA DE AROSA by A. J. Pannekoek

Before the continuous seismic profiles discussed in this paper had been made, it was known that the wide depression in which the Ría de Arosa is situated, already existed in almost its present form during the older glacial phases of the Pleistocene, and even earlier. This conclusion was based, among other evidence, on the occurrence of bedded fan deposits on the lower slopes on land. Because these deposits contain kaolinite and completely weathered pebbles, are strongly dissected, and continue below the present sea-level, they are thought to date from one of the older glacial phases of the Pleistocene(Nonn, 1964, 1966; Pannekoek, 1966). The drowned parts of the low-angle slopes were supposed to have, below the veneer of marine mud, the same characteristics as the subaerial parts, which consist of some granitic residual hills having between them thick masses of weathered granite and colluvium, with probably a thin band of fluvial deposits along the drowned central river course.
The most important contribution of the recent seismic survey of the ria is the discovery of extensive areas with bedded deposits, probably of fluvial origin, with thicknesses of 30 m and more, far below the present sea-level. These deposits fill up a wide central valley and may represent coalescing alluvial fans.

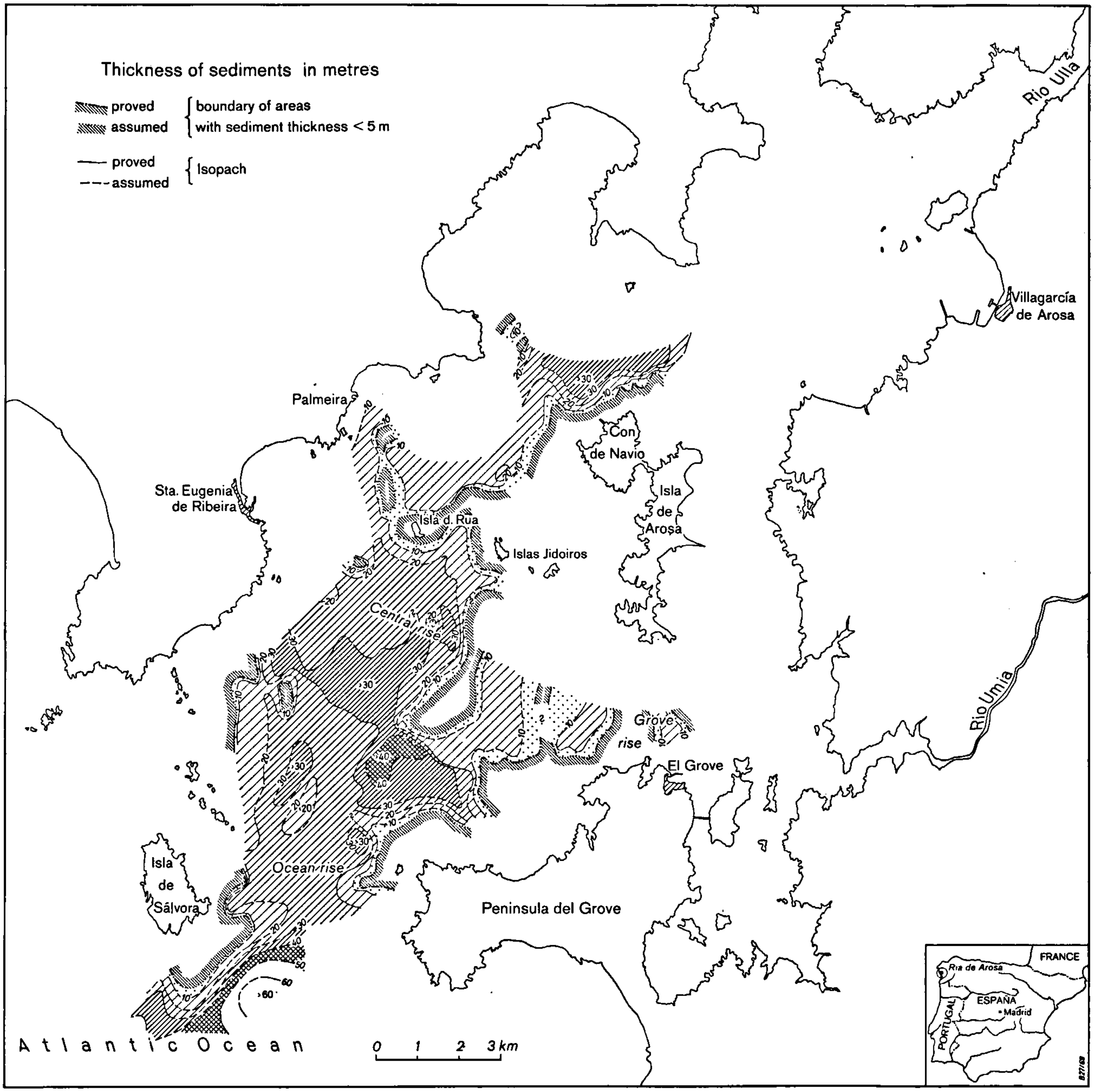

Fig. 5. Thickness of the deposits on the bottom of the Ría de Arosa. Scale 1 : 150,000.

These are not, however, the oldest parts of the valley fill. In many places they are underlain by seismically transparent material interpretable as weathered granite and colluvium. We may therefore assume the following sequence of events.

Subaerial deep weathering and slope wash were probably already active in this wide valley in early-Pleistocene times. Since thick masses of weathered material and colluvium also occur in the deepest part of the valley now occupied by sea-water, this part must have been dry at that time. It may have subsided, as has been assumed by various authors, but it seems equally, or even more, probable that the weathering occurred during low stands of the sea-level during the earlier glacials, which may have had a cool rather than a very cold climate. The actual down-cutting of the central and lateral channels must have been the work of the main river (Ulla) and its tributaries.

This channeling may have occurred in several phases. Profile III B shows a deep valley eroded into an older granitic surface covered by what are probably weathered material and colluvium, which appear as a terrace. The older surface could have been eroded and strongly weathered during, let us say, the Günz or the Mindel glaciation, and the deeper erosion could then tentatively be assigned to either the Mindel or the Riss glacial. Headward erosion to a depth of about 80 m must at that time have proceeded at least as far as a point north of Con de Navia, according to profiles I and X.

A later stage in the development is represented by the extensive fan-like fluvial deposits, the base of which is found at 67—80 m and the top at about 47—60 m below the present sea-level. They must have been deposited during a glacial stage with a low sea-level. Since they are rather well preserved and only eroded at the top, it seems probable that they date from either the Riss glaciation or, perhaps, from the early and middle Würm glacial. The accumulation may have been accompanied by a slow rise of the sea-level, to about 50 m below the present one. This would also explain the subsequent formation, below sea-level, of the presumed Umia delta (profiles VI and VII).

The erosion of a gully into the fluvial deposits (unless it was a tidal gully) could then be ascribed to a drop of the sea-level during the last glacial maximum of the Würm glaciation. This is, however, no more than an assumption.

A remarkable feature is that the depth of the central channel in the upstream part of the ria (profiles III B and V and the right part of VII), seems to be greater (surface of the granite about 77 m) than that of the gullies in the fluvial fan deposits farther downstream. If this difference is real and not due to instrumental errors, it would mean that the fan deposits, probably supplied by tributaries, must have dammed the pre-existing channel and that further upstream a drowned channel section persisted as a lagoon. The coalescing fans would at that time have formed an alluvial coastal plain behind an off-shore bar.

The inclined beds visible on profile V may either represent slope deposits or, more probably, a delta of a northern tributary draining the Barbanza area, for instance a downward continuation of the Rio Coroño. If this was a delta front, it could date from a time when the sea-level was only 30 m or less below the present one, which would place it in the post-Riss or even the Flandrian transgression.

The last phase in the development of the ria is represented by the Holocene deposits of mud and sandy mud covering the whole ria bottom and passing into sands near the shores and at some other places. The thicknesses of these deposits can be estimated from the profiles at some 7—12 m in the central parts where they cover the fluvial deposits, the top of the latter being a marked reflection horizon. Assuming that the deposition started when the sea-level was still considerably below the present level, say 10,000 years ago, and taking an average thickness of 10 m, the sedimentation rate would be roughly 1 m in 1000 years. This is approximately in accordance with ^{14}C-ages determined by Dr. M. A. Geyh of the Bundesanstalt für Bodenforschung (Hannover) in a core from the marine muds, from which a sedimentation rate of about 1.0 to 1.5 m/1000 y can be calculated. The sedimentation rate in the delta-front deposits of the Ulla River is higher. From deposits lying 10.0 and 9.5 m below the shallow sea floor, ages of 2750±90 B.P. and 2455±80 B.P., respectively, have been obtained. This results in sedimentation rates of 3.6 to 3.9 m/1000 y. For the upper end of the Ría de Vigo, comparison of old and modern charts gives a sedimentation rate of 4 m/1000 y (Nonn, 1966). Comparable results are known from similar environments.

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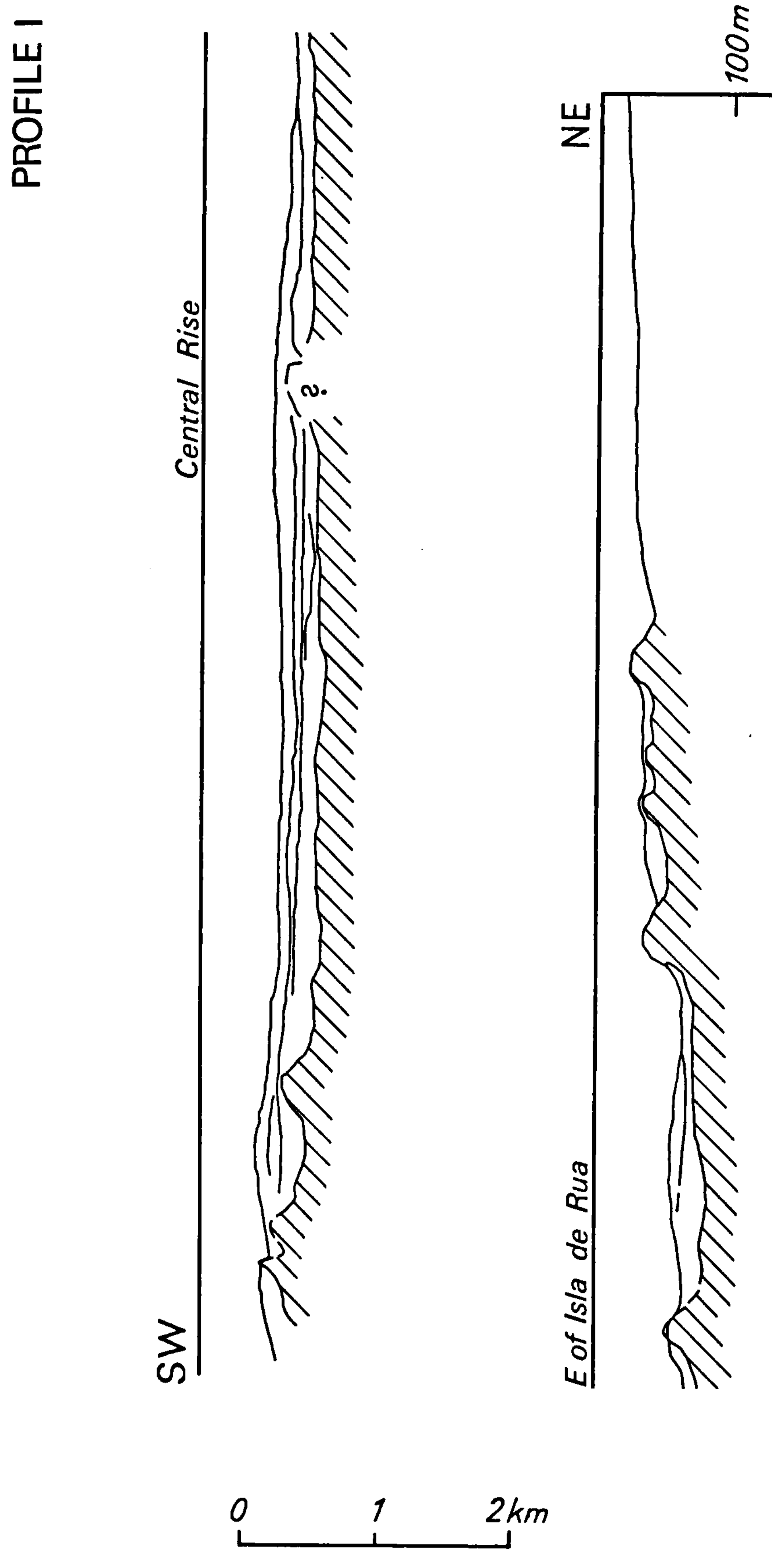
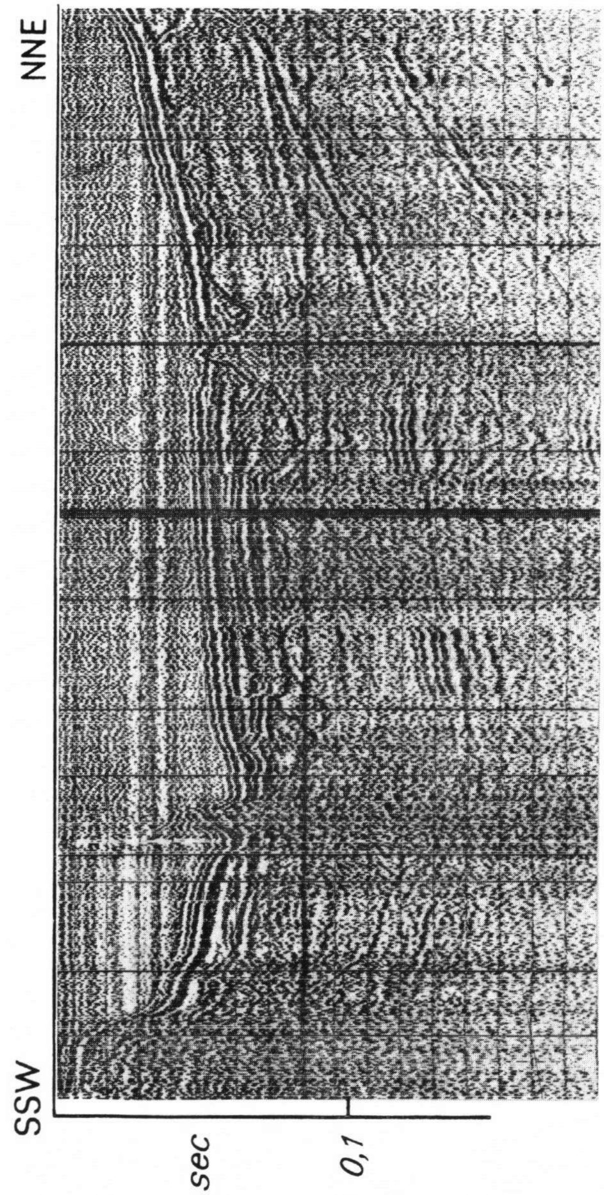
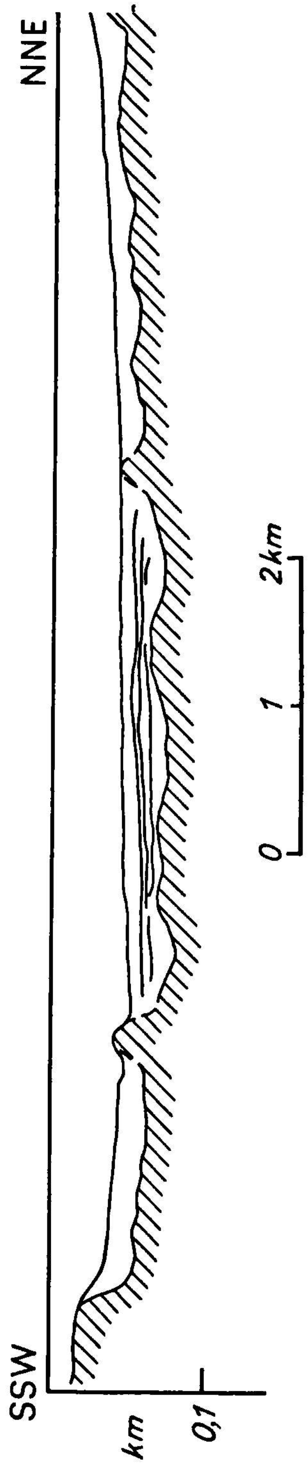
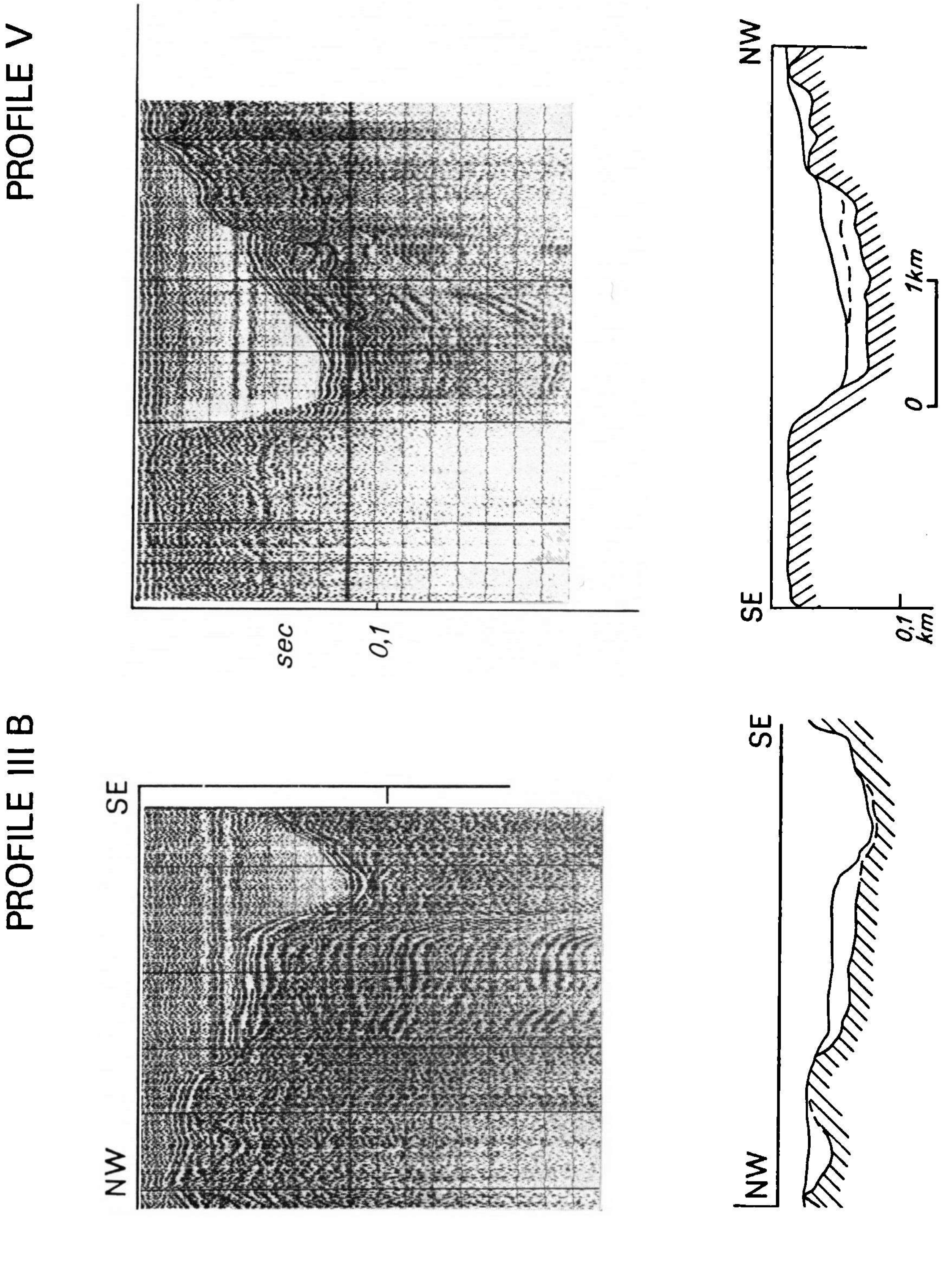
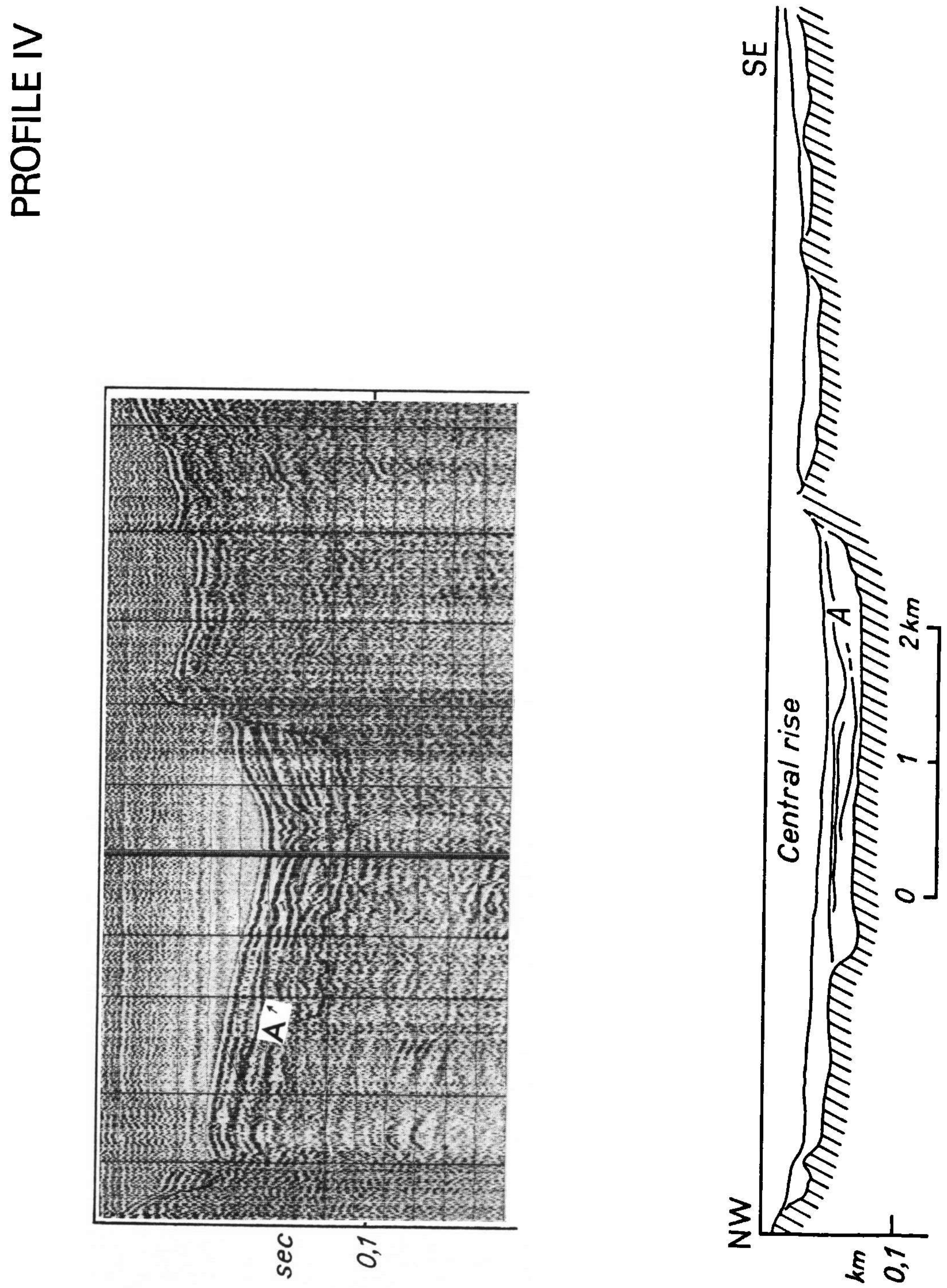

PROFILE I
SW
Central Rise
?
NE
100m
E of Isla de Rua
0 1 2km

PROFILE III A

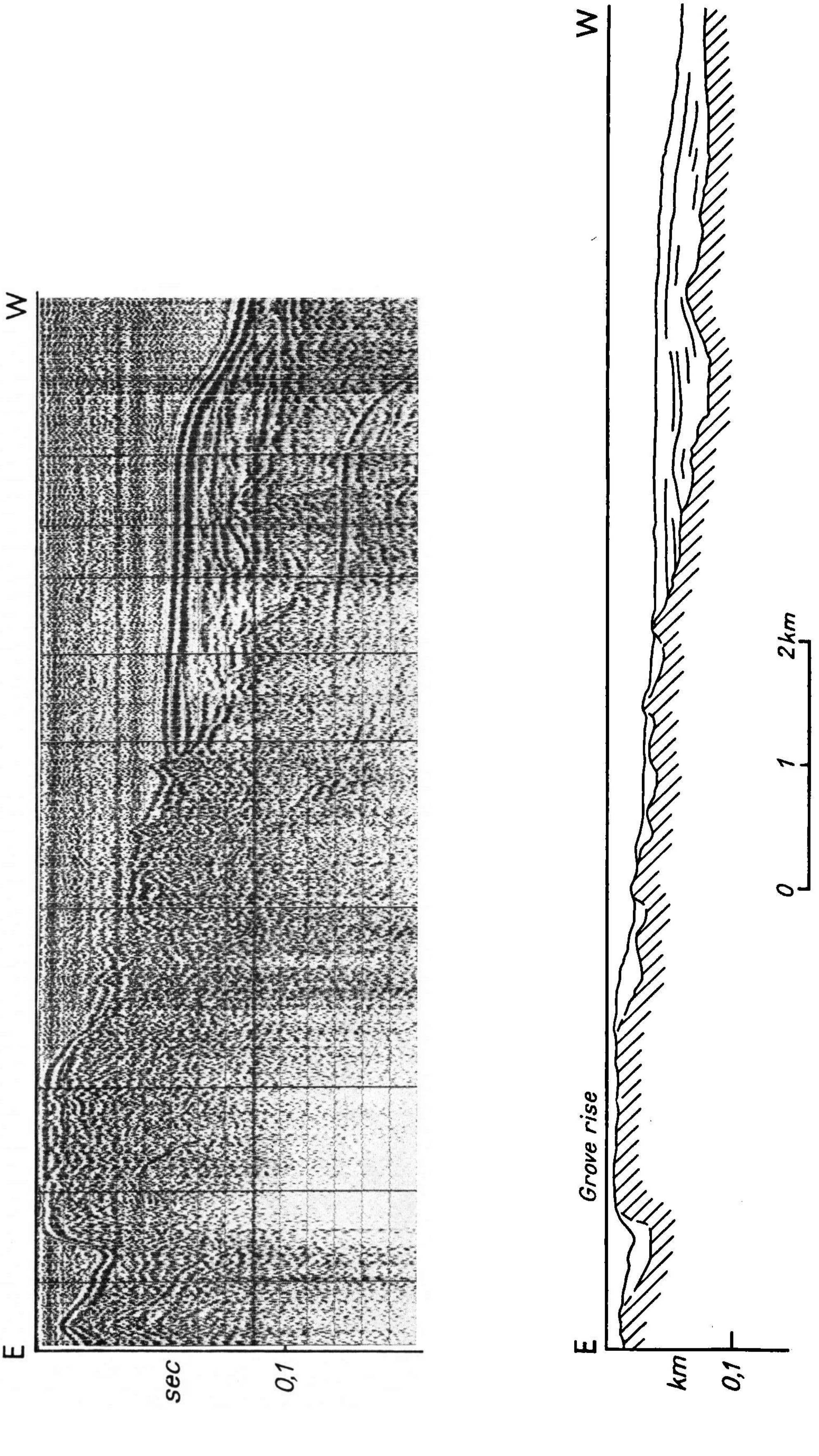


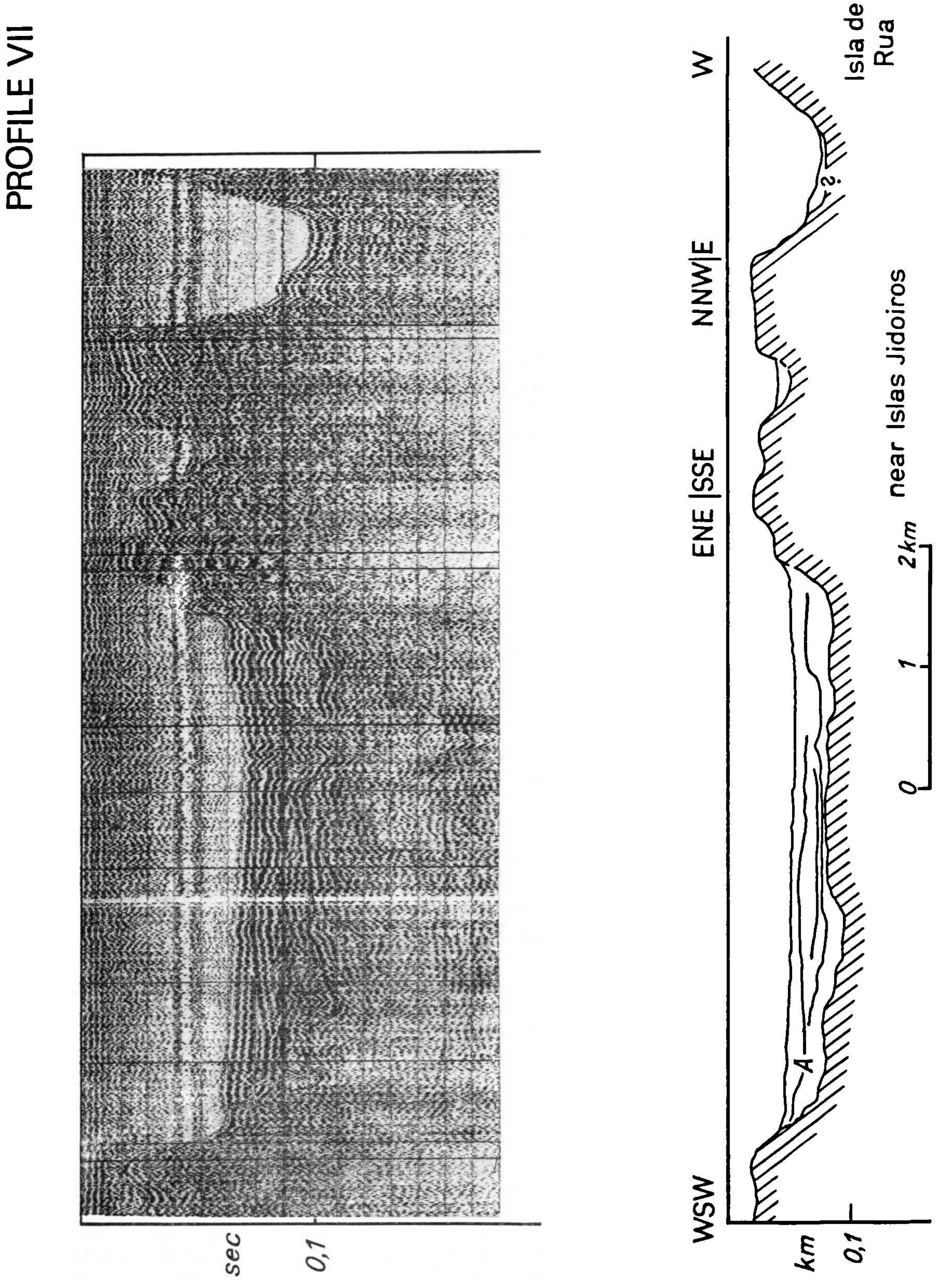



PROFILE V
NW
SE
sec
0,1
0
1km
0,1 km
PROFILE III B
SE
NW

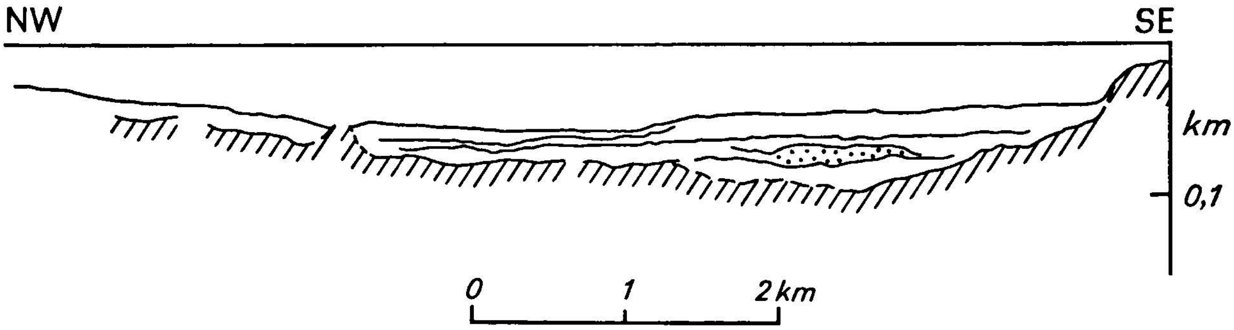

PROFILE IV
A'
sec
0,1
SE
NW
Central rise
A
0
1
2 km
km
0,1

PROFILE VI

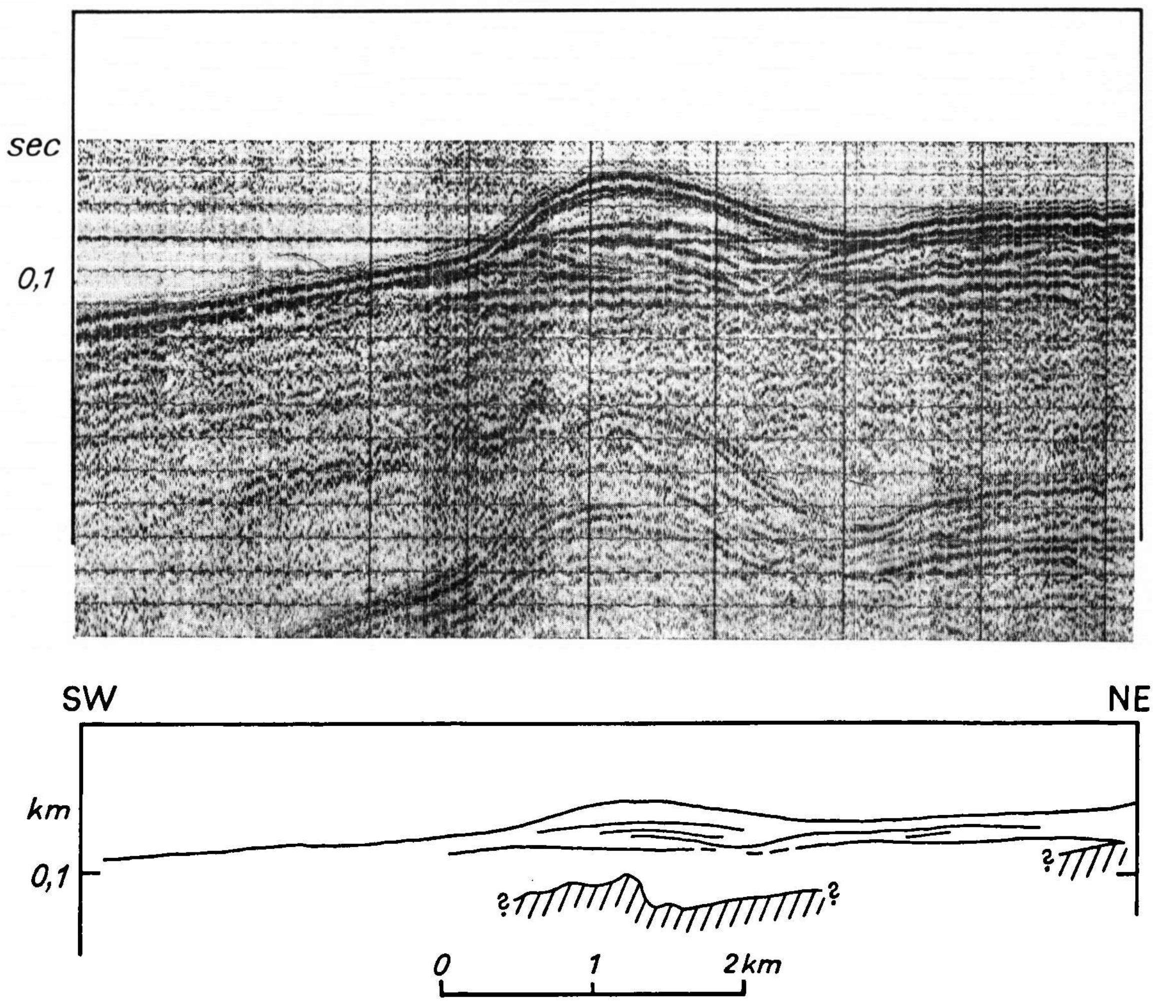


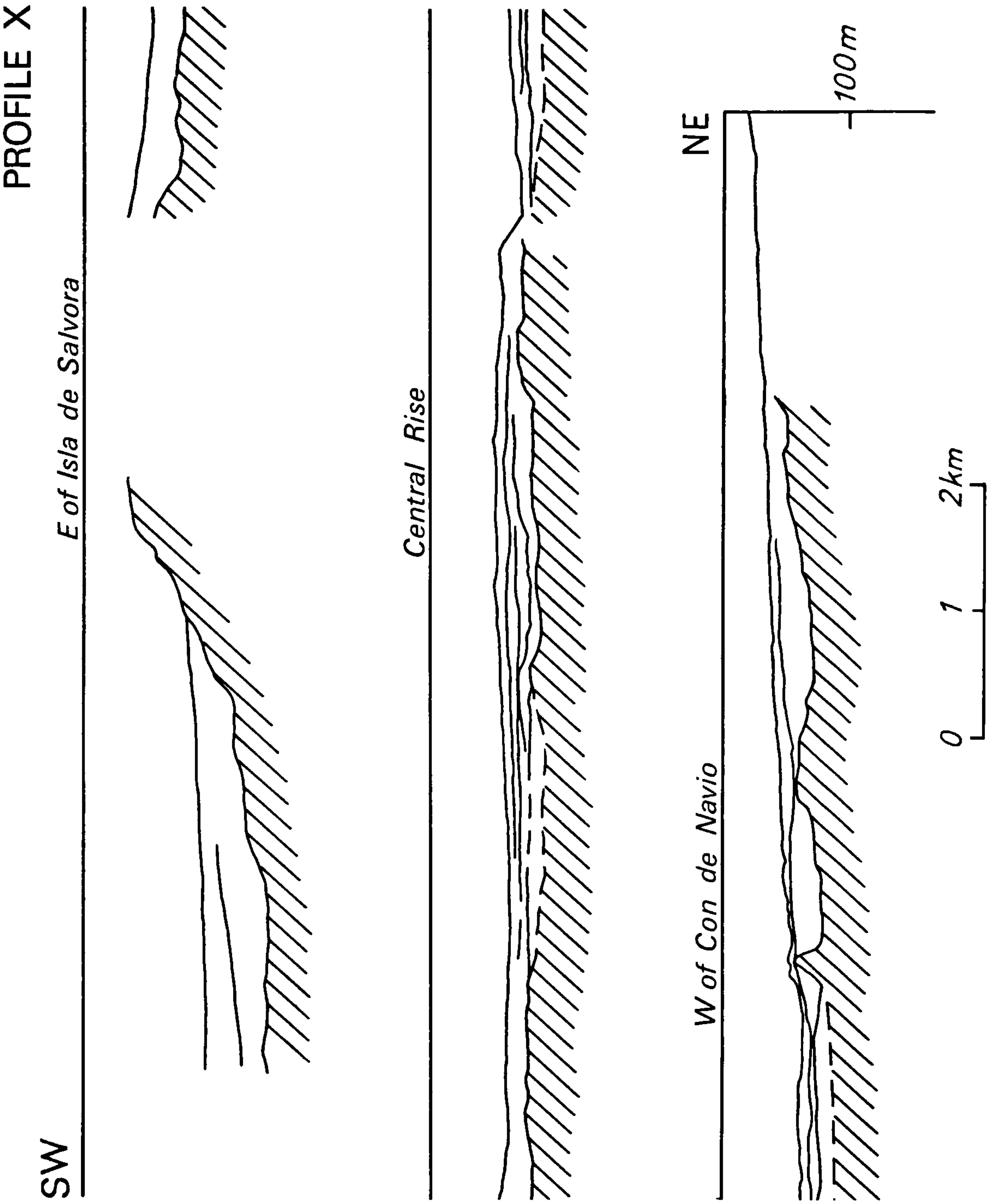

PROFILE VII
sec
0,1
WSW
ENE |SSE
NNW|E
W
Isla de
Rua
A
?
km
0,1
0
1
2km
near Islas Jidoiros

PROFILE VIII



PROFILE IX




PROFILE X
SW
NE
E of Isla de Salvora
Central Rise
W of Con de Navio
100m
0
1
2km