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ROYAL NORWEGIAN COUNCIL FOR SCIENTIFIC AND INDUSTRIAL RESEARCH

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PREFACE

The Norwegian Institute for Air Research (NILU) has conducted a research programme to investigate the state of air pollution in the Norwegian Arctic, and its possible sources. The programme was financed by British Petroleum Ltd. (BP). This report is one in a series on the results of this research programme.

SUMMARY

Sulphate concentrations measured at ground level on Bjørnøya (Bear Island) and at Ny Ålesund are studied. Measurements have been made on a regular, daily or multi-day basis since 1979-08-24, and the analyses cover the period until 1984-08-31. Missing data in the time series are recovered by linear regression between the respective stations. Only 11 out of the 1835 days of measurements lack data at both stations, which are estimated by linear interpolation in time.

Seasonal cycles in mean values and variances are observed, both having maxima during the cold season. The Ny Ålesund and Bjørnøya series are transformed into approximately second-order stationarity by logarithmic transformation and subtraction of Fourier components with periods longer than 100 days. From these, episodes of polluted and clean air are identified objectively, by the upper and lower 25%-percentiles (approximately), respectively.

Pollution episodes are frequent during late winter/early spring and during the early autumn. In between these periods the frequency is lower. The actual concentrations of sulphate, however, are much lower during the early autumn episodes than during the cold season. At Ny Ålesund, for example, the mean concentrations during clean air episodes in March are higher than during pollution episodes in August. This seems to indicate that there is a certain level of background pollution build-up up during the cold season in the Arctic.

The meteorological analysis is based upon the selection of quasistationary phenomena leading to extended meridional exchange of air. "Blockings" are defined as suggested by Lejenäs and Økland (1983), by using the zonal index between 60^0N and 40^0N. In addition, quasi-stationary northward flows are selected by taking into account only the four longest planetary waves. A meridional index, that is proportional to the poleward geostrophic wind, is used to define such features.

The seasonal variations in blocking and quasi-persistent poleward flows are very much related to the seasonal cycle of Arctic pollution. On the episodic level, there is a vanishing covariance between pollution in the Norwegian

Arctic and the flow systems during summer. During the cold seasons, however, the correspondence is significant for longitudes between 30^0W and 60^0E. Clean air episodes are associated with a central-European blocking and quasi-stationary, northward flow from the eastern Atlantic Ocean. During pollution episodes, blocking is not present over Europe, and quasi-persistent poleward flows from central Eurasia are normal. There is, however, no significant, positive correlation between episodes and blockings (as defined by Lejenäs and Økland) at any longitude.

The lack of correlation during summer is releated to the very small variability in pollution concentrations during this season. Only under exceptional conditions do the sulphate concentrations increase to a level that may be called pollution. Other factors than long range transport normally determine the small concentration variations during summer. Nevertheless, the seasonal variation in correlations demonstrates that the importance of processes other than atmospheric transport is at a minimum during the cold season. Such processes include dry deposition, scavenging underway from mid to polar-latitudes, lifting into the free troposphere, and rate of chemical production of sulphate in the air. Local deposition due to boundary layer clouds in the Arctic also has the same annual efficiency cycle.

The main conclusion of this study is that large scale, quasi-stationary, atmospheric flow systems determine the basic conditions for long range transport from mid- to polar-latitudes.

CONTENTS

ON AIR POLLUTION TRANSPORT TO THE NORWEGIAN ARCTIC

1 INTRODUCTION

Arctic air pollution is quite a new topic of research. The Arctic being remote from human activity, has been regarded as a clean area in all respects. Recent empirical evidence has shown, however, that the Arctic air is polluted during the cold seasons as a result of human activities at lower latitudes. Several special issues of scientific journals published recently (Atmos. Environ., 15, no. 8, 1981; Geophys. Res. Lett., 11, no. 5, 1984; Atmos. Environ., 1985, in press), document an increasing scientific interest in this field. Although most measurements of pollution in the Arctic have been made at ground level, recently there have also been periods with extended measurements of the upper air from aircraft. A breakthrough in this regard occurred in the spring of 1983, when an extensive upper air measurement campaign was conducted by scientists from several countries (Geophys. Res. Lett., 11, no 5, 1984).

In this report, ground-level sulphate concentrations at Ny Ålesund and Bjørnøya (Bear-Island) (Figure 1) are analysed. The measurements cover the period 1979-08-24 through 1984-08-31. At Bjørnøya the data are 24-h concentrations. At Ny Ålesund the sampling duration was either 2 or 3 days before 1984, but since 1984-01-01 the concentrations are daily averages. The analyses include identification of seasonal variations, as well as short-term, episodic variations.

In order to assess the importance of some basic mechanisms leading to long range transport of air pollutants into the Arctic, daily meteorological data are considered. Objective methods for identifying flow systems are used, in contrast to the subjective methods applied earlier by, e.g., Raatz and Shaw (1984). As recommended by Iversen and Joranger (1985), quasi-stationary atmospheric flow systems such as blocking are addressed, since they are believed to provide conditions for extended poleward transport of air at certain longitudes. The idea was implicit in the work of Reiter (1981), and

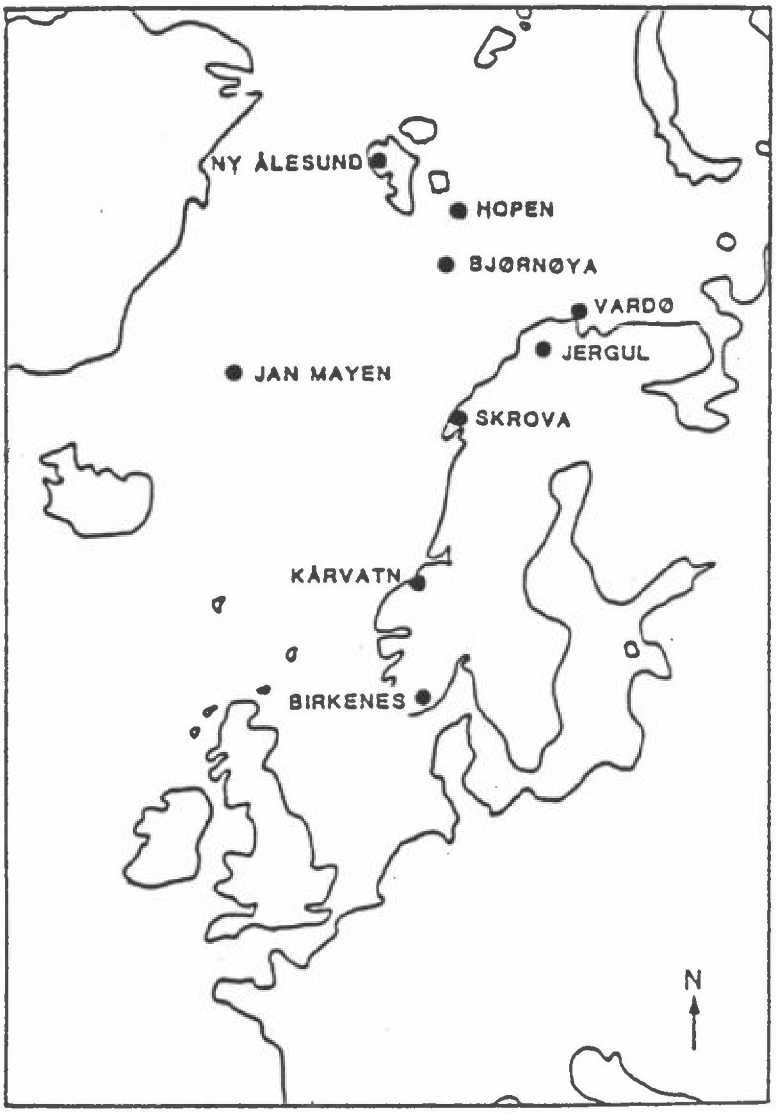


Figure 1: Location of Norwegian Arctic and sub-Arctic stations.

the importance of the blocking phenomenon has also been earlier suggested by Raatz (1983).

The meteorological data used in this study have been made available by the National Center for Atmospheric Research (NCAR), Boulder, Colorado, USA. The data consist of hemispheric analyses of geopotential height of the 500 mb pressure surface made by the US National Meteorological Center (NMC). They cover the period 1982-05-01 through 1984-07-31, which is the measurement period for the British Petroleum Ldt. (BP-programme). In what follows, this period is referred to as "the BP period" in this report.

2 *UNIVARIATE ANALYSIS OF SULPHATE CONCENTRATIONS*

The observations of ground-level sulphate concentrations have been made on a regular basis since 1979-08-24. The univariate analysis of the time series in this chapter is performed on concentration measurements from 1979-08-24 to 1984-08-31. For averages over several days (Ny Ålesund) each day within the averaging period is given the same measured value. For purpose of the time series analysis, the series consist of one day sampling averages.

2.1 MISSING DATA

In practical situations, there will always be a number of days when observations lack in a long time series of measurements. In order to apply statistical tools on the series, one has to fill-in such "holes" in a proper way. Since the two measurement sites are reasonably close to each other, at least when compared to the distances to mid-latitude source areas of anthropogenic pollutants, the missing data at one site can be estimated by means of the observations at the other, provided that there are no common dates with lacking data. Out of the total of 1835 observation days, 129 days had no measurement data at Ny Ålesund and 49 days at Bjørnøya. Only 11 of these days, had no measurements at both sites.

To recover missing data in the time series, linear regression between the concentrations measured at the two stations was made. On the 11 days with no measurements at both sides, a linear interpolation in time was used. The mathematical details for these procedures are given in the following.

Let $C(y,d)$ and $B(y,d)$ denote the sulphate concentrations on day No. d of year y at Ny Ålesund and Bjørnøya, respectively. The day numbering is treated as if each year is a leap year. Hence, d varies from 1 through 366, although observations on day No. 60 exist only for two of the years (1980 and 1984). Before any comparison of C and B can be performed, 2 and 3 day-averages of B must be computed:

$$B_A(y,d+m) = \frac{1}{N} \sum_{n=0}^{N-1} B(y,d+n) \qquad (2.1)$$

where B_A is the multi-day average, $m = 0,\ldots,N-1$; $d = 1,3,5,8,10,\ldots$ and $N = 2,2,3,2,2,3,\ldots$. For each day of the year an average concentration over the years is calculated from the existing data:

$$\left.\begin{aligned} \bar{C}(d) &= \frac{1}{Y(d)} \sum_{y=1}^{Y(d)} C(y,d) \\ \bar{B}_A(d) &= \frac{1}{Y(d)} \sum_{y=1}^{Y(d)} B_A(y,d) \end{aligned}\right\} \quad d = 1, \ldots, 366 \qquad (2.2)$$

where $Y(d)$ is the number of years with concentration measurements on day No. d. The average year is then smoothed by applying a moving-average filter:

$$\left.\begin{aligned} \hat{C}(d) &= \frac{1}{2N+1} \sum_{n=-N}^{N} [\bar{C}(d+n)] \\ \hat{B}_A(d) &= \frac{1}{2N+1} \sum_{n=-N}^{N} \bar{B}_A(d+n) \end{aligned}\right\} \qquad (2.3)$$

where $N=10$ is the averaging amplitude. $\hat{C}$ and $\hat{B}_A$ can be interpreted as an "annual climatology" of sulphate at Ny Ålesund and Bjørnøya. On the basis of the 1668 days with measurements made at both sites, the deviations are calculated:

$$\left.\begin{aligned} c(y,d) &= C(y,d) - \hat{C}(d) \\ b(y,d) &= B_A(y,d) - \hat{B}_A(d) \end{aligned}\right\} \qquad (2.4)$$

We now assume the relation between c and b to be linear. E.g., the estimated c is then

$$c_E = \alpha\, b + \beta. \qquad (2.5)$$

The parameters α and β are determined by minimizing the mean square deviation between the estimated and the measured c:

$$M = \langle (c - c_E)^2 \rangle = \min \qquad (2.6)$$

where $\langle c \rangle = \frac{1}{N} \sum_{n=1}^{N} c_n$

and N is the number of days with both c and b measured.

By introducing Eq. (2.5) into Eq. (2.6) and require that $\partial M/\partial\alpha = 0$ and $\partial M/\partial\beta = 0$, one arrives at

$$\alpha = r_{cb}\, \sigma_c/\sigma_b, \text{ and } \beta = \langle c \rangle - \alpha \langle b \rangle \qquad (2.7)$$

where r_{cb} is the correlation coefficient

$$r_{cb} = \frac{\langle cb \rangle - \langle c \rangle \langle b \rangle}{\sigma_c\, \sigma_b} \qquad (2.8)$$

and σ_c and σ_b are the standard deviations, e.g.:

$$\sigma_c = (\langle c^2 \rangle - \langle c \rangle^2)^{1/2} \qquad (2.9)$$

The formulas for b_E (estimated b) are of course exactly corresponding to Eqs. (2.5) and (2.7), with only c and b interchanged. Since c and b are residuals from the climatological mean, $\langle c \rangle$ and $\langle b \rangle$ are very close to zero, and $\beta \approx 0$.

The results are given in Table 1.

Table 1: Statistical parameters used to estimate concentrations taken at one site from concentration measurements at the other.

Concentration to be estimated	Correlation	Mean $\mu g\ S\ m^{-3}$	Standard deviation $\mu g\ S\ m^{-3}$	α	$\beta / \mu g\ S\ m^{-3}$
Bjørnøya	0.4058	-0.0005	0.3292	0.5904	-0.0005
Ny Ålesund		0.0001	0.2263	0.2790	0.0003

The estimated values for c and b, whenever only one of them is missing are computed from Eq. (2.5). Holes in the series that are common for the two stations (11 days) are filled by performing a linear interpolation in time. The total concentrations are then computed by adding the climatological mean and accepting only concentrations $\geq 0.01\ \mu g\ S\ m^{-3}$.

2.2 THE ANNUAL CYCLE

The completed series of sulphate given as sulphur (SO_4-S) are shown in Figure 2. Three quite definite features are apparent: the short-term variability, the annual cycle of the mean, and the annual cycle of the variance.

The short-term variability shows that the atmospheric processes influencing pollutant levels lead to episodically-polluted air and episodically-clean air. These episodes have stochastic characteristics, and are the main interest in this study.

The long term variability, that shows up as an annual cycle in pollutant levels, is quite deterministic in nature. It is also quite obvious that the variance increases with the mean. In order to study the episodicity, these

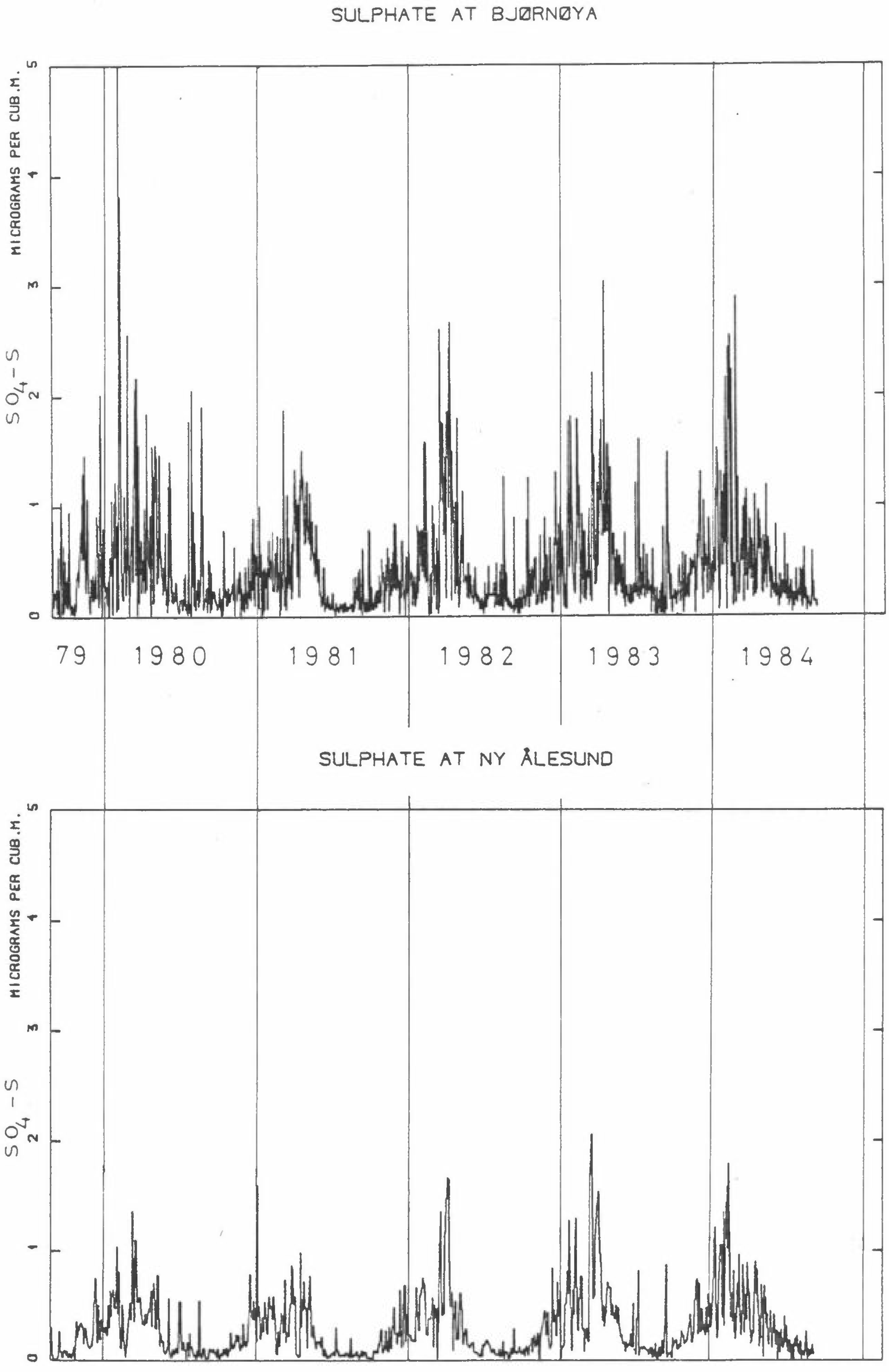


Figure 2: The series of observed sulphate. Missing data are supplied by the method in Section 2.1.

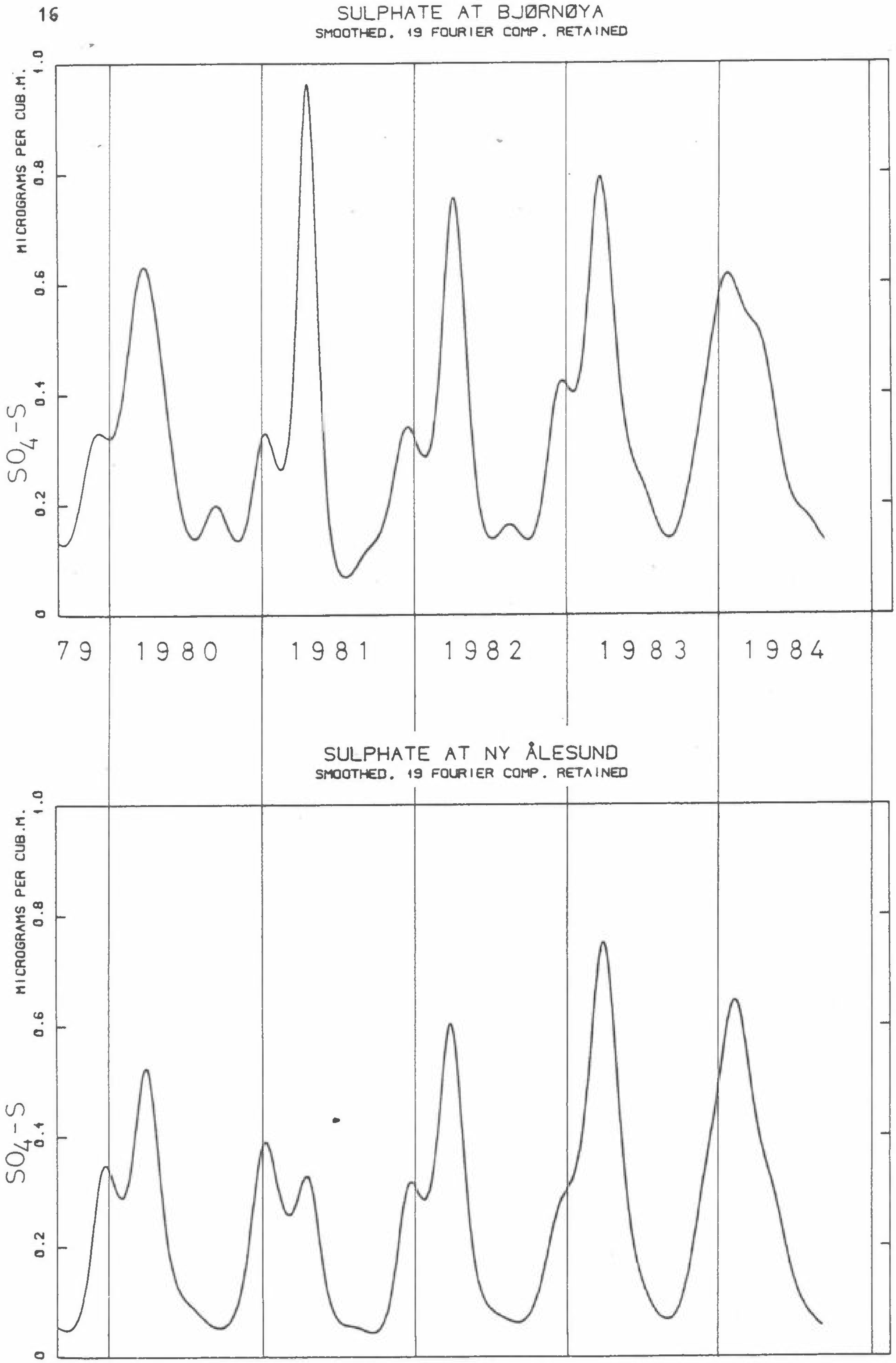


Figure 3: The low-pass filtered series.

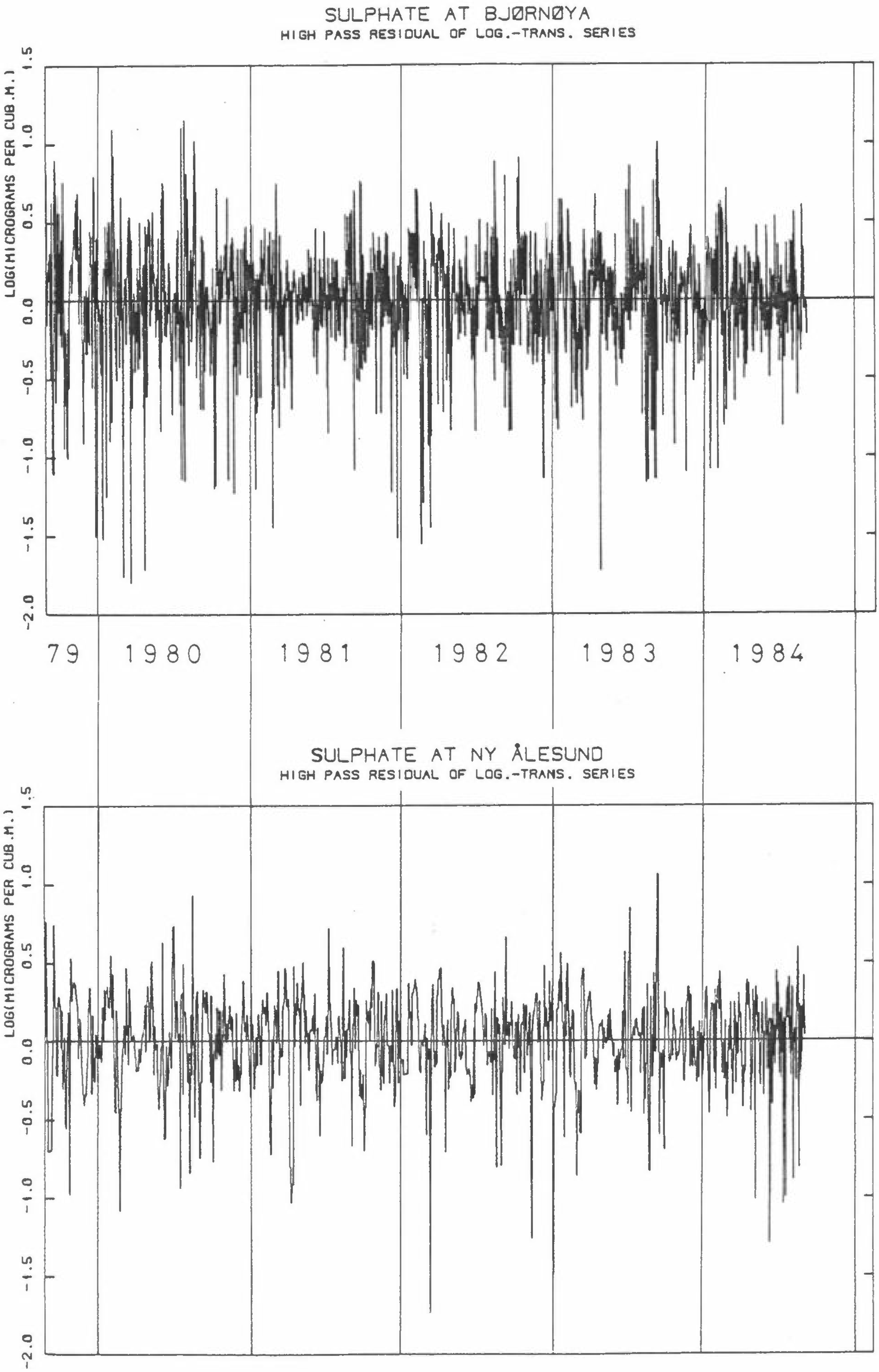


Figure 4: The high-pass filtered, logarithmically transformed series.

systematic variations must be removed from the series. Assuming that the standard deviation is proportional to the mean, the series can be transformed by taking common logarithms of the concentrations. To remove the annual cycle, this logarithmically transformed series is Fourier-transformed. The sum of the 19 Fourier components of lowest order (after applying antilogs) is shown in Figure 3.

The low-pass filtered data contain periods longer than ca. 100 days. The high-pass residual shown in Figure 4, shows that the new series has no noticable, systematic variation of neither the mean nor the variance. The rest of this report deals mainly with the series shown in this figure.

The transformation can be written mathematically:

$$c_i = \log_{10} C_i - \sum_{n=0}^{18} A_n \cos\left(2\pi n \frac{i-1}{I} - \hat{\theta}_n\right); \qquad (2.10)$$

for i = 1,2,...,I and I = 1835.

Here

$$A_n = \begin{cases} a_o/2 \text{ for } n=0 \\ (a_n^2 + b_n^2)^{1/2} \text{ for } n=1,2,\ldots,N \end{cases}$$

and for n=0,...,N:

$$\hat{\theta}_n = \begin{cases} \pi/2 & \text{for } b_n > 0 \text{ and } a_n = 0 \\ 0 & \text{for } b_n = 0 \text{ and } a_n = 0 \\ -\pi/2 & \text{for } b_n < 0 \text{ and } a_n = 0 \\ \arctan(b_n/a_n) & \text{for } a_n > 0 \\ \arctan(b_n/a_n) + \pi & \text{for } a_n < 0 \end{cases}$$

The Fourier coefficients are

$$a_n = \frac{2}{I} \sum_{i=1}^{I} (\log_{10} C_i) \cdot \cos 2\pi n \frac{i-1}{I}; \qquad n=0,1,\ldots,N$$

$$b_o = 0 \text{ and } b_n = \frac{2}{I} \sum_{i=1}^{I} (\log_{10} C_i) \cdot \sin 2\pi n \frac{i-1}{I} ; \qquad n=1,\ldots,N$$

In this particular case, I is an odd number (1835) and $N = (I-1)/2$.

2.3 EPISODES

If one assumes that the transformed series of Eq. (2.10) is stationary, stochastic models can be fitted, until one arrives at a purely random residual. For the daily data from Bjørnøya, an AR(1)-process (i.e. the Markov process) fits well: $c_i = \alpha c_{i-1} + R_i$, where $\alpha \approx 0.3494$ and R_i is a purely random series with mean $\langle R_i \rangle = 0$ and standard deviation $\sigma_R \approx 0.3385$. The autocorrelation at time lag 1 for R_i is -0.032. Since the data for Ny Ålesund are 2- or 3-days averages, the stochastic model must contain more terms. However, this is only due to the method of averaging.

By the ergodic theorem, the long-term mean and variance is an estimate of the ensemble averaged quantities. Since the mean is vanishing $\langle c_i \rangle = 0$, the standard deviation is $\sigma_c = \langle c_i^2 \rangle^{1/2}$. The three main concepts of this report can then be defined.

1) Pollution episodes:

$$c_i \geq 0.67\sigma_c$$

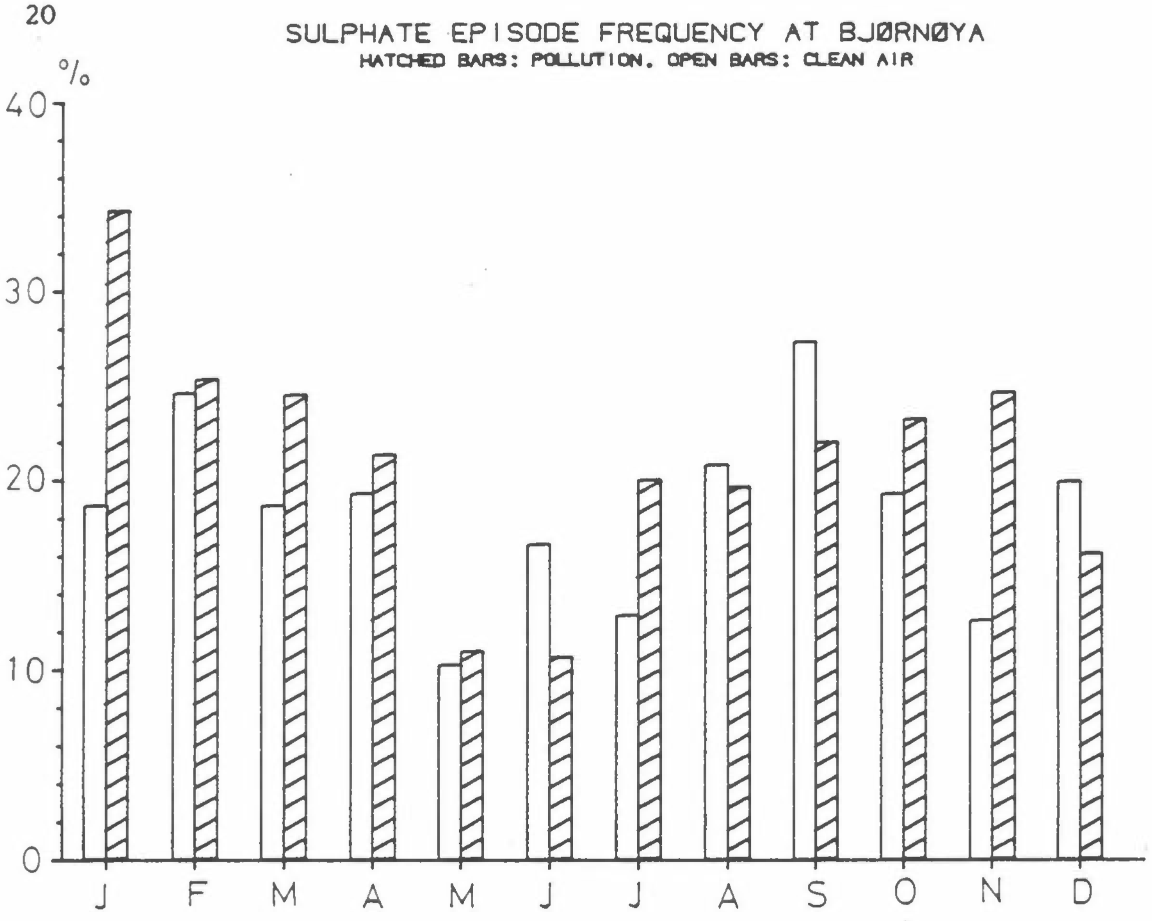
2) Normal conditions: (2.11)

$$|c_i| < 0.67\sigma_c$$

3) Clean air episodes:

$$c_i \leq -0.67\sigma_c$$

If $\{c_i\}$ is normally distributed, then approximately 50% are normal condition cases, 25% are pollution episodes, and 25% are clean air episodes.



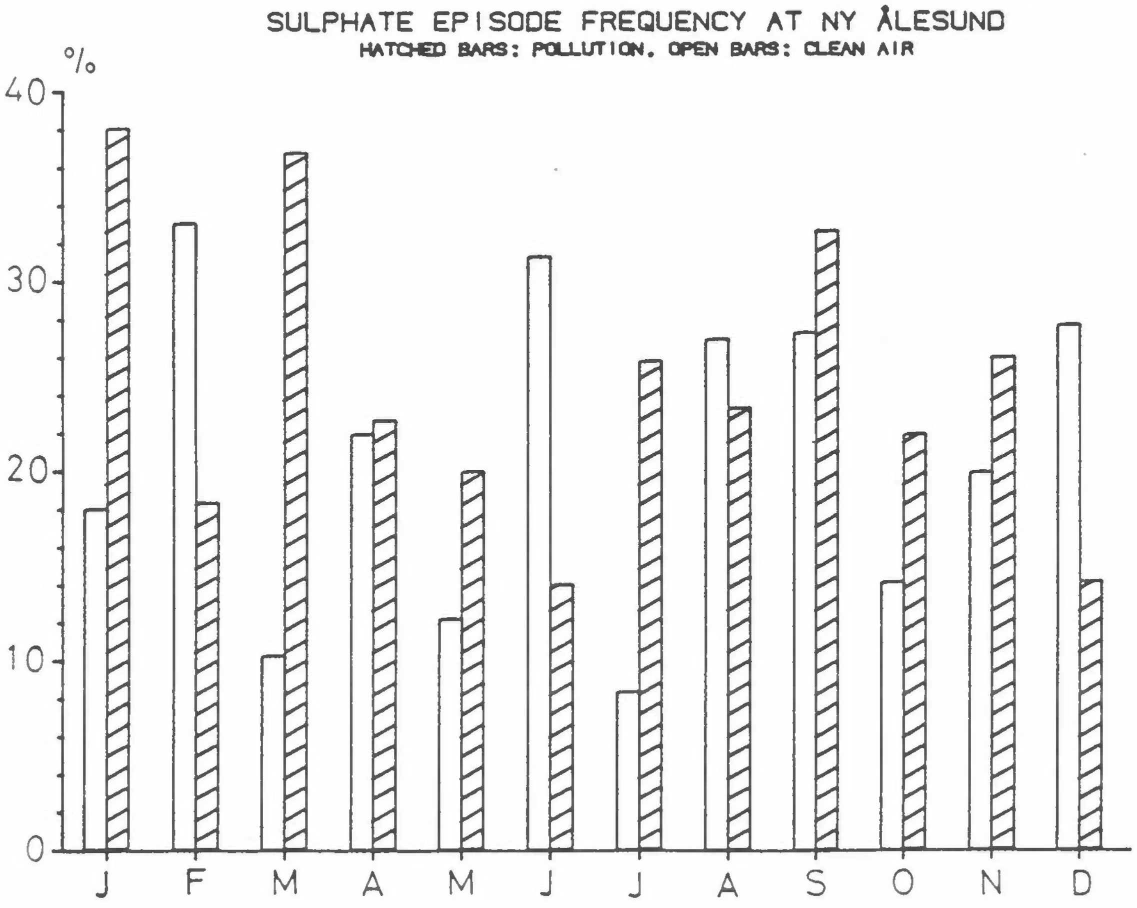


Figure 5: Episode frequencies for each month for the five-year period.

Figure 5 shows the monthly frequency of days with pollution episodes and days with clean air episodes within the data sets from Ny Ålesund and Bjørnøya. At both places, pollution episodes have high frequency during winter and autumn, and low frequency during May-June and in December. At Ny Ålesund, pollution episode frequency in February is low .

The clean air episodes at Bjørnøya have a similar annual frequency variation as the pollution episodes. However, in January and November, when pollution episodes are very frequent, clean air episodes have low frequency. This pattern is more evident at Ny Ålesund, where high frequency of pollution episodes goes together with less frequent clean air episodes and *vice versa*.

The mean sulphate (as S) concentrations during pollution and clean air episode days in each month are shown in Figure 6. There is a clear annual cycle in these mean concentrations, with maximum in the winter season and minimum in the summer season. In particular, even if there is a high frequency of pollution episodes during July through October, the mean concentrations during these episodes are the lowest of the year. At Ny Ålesund, the mean concentrations during clean air episodes in winter are higher than the mean concentrations during pollution episodes in August and September. On the basis of these observations, two hypotheses can be put forward. Firstly, it is reasonable to believe that pollution episodes during the autumn months only exceptionally are due to long range transport. Secondly, processes that remove pollutants from the Arctic air are less efficient during the winter season than in summer and early autumn. This is in accordance with the fact that boundary layer clouds in the Arctic have maximum frequency during the summer season (Shaw, 1981; Heintzenberg and Larssen, 1983).

3 ATMOSPHERIC TRANSPORT

The basic hypothesis to be confirmed or rejected is: Arctic air pollution is caused by long range, atmospheric transport of air pollutants. To be able to arrive at a decision, the concentrations of pollutants must be compared with quantities that contain essential information about large scale atmospheric flows.

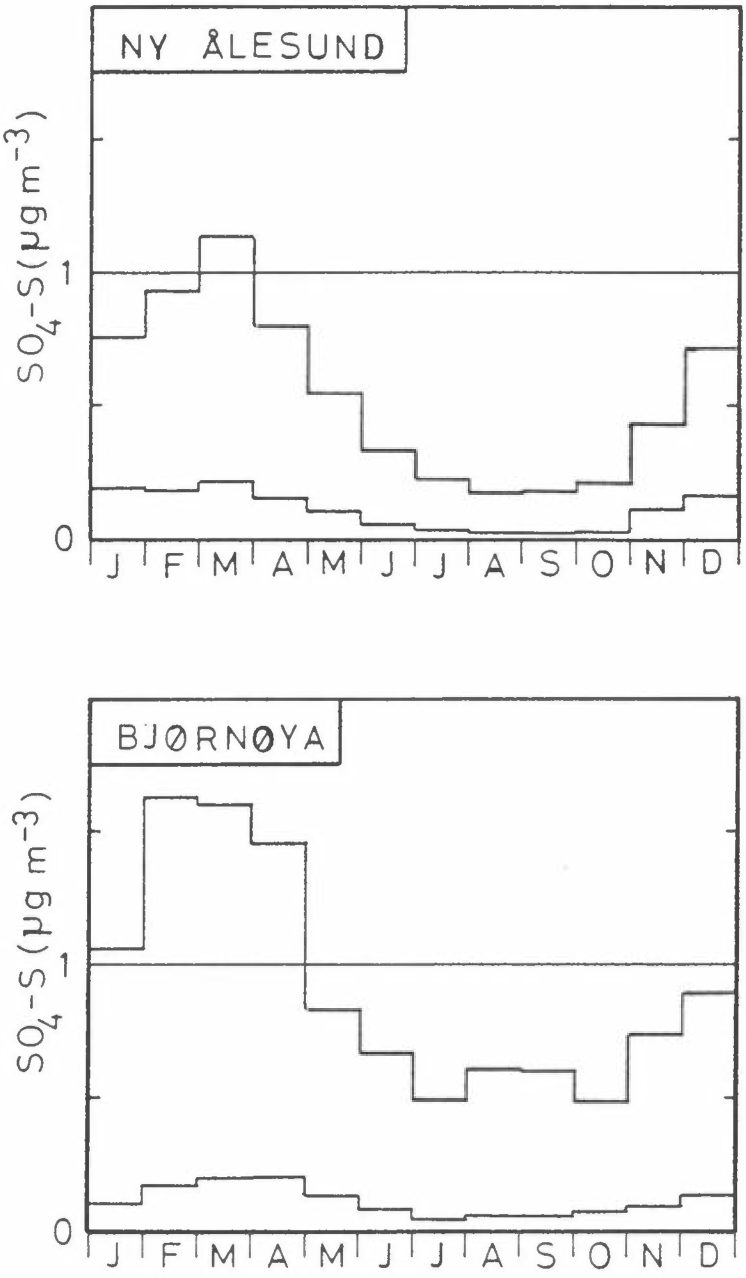


Figure 6: Monthly averaged concentrations of sulphate (as S) during pollution episodes (upper diagram) and clean air episodes (lower).

3.1 PROCESSES INFLUENCING ARCTIC AIR QUALITY

The basic mechanism that has to be present in order to explain the existence of Arctic air pollution, is atmospheric transport of air from the large mid-latitude industrial source areas. This transport process must have a large and deep meridional component, and it must be stationary for some time so that the air pollutants can reach the Arctic within reasonable time. Having established the transport process, the behaviour of the pollutants depends on modifying processes, such as scavenging "en route", dry deposition, atmospheric chemical reactions, vertical mixing and advection, and deposition within the Arctic. In this paper, the atmospheric flow systems that may account for the basic atmospheric transport will be identified.

The dynamic processes of the terrestrial atmosphere are driven by the solar radiation. The mean energy input is received at low latitudes, and is lost through net radiation to space, mainly at polar latitudes. The mean, total energy of the atmosphere is thereby conserved. This differential heating on the planetary scale and the earth's rotation lead to the formation of a mid-latitude, westerly jet stream system. Within this jet stream, the travelling cyclones and anticyclones are created through the release of baroclinic instability. The circulations created by these travelling systems are seldom very deep in the meridional direction, and their rather fast, eastward motion prevents systematic poleward transport of air from specific areas.

In the northern hemisphere, oceans and continents, with their very different thermodynamic and orographic properties, fall into certain meridional sectors. These lead to sources and sinks of vorticity for the jet stream. The atmospheric response can be of two types: a high zonal index situation with an almost zonal jet, or a low zonal index situation with waves of large amplitudes and long wavelengths, which move very slowly (e.g., Palmén and Newton, 1969).

It is of course the low-index situation that provides the best conditions for extended poleward transport of air. These are conditioned by the longest planetary waves having much energy, and resonance seem to develop for wave-number 4 (Austin, 1980). Austin (1980) showed that, depending on the phases and amplitudes of wavenumbers 1, 2, and 3, a certain quasi-stationary phenomenon known as "blocking" will occur at certain sectors. A blocking is known by the weather service as a phenomenon preventing the normal, eastward propagation of highs and lows, which being quasi-stationary leads to local weather with a large persistency. Its synoptic characteristics are a warm anticyclone at about 60^0N, often with a corresponding cold cyclone at about 40^0N (i.e., a dipole). There is a split in the jet stream at the upstream side of this dipole system, and the northernmost branch will often carry air polewards over large meridional distances.

3.2 DEFINITION OF BLOCKING AND QUASI-STATIONARY, MERIDIONAL FLOWS

Several papers have discussed the occurence and climatology of blockings (e.g. Rex, 1950; Shukla and Mo, 1983; Lejenäs and Økland, 1983; Kanestrøm et al., 1984). They may have different definitions of the phenomenon, but nevertheless arrive at very similar climatological results. Two geographical areas are favourable for their occurrence, the Atlantic-European sector and the Pacific. There is a marked seasonal cycle, with a maximum frequency during winter/spring and a minimum during summer for all longitudes.

For this work, the simplest definition of blocking that has appeared in the literature has been chosen. It was proposed by Lejenäs and Økland (1983). A blocking is defined in terms of an index.

$$I(L) = z(60^0N,L) - z(40^0N,L) \qquad (3.1)$$

where z is the geopotential height of the 500 mb pressure surface, and L is the longitude. It can also be written as:

$$I(L) = \frac{f_{50^0N}}{g} \cdot U_g(L) \qquad (3.2)$$

where f_{50^0N} is the Coriolis-parameter at 50^0N latitude, $g = 9.8$ ms^{-2}, and U_g is the mean easterly geostrophic wind between 40^0N and 60^0N. For a blocking, as it was described at the end of Section 3.1, I(L) is expected to be positive at the longitude L, where the dipole is found. The definition of a blocking is thus motivated by that fact. The index I is calculated for each ten degree longitude. The basic condition of a blocking at longitude L is that

$$I(L) > 0. \tag{3.3}$$

Lejenäs and Økland (1983) stated, however, that this specification also includes cases that are not typical blocking events in regard to persistency. A stronger definition takes this into account:

$$\begin{aligned} & I(L) > 0 \\ \underline{\text{and}}\quad & I(L-10^0) + I(L) + I(L+10^0) > 0 \end{aligned} \tag{3.4}$$

leaving out most cases with only 1-day persistence. In the following, the situations defined by Eq. (3.4) will be referred to as L-Ø-blockings (i.e., after Lejenäs and Økland).

By definition, the L-Ø blockings do not explicitly lead to extended meridional transport of air. Additional quasi-stationary phenomena has been selected, by means of an explicit measure of poleward transport. It has been shown, that the linear, atmospheric response to mid-latitudinal thermal and orographic forcing does not allow wavenumbers larger than 4 to be stationary at high latitudes (e.g., Hoskins and Karoly, 1981). This has also been confirmed by actual data analyses (e.g., Blackmon, 1976). The very long, planetary waves also have much more low frequency energy than shorter waves.

Accordingly, the parameter $\breve{z}$ is defined as the sum of wavenumbers 1, 2, 3, and 4:

$$\breve{z}(B,L) = \sum_{n=1}^{4} A_n \cos\,(nL + \hat{\theta}_n), \tag{3.5}$$

where $A_n = (a_n^{\,2} + b_n^{\,2})^{1/2}$,n = 1, 2, 3, 4 and

and

$$\hat{\theta}_n = \begin{cases} \pi/2 & \text{for } b_n > 0 \text{ and } a_n = 0 \\ 0 & \text{for } b_n = 0 \text{ and } a_n = 0 \\ -\pi/2 & \text{for } b_n < 0 \text{ and } a_n = 0 \\ \arctan\,(b_n/a_n) & \text{for } a_n > 0 \\ \arctan\,(b_n/a_n) + \pi & \text{for } a_n < 0 \end{cases}$$

The Fourier coefficients are

$$a_n = \sum_{i=1}^{I} z(B,L_i) \,.\, \cos nL_i$$

and

$$b_n = \frac{2}{I} \sum_{i=1}^{I} z(B,L_i) \,.\sin nL_i$$

The hemispheric data used are given in a geographical grid, with grid distance 2.5 degrees longitude and latitude, hence I = 144. Following Shukla and Mo (1983) and Kanestrøm et al. (1984), who used the wavenumbers 1, 2, 3, and 4 to study persistent quasi-stationary anomalies, troughs and ridges, persistent quasi-stationary meridional flows are identified by the index M(B,L), defined for every 10 degrees latitude by means of $\breve{z}$ (Eq.(3.5)):

$$M(B,L) = \breve{z}(B,L+5^0) - \breve{z}(B,L-5^0). \qquad (3.6)$$

This index can also be written

$$M(B,L) = V_g \,.\, \frac{f_B}{g} \,.\, \frac{a\pi}{18} \,.\, \cos B \qquad (3.7)$$

where V_g is the mean poleward, geostrophic wind between $L-5^0$ and $L+5^0$

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(produced by wavenumbers, 1, 2, 3, 4), and 'a' is the mean radius of the earth. M(B,L) is therefore called the "meridional index" at a latitude B and longitude L.

At a specified L and B, an incident of <u>high meridional index</u> occurs when

$$M(B,L) > M_C(B) \tag{3.8}$$

where M_C is the value of M corresponding to a poleward wind speed of 10 deg/day. M(B,L) is computed for each ten degree longitude and for $B=70^0$N, 65^0N, and 60^0N, and

$$M_C(B) \approx \begin{cases} 45.6\text{ m};\ B = 70^0\text{N} \\ 54.3\text{ m};\ B = 65^0\text{N} \\ 61.3\text{ m};\ B = 60^0\text{N} \end{cases} \tag{3.9}$$

The meteorological data (i.e., the z(B,L) fields) are hemispheric analyses from the US National Meteorological Center (NMC), made available through the National Center for Atmospheric Research (NCAR). These data cover (except for some missing data periods) the entire BP period from 1982-05-01 through 1984-07-31. A detailed analysis of episodes at Bjørnøya and Ny Ålesund, together with L-Ø blocking events and incidents of high meridional index, is given in the Appendix.

4 BIVARIATE ANALYSIS

In this chapter, some general statistics on the relationship between ground-level sulphate concentrations at Bjørnøya and Ny Ålesund, and large-scale, quasi-stationary flows, are presented. Quasi-stationary flow types are defined by means of the indices I and M of Section 3.2. Earlier, Reiter (1981), related long, planetary waves (1, 2, 3, and 4) to the concentrations of vanadium at Point Barrow, Alaska.

4.1 FREQUENCIES AND CORRELATIONS

The BP period (1982-05-01 through 1984-07-31) is separated into polluted days, normal days and clean air days, according to the definitions of Eq. (2.11). For each category, the frequency of L-Ø blockings and high meridional index is computed. For days, when meteorological data are lacking, no index is computed, and they therefore do not contribute to the statistics. For the sake of completeness, Table 2 shows the frequency of such days for each category of days at Bjørnøya and Ny Ålesund.

Table 2: Frequency of days with missing meteorological data for each category of days (%).

	Episode category			
	Pollution	Clean air	Normal	Total
Bjørnøya	17.95	13.61	10.96	12.76
Ny Ålesund	11.70	15.09	12.39	12.76

The condition specifying high meridional index is here somewhat stronger than defined by Eq. (3.8), to be certain that it identifies deep poleward flows:

$$\left.\begin{array}{ll} & M(70^0N,L) > M_C(70^0N) \\ \underline{\text{and}} & \\ & [M(65^0N,L) > M_C(65^0N) \quad \underline{\text{or}} \quad M(60^0N,L) > M_C(60^0N)] \end{array}\right\} \qquad (4.1)$$

Figures 7, 8, and 9 show the frequencies of days with strong L-Ø blockings or high meridional index, for the three different pollution conditions (Eq. (2.11)) at Bjørnøya and Ny Ålesund. As a reference, the total frequencies for the entire BP period are also shown. The year has been separated into seasons, defined as follows:

winter ≡ December, January, and February
spring ≡ March, April, and May
summer ≡ June, July, and August
autumn ≡ September, October, and November

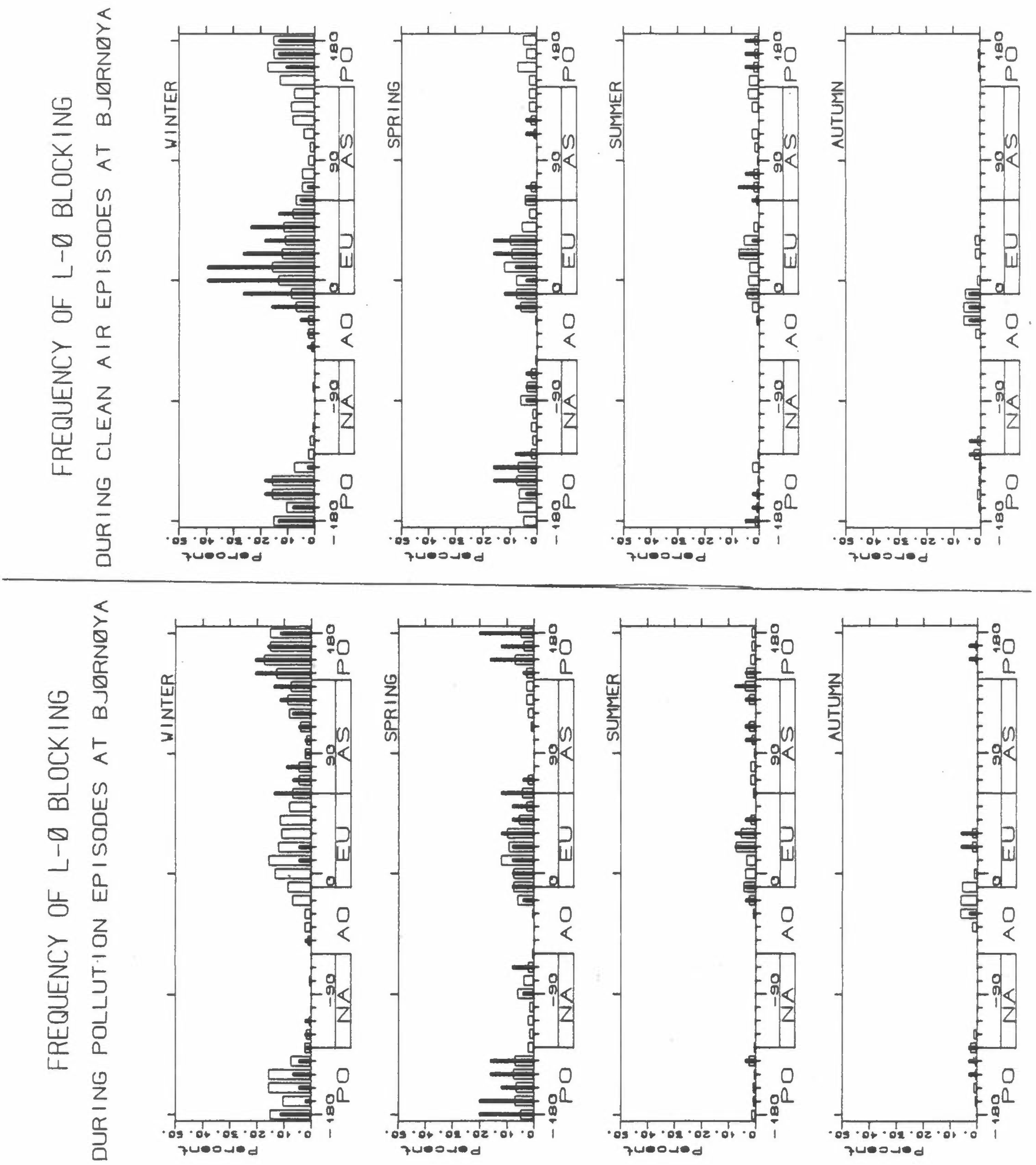


Figure 7: Seasonal L-Ø blocking frequencies for each ten degree longitude. Oceans and continents along the latitude 50^{0}N are indicated below each graph.

PO = Pacific Ocean EU = Europe
NA = North America AS = Asia
AO = Atlantic Ocean

Solid narrow bars are frequencies during episodes.
Open wide bars are frequencies during the whole period.
a) Bjørnøya

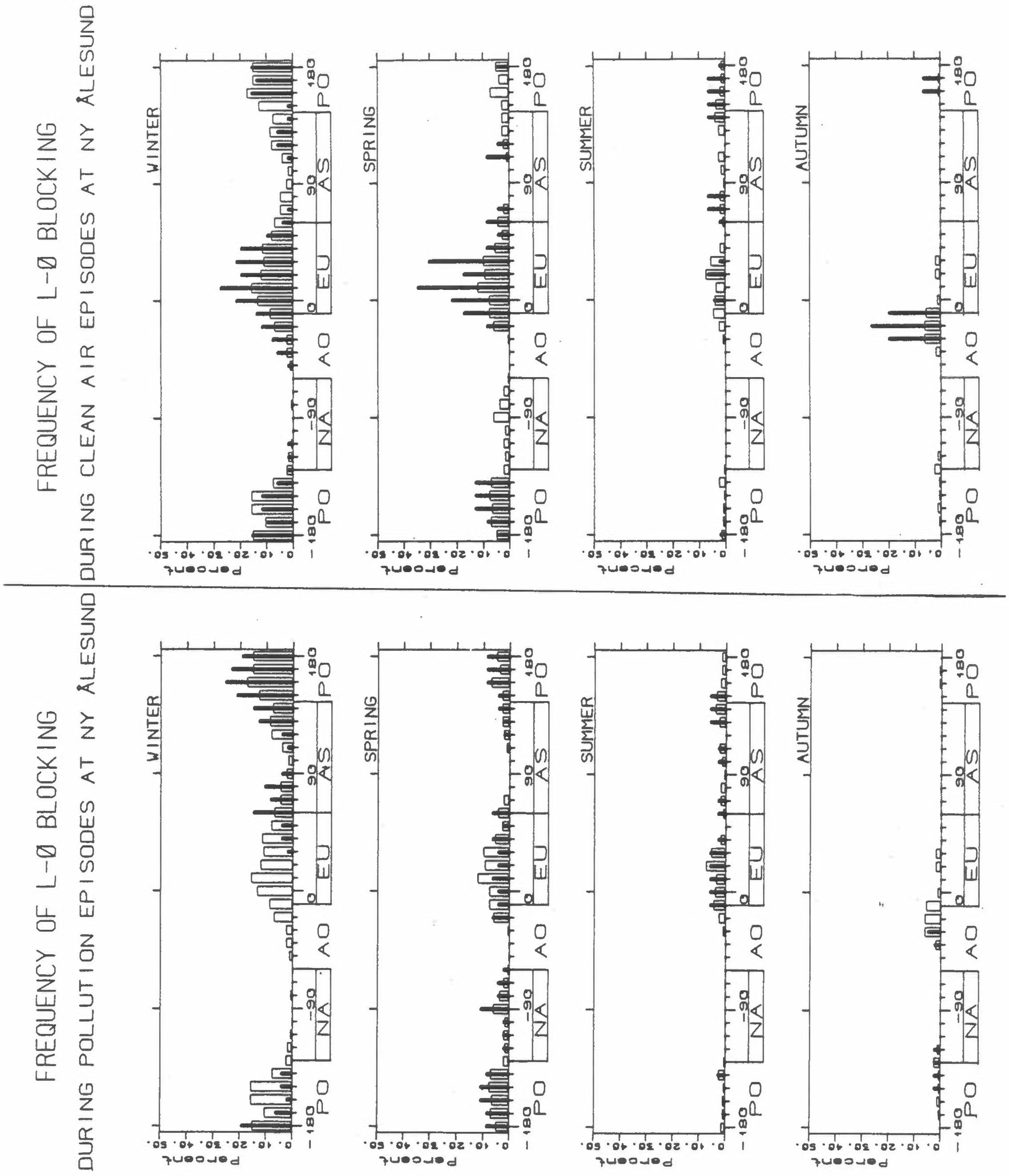


Figure 7: b) Ny Ålesund

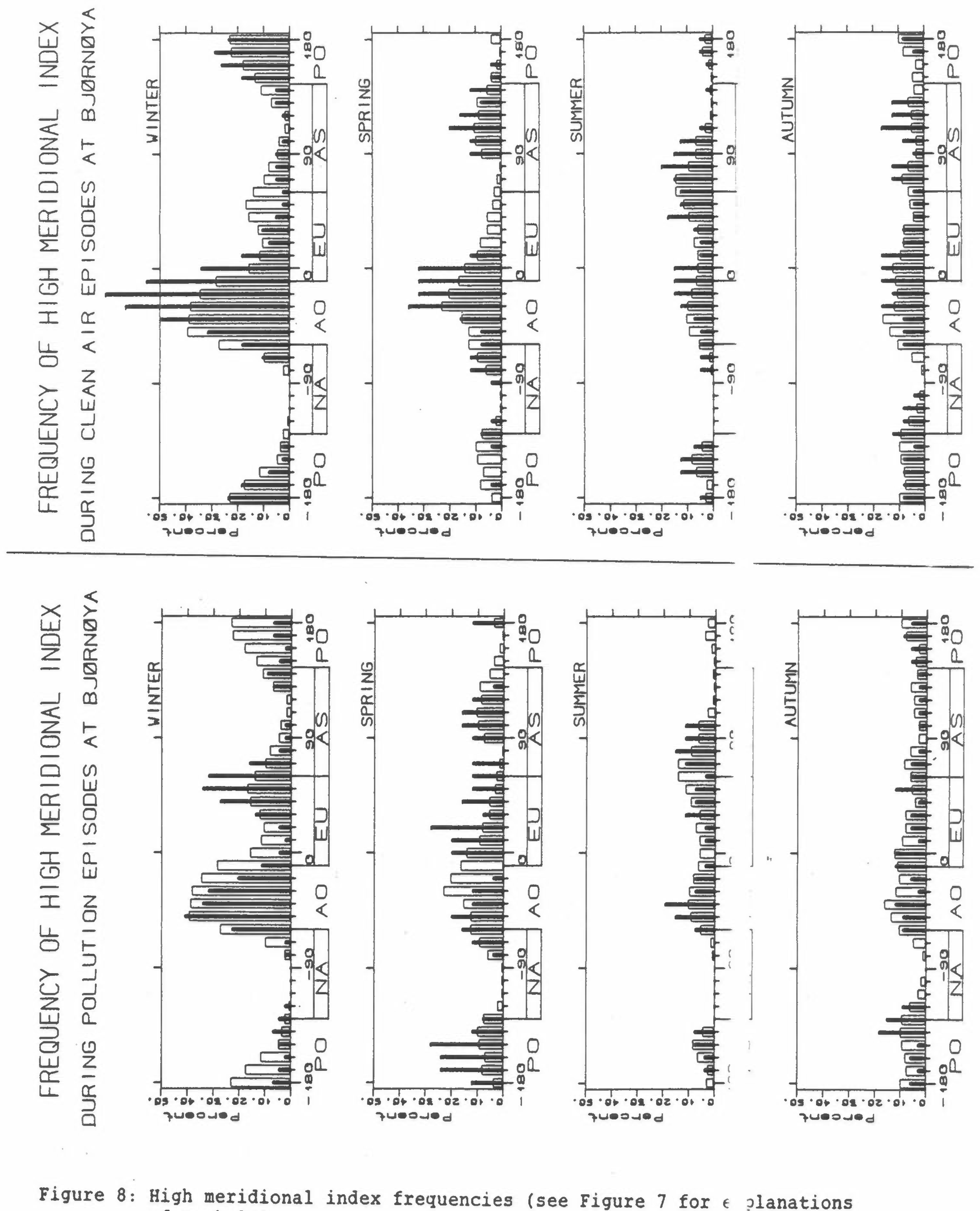


Figure 8: High meridional index frequencies (see Figure 7 for explanations of symbols).
a) Bjørnøya

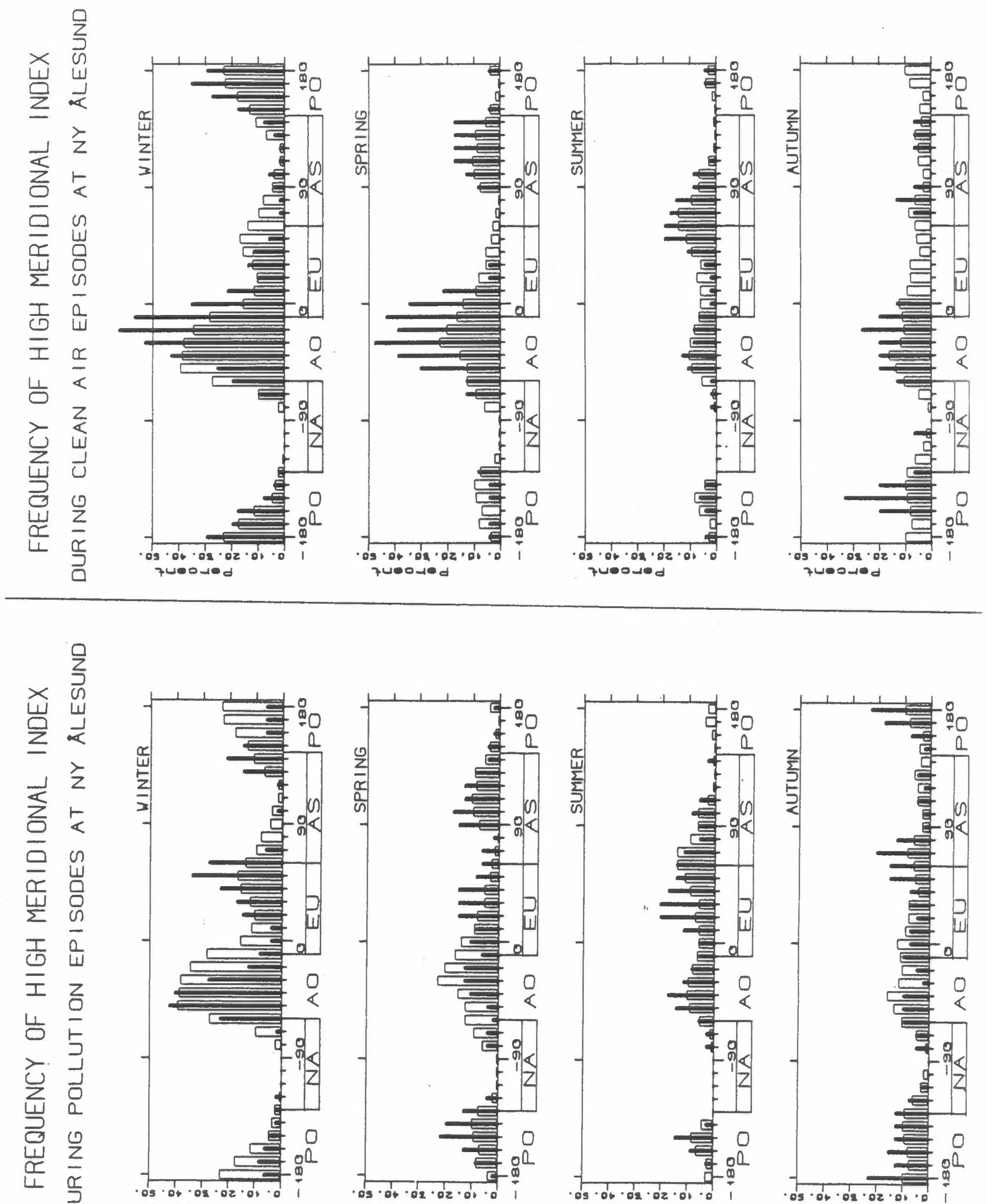
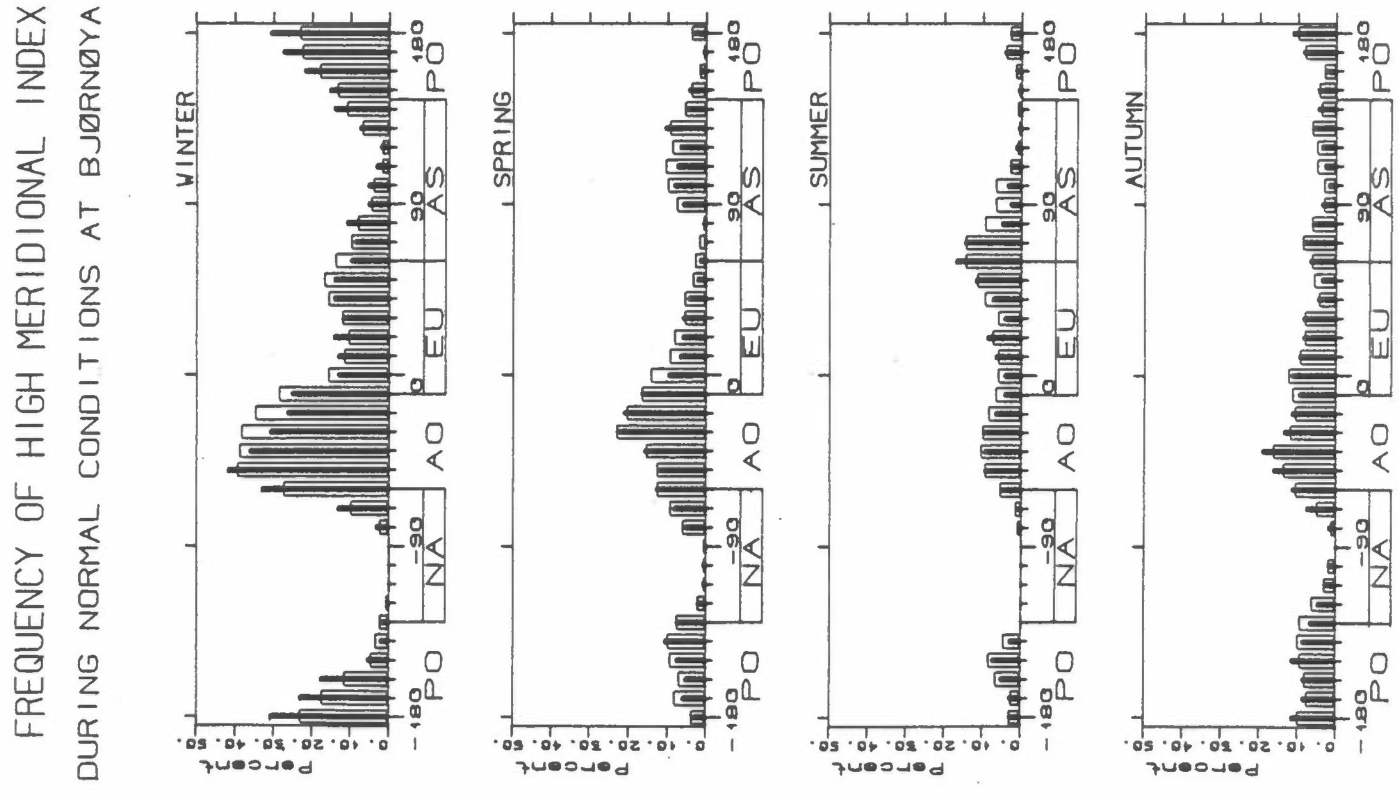


Figure 8: b) Ny Ålesund



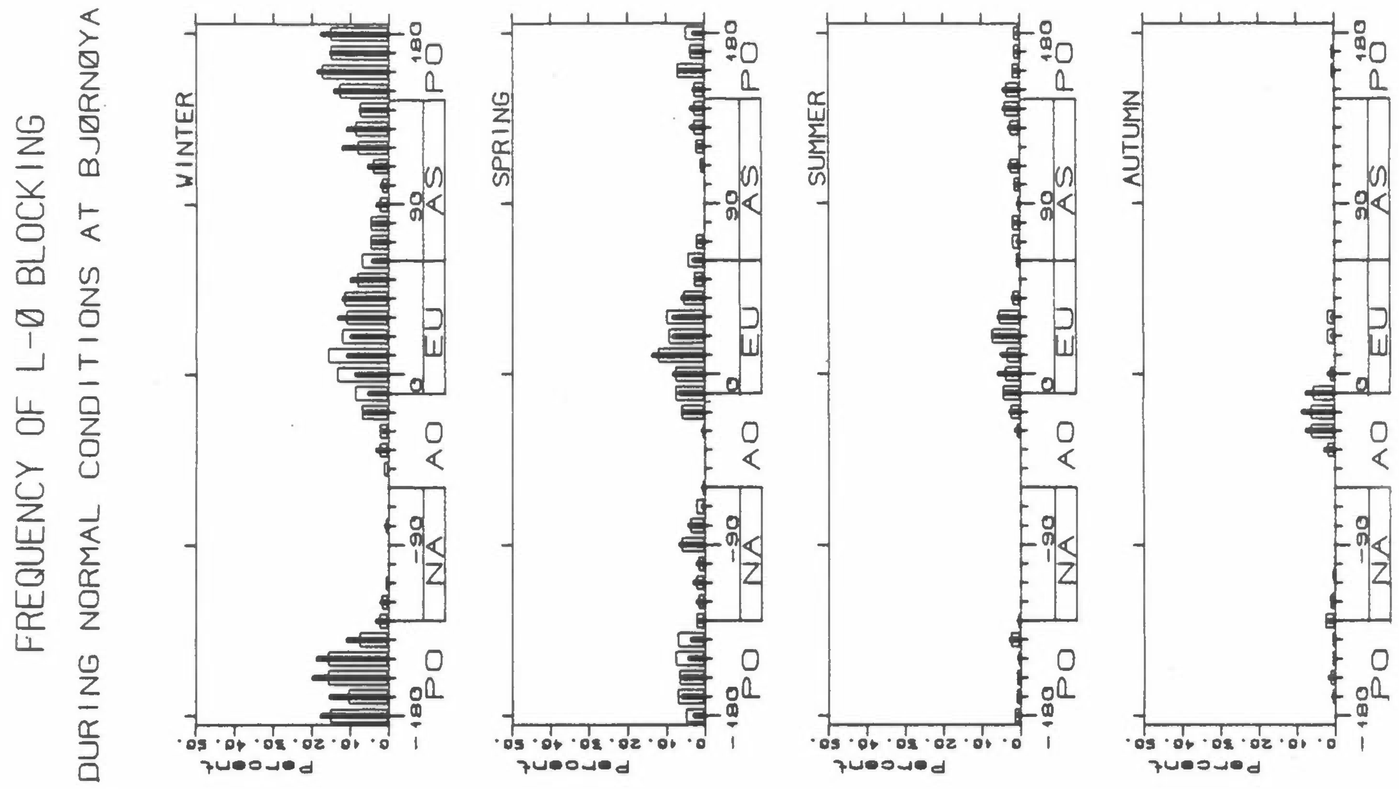


Figure 9: Frequencies during normal conditions (see Figure 7 for explanations of symbols).
a) Bjørnøya

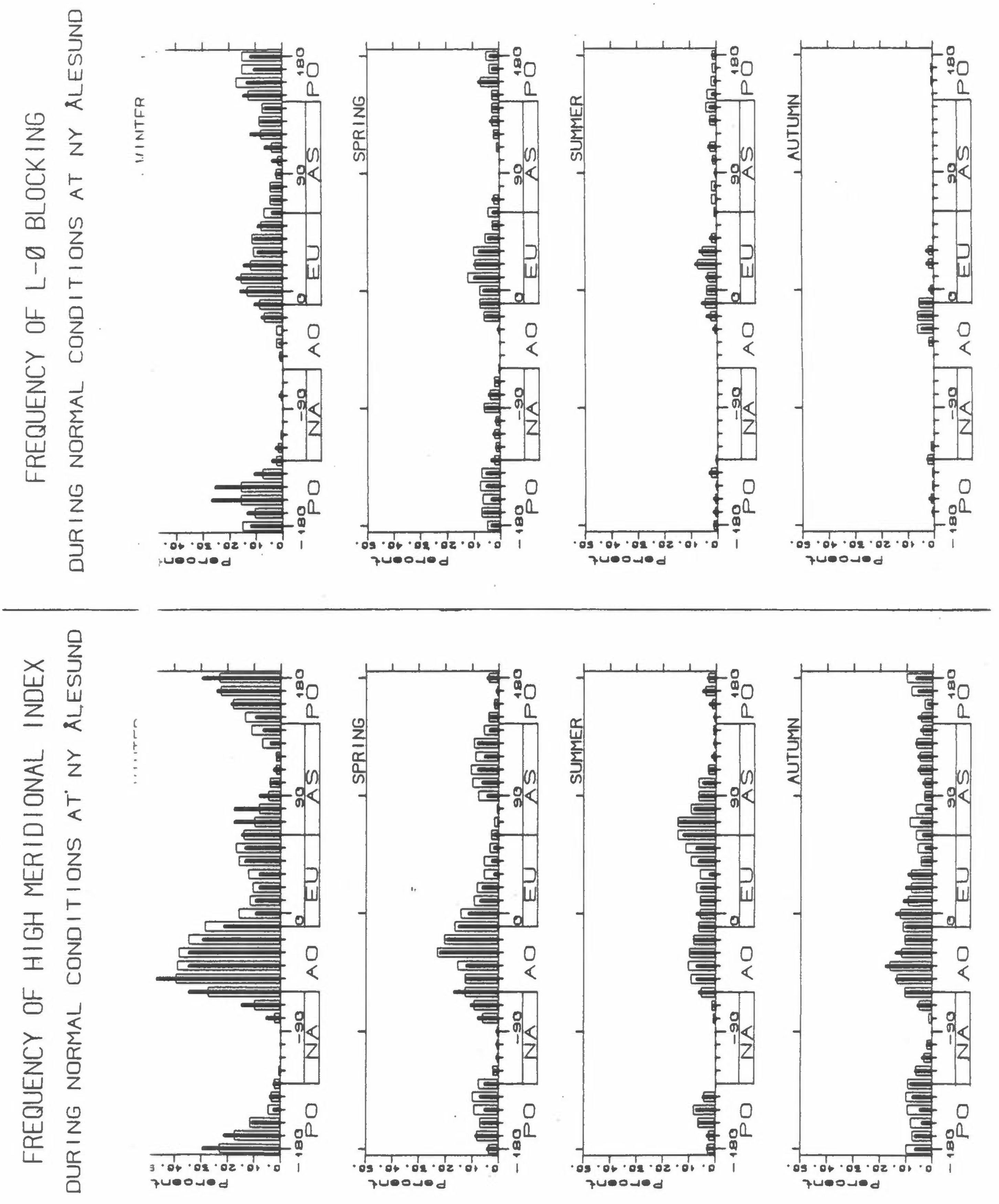


Figure 9: b) Ny Ålesund

From the figures (particularly Figure 9), a clear seasonal cycle in the occurence of the two atmospheric flow systems is seen. Both have a maximum frequency during winter and a miniumum during summer/autumn. They also have a marked longitudinal variation. L-Ø blockings, whenever occuring, are normally situated either in the Pacific Ocean or over Europe, while situations with high poleward meridional index are found most frequently in the Atlantic or Pacific oceans. This is in accordance with the results from climatological studies of blockings (Rex, 1950; Lejenäs and Økland, 1983). It is also seen that Eq. (3.4) represents a more restrictive condition than Eq. (4.1), i.e., L-Ø blockings are more rare than cases with high meridional index.

The seasonal cycle of the means and variances of the sulphate concentrations at ground level in the Arctic, fits well the long term behaviour of the large-scale quasi-stationary flow systems. However, in order to accuse these atmospheric phenomena for being responsible for the long range transport of air pollutants into the Arctic, they also have to show a correspondence with the episodes. Figure 7 shows that there is a quite clear connection between episodes and L-Ø blockings during winter and, to a certain extent at Ny Ålesund, in the spring. During pollution episodes, blocking events are less frequent than normal over Europe, and a little more frequent than normal over Eastern Asia. During clean air episodes the opposite is true: more than normal frequency over Europe and less than normal frequency over eastern Asia.

The high meridional index, as defined by Eq. (4.1), shows a more pronounced relation to the ground level Arctic pollution behaviour than the L-Ø blockings. As seen in Figure 8. Although very weak, there is a small correspondence during summer and autumn. Once again, for seasons other than winter, the correspondence is more evident for Ny Ålesund than for Bjørnøya. The trend is clear: pollution episodes are related to poleward transport from central Eurasia, while clean air episodes occur with to poleward transport from the Atlantic Ocean. As a reference, Figure 9 shows the frequencies during normal conditions. The results are very close to the mean pattern for the total BP period.

To complete this section, information about ground level Arctic air pollution and large-scale quasi-stationary flows is extracted by the use of cross correlation. For the total zone 60^0N - 70^0N, the index M_T through is defined as a weighed mean

$$M_T(L) = 0.5 \, . \, M(70^0N,L) + 0.3 \, . \, M(65^0N,L) + 0.2 \, . \, M(60^0N,L) \qquad (4.2)$$

where M(B,L) is a given in Eq. (3.6). The index M_T and the Lejenäs-Økland index (Eq. (3.1)) is now correlated to the residual sulphate concentration c_i (Eq. (2.10)) for each of the four seasons, and for each ten longitudinal degree. For the whole BP period the number of observation days within each season is between about 170 and 220. Supposing the c_i's are independent and normally distributed, then the 1% level of significance for the correlation coefficient is between 0.16 and 0.18. The results are shown in Figure 10. There are correlations significantly different from zero for some longitudes during winter and spring at both sites, and during autumn at Ny Ålesund. The correlations for spring are also better at Ny Ålesund. The trend is the same as noted in Figures 7, 8, and 9; however, it shows more clearly that the L-Ø blockings have a much closer connection to clean air episodes than pollution episodes. The meridional index is positively correlated over eastern Europe, and negatively correlated over the eastern Atlantic Ocean.

4.2 DISCUSSION

Popularly, the correlation coefficient measures the amount of variance that can be explained by a linear regression between the two quantities. If the sample correlation coefficient is significantly different from zero, but different from 1 and -1, there is a deterministic correspondence between the two quantities, although other factors influence the behaviour of the quantity be explained. From Figure 10 it can be concluded that there is a deterministic correspondence between the episodic behaviour of ground-level air quality in the Norwegian Arctic and large-scale quasi-stationary, atmospheric flow systems. This is true for the winter and spring seasons, and, to a certain extent, the autumn. (Correlations significantly different from zero, at longitudes far from the Norwegian sector of the Arctic, must be carefully interpreted. Occurrence of quasi-stationary flows at a certain longitude is not independent of the flow types at other longitudes, i.e., there is some intercorrelation.) The correlations are generally poorer for Bjørnøya than Ny Ålesund.

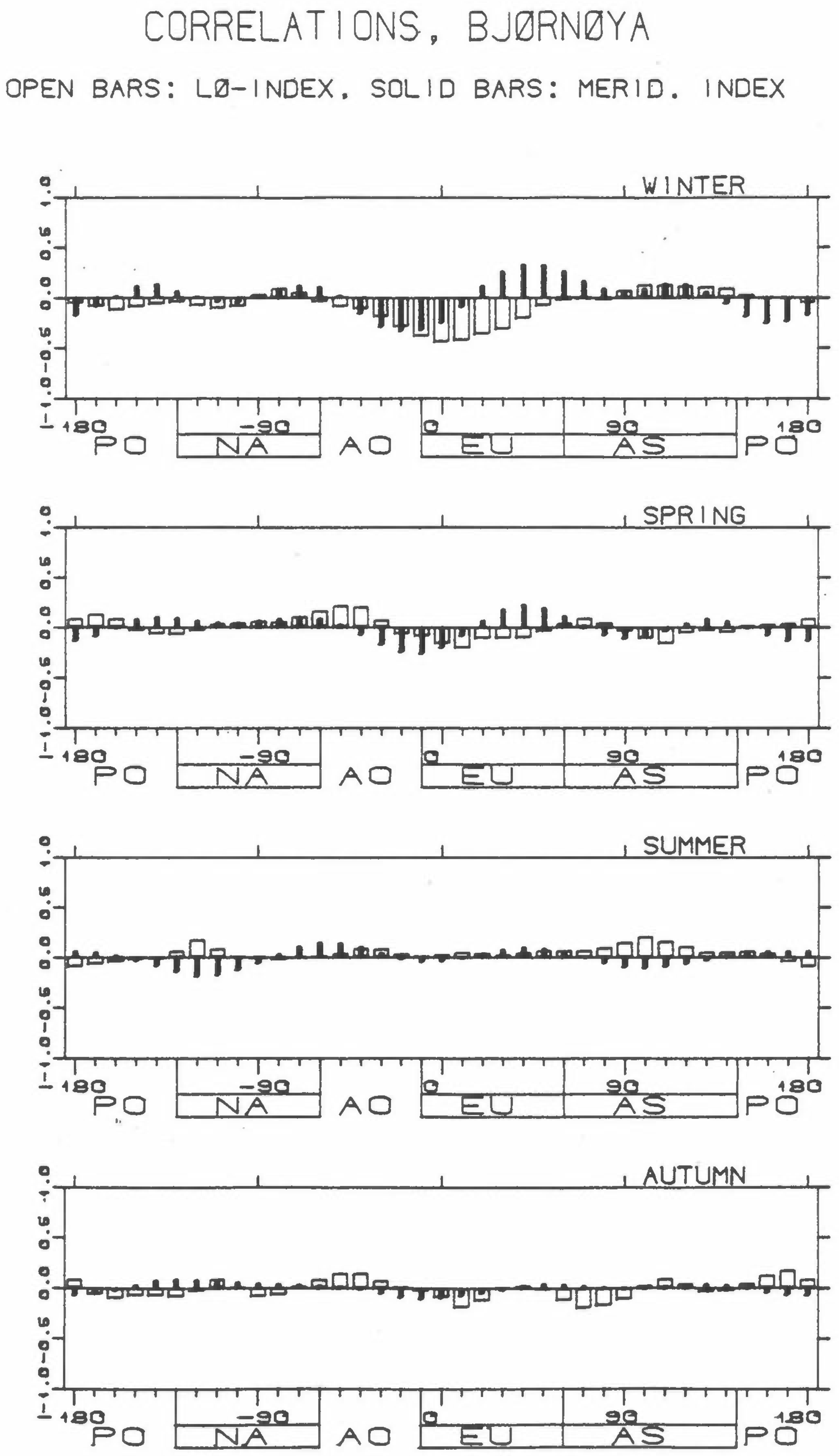


Figure 10: Correlations, for each ten degree longitude, between the residual concentrations and sonal index (open, wide bars) and meridional index (solid bars).
a) Bjørnøya.

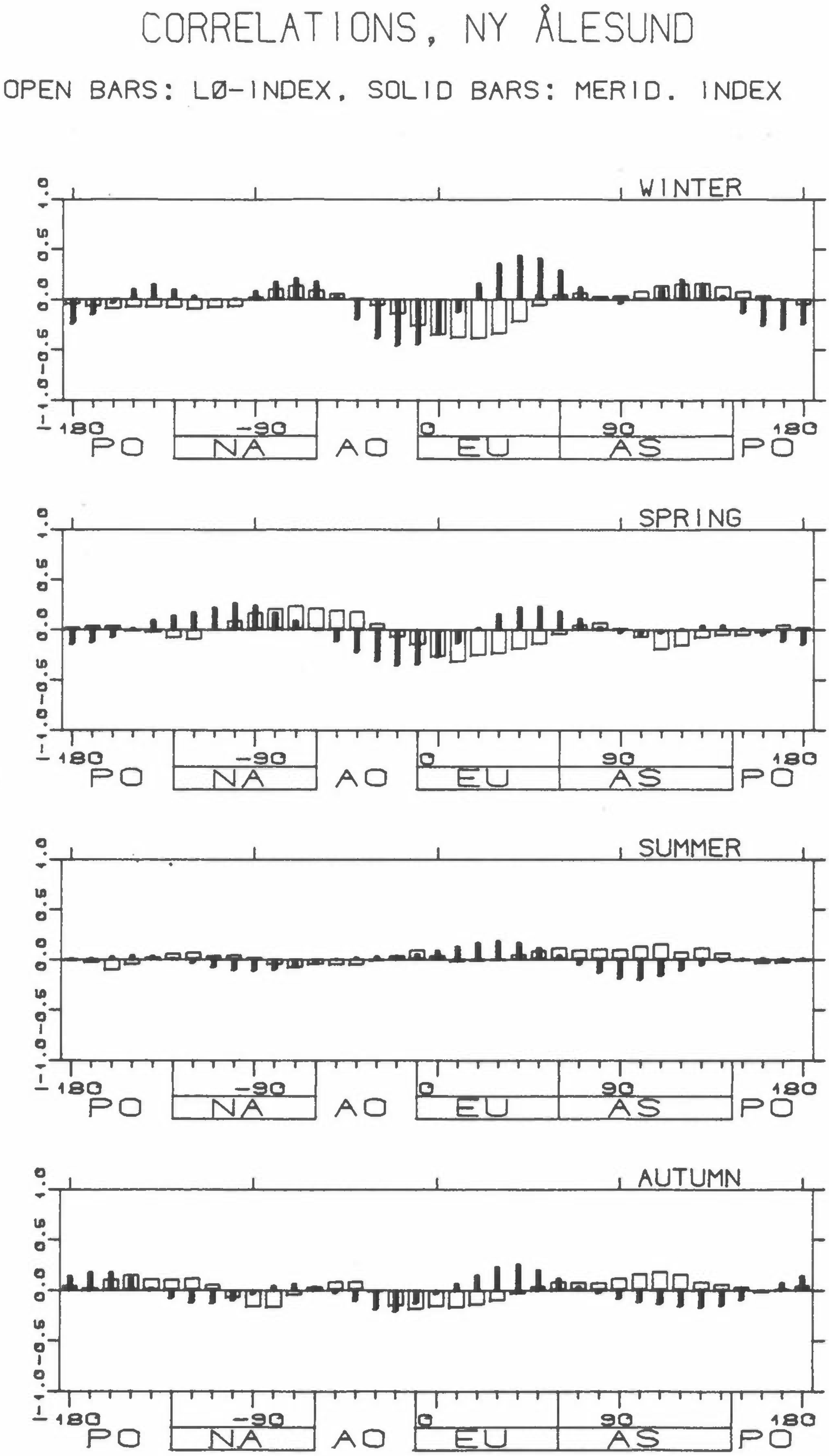


Figure 10: b) Ny Ålesund.

Factors other than pure transport of air, which are important for the episodic behaviour of ground-level Arctic air pollution, are: (i) removal of pollutants from the air, (ii) lifting of pollutants to higher altitudes, and (iii) chemical reactions in the atmosphere.

(i) Cleansing mechanisms for removal of air pollutants have been discussed by several authors. Scavenging of pollutants underway from their mid-latitudinal sources to the Arctic was discussed by Barrie et al. (1981). This effect is probably more efficient during warm seasons, since this is when the mass of precipitated H_2O normally has its maximum. Local scavenging within the Arctic is probably a less important factor in explaining the episodic behaviour. This is due to the fact that the air pollutants must be brought into the Artic before local scavenging can become active. It is probably more important in determining the general background pollution level, since it has a seasonal efficiency cycle (Heintzenberg and Larssen, 1983).

Dry deposition of air pollutants is largely dependent on the static stability in the lowest (surface) layer of the atmosphere. During the cold seasons, the Arctic and sub-Arctic areas are covered with ice and snow, except for the Northern Atlantic Ocean. This cold ground surface loose energy through infrared radiation during the winter darkness, creating a very stable surface layer where dry deposition velocity is low (e.g. Dovland and Eliassen, 1976). During the warm seasons the snow and ice covers shrink considerably, and even the Siberian coast is normally icefree. The sub-Arctic areas are well heated by the solar radiation. Dry deposition of air pollutants underway from the midlatitudes to the Arctic is therefore much larger during the warm season.

(ii) Lifting of air pollutants to higher altitudes is a phenomenon that is especially important for long range transport to the Arctic (Carlson, 1981; Iversen, 1984). The air parcels tend to flow along surfaces of constant entropy; motion through such surfaces requires heating or cooling of the air parcels, which normally is a slow process in the atmosphere. The isentropic surfaces tend to rise towards the Arctic, and air pollutants released at mid-latitude will accordingly be lifted, when advected northwards. The actual difference in ground level entropy, between source areas and the Arctic receptor, is the important quantity in assessing what level in the Arctic air the source area has the potential to pollute. This difference may vary from case to case, thus influencing the ground-level episodic behaviour.

(iii) Sulphate is a secondary pollutant, i.e., it is not emitted directly but formed in the atmosphere through chemical reactions. Oxidation of SO_2 to sulphate is a complicated process. Its efficiency depends on the presence of several chemical species, existence of water droplets and favourable temperature conditions (e.g., Rohde and Isaksen, 1980; Bøhler and Isaksen, 1984;). This may influence the episodic behaviour of sulphate concentrations, as well as the annual cycle; however, it is not easily assessed to what extent. Iversen and Joranger (1985) indicated that the oxidation is more efficient for cold air travelling over open sea than over ice.

The processes (i) and (ii) have both maximum efficiency during the warm season. Given that quasi-stationary meridional frequency transport is also at a minimum during the same season, it is not surprising that the occurence of these and Arctic sulphate pollution is at a minimum. Furthermore, as pointed out in Chapter 2, the variance in sulphate concentrations has also a warm-season minimum. The concentration variations are normally so small that episodes have nothing to do with long range transport, except for some exceptional cases.

The probable reason for Bjørnøya having lower correlations than Ny Ålesund, is that the island is exposed year-around to the open sea. Non-transport effects of the kinds (i) and (ii) above have therefore higher efficency at Bjørnøya. For example, the fog frequency at Bjørnøya is much higher than at Ny Ålesund (Steffensen, 1982). Cold air travelling over the open sea to Bjørnøya leads to much more effective dry deposition than air travelling over ice to Ny Ålesund. In addition, Bjørnøya is much closer to the sources on the Kola peninsula in U.S.S.R, and hence a quasi-persistent flow system over large meridional distances should not allways be necessary for pollution episodes there.

The L-0 blocking does not seem to be a flow type that exemplifies specific properties favourable to poleward transport of air pollutants, measured at ground level in the Arctic. The main finding here is that the lack of L-0 blocking over Europe is a positive factor in creating long range transport of air pollutants into the Norwegian Arctic. Existence of L-0 blocking over Europe is, on the other hand, related to clean air episodes in the Norwegian Arctic. Only small positive correlations are found at any longitude. The meridional index, however, provides more essential information about the transport.

5 *CONCLUSIONS*

The main conclusions of this work are:

(i) The air pollutants in the Norwegian Arctic shows an annual cycle in both mean values and variance, which coincide well with the seasonal variation of large-scale quasi-stationary atmospheric flows.

(ii) The episodic behaviour of air pollution is well explained by the occurrence of quasi-stationary poleward transport of air during the cold season. The very small variations in pollutant concentrations during summer is very little influenced by long range transport of air.

On the whole, the large scale quasi-stationary atmospheric flows, brought about by the very long planetary waves, are the basic mechanisms that provides conditions for long range transport of air pollutants from mid-latitudes into the Norwegian Arctic. The residence times of pollutants, once brought into the Arctic, seem to be much longer during the cold than during the warm season . There is a certain background level of air pollution during the cold season which is effectively removed during late spring. It remains low throughout summer and most of autumn, and increases gradually in the late autumn/early winter.

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APPENDIX

On the following 27 pages, sulphate concentration(as $\mu g\ S\ m^{-3}$), episodes and events with L-Ø blocking and high meridional index for each of the months within the BP period (82-05-01 through 84-07-31), are shown. Each figure consist of four diagrams, with the day of the month (increasing downwards) given on the ordinate axes,

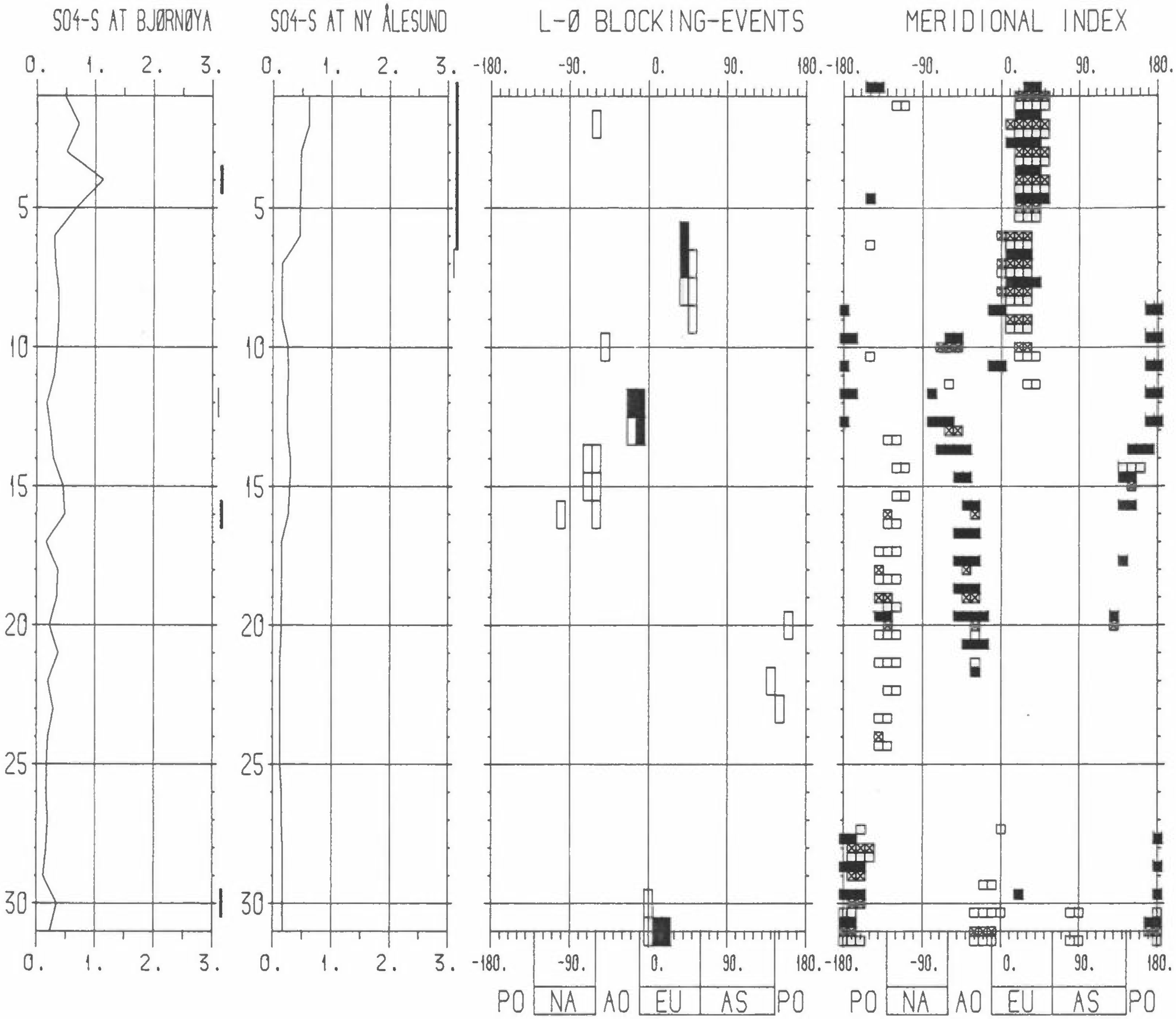
The two leftmost diagrams show concentrations of sulphate. Along the right side of each diagram, pollution episodes are denoted with thick, vertical lines and clean air episodes with thin, vertical lines.

The third diagram to the right shows events with L-Ø blockings for every ten degrees of longitude. Weak blockings are denoted with open rectangles (▯) and strong blockings with filled rectangles (▮). The abscissa gives the longitude from 180^{0}W through 180^{0}E. Positions of oceans and continents are indicated by:

PO = Pacific Ocean
NA = North America
AO = Atlantic Ocean
EU = Europe
AS = Asia

The rightmost diagram shows events with high meridional index. For each day, events at 70^{0}N are denoted with filled squares (■), events at 65^{0}N with crossed squares (⊠), and events at 60^{0}N with open squares (□).

Days for which meteorological data were missing are denoted by horizontal dotted lines on the two rightmost diagrams.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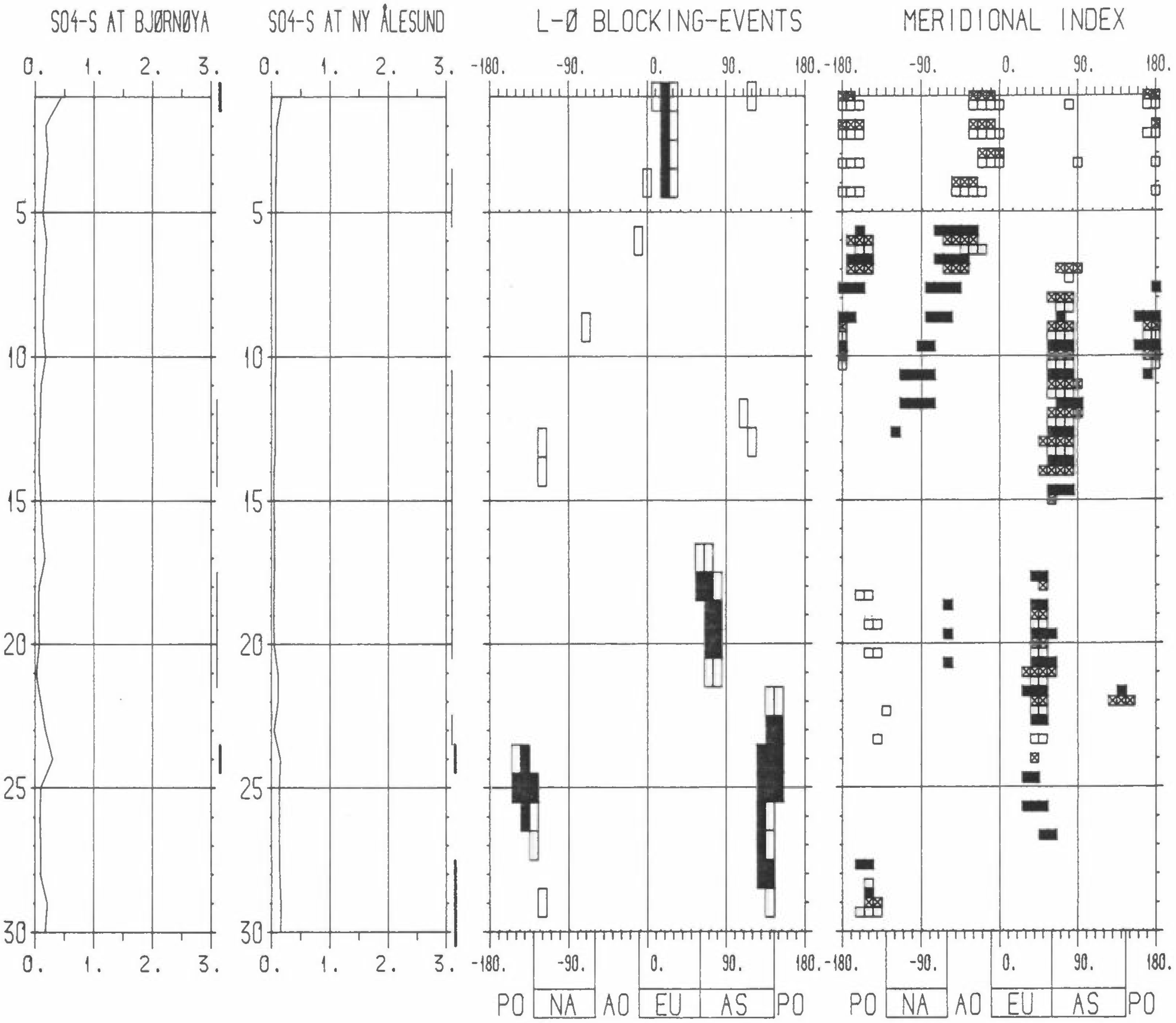
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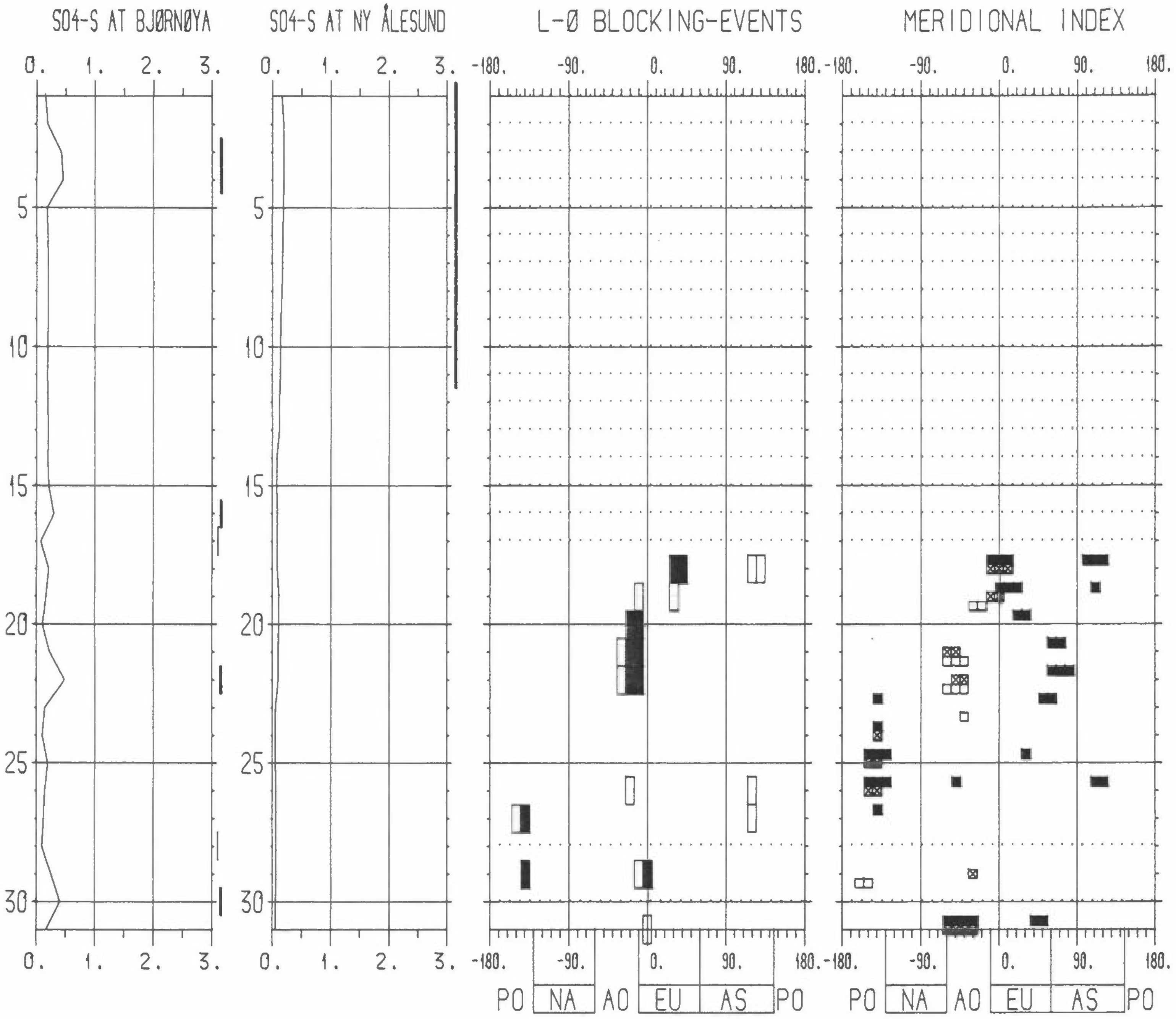
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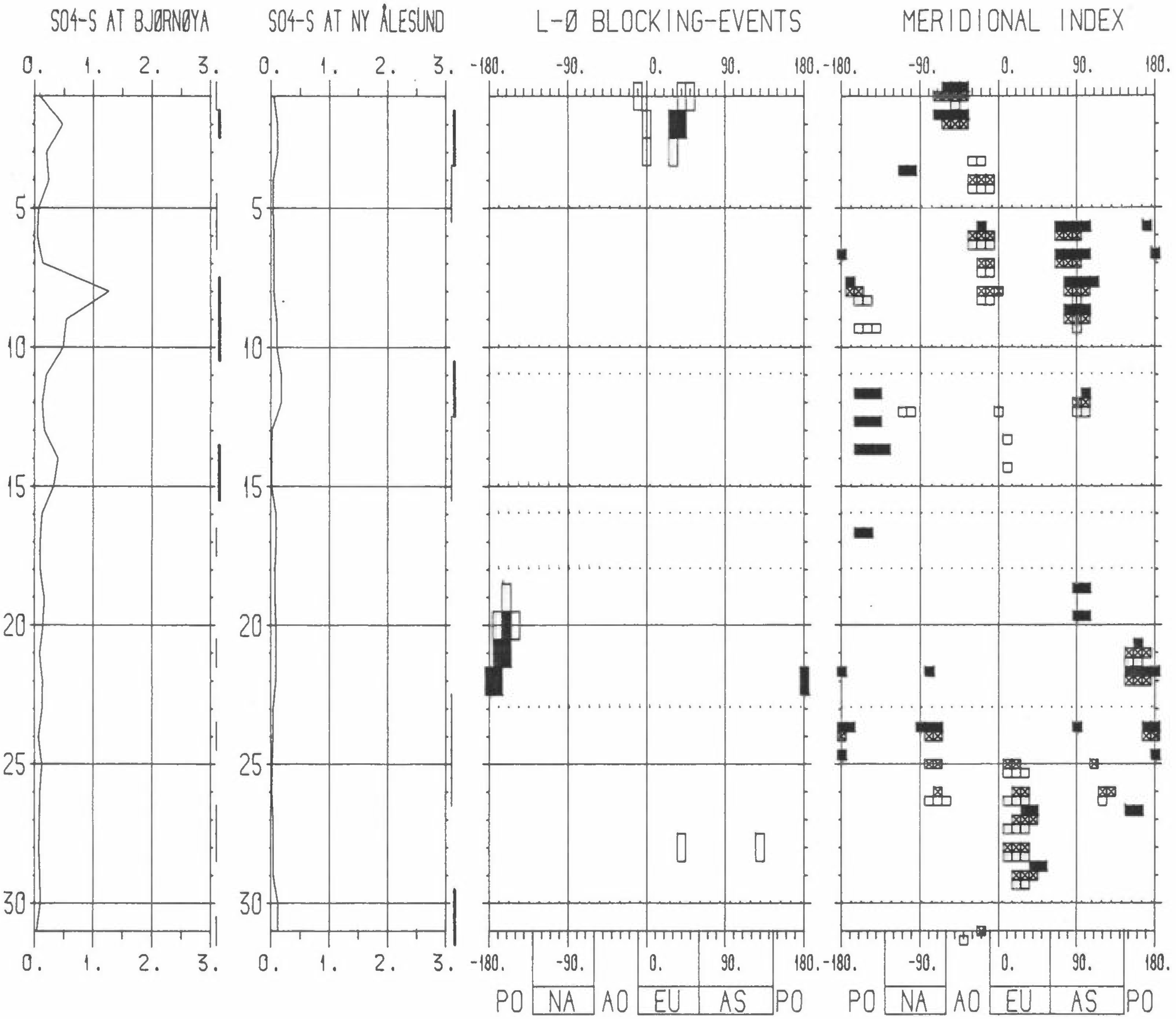
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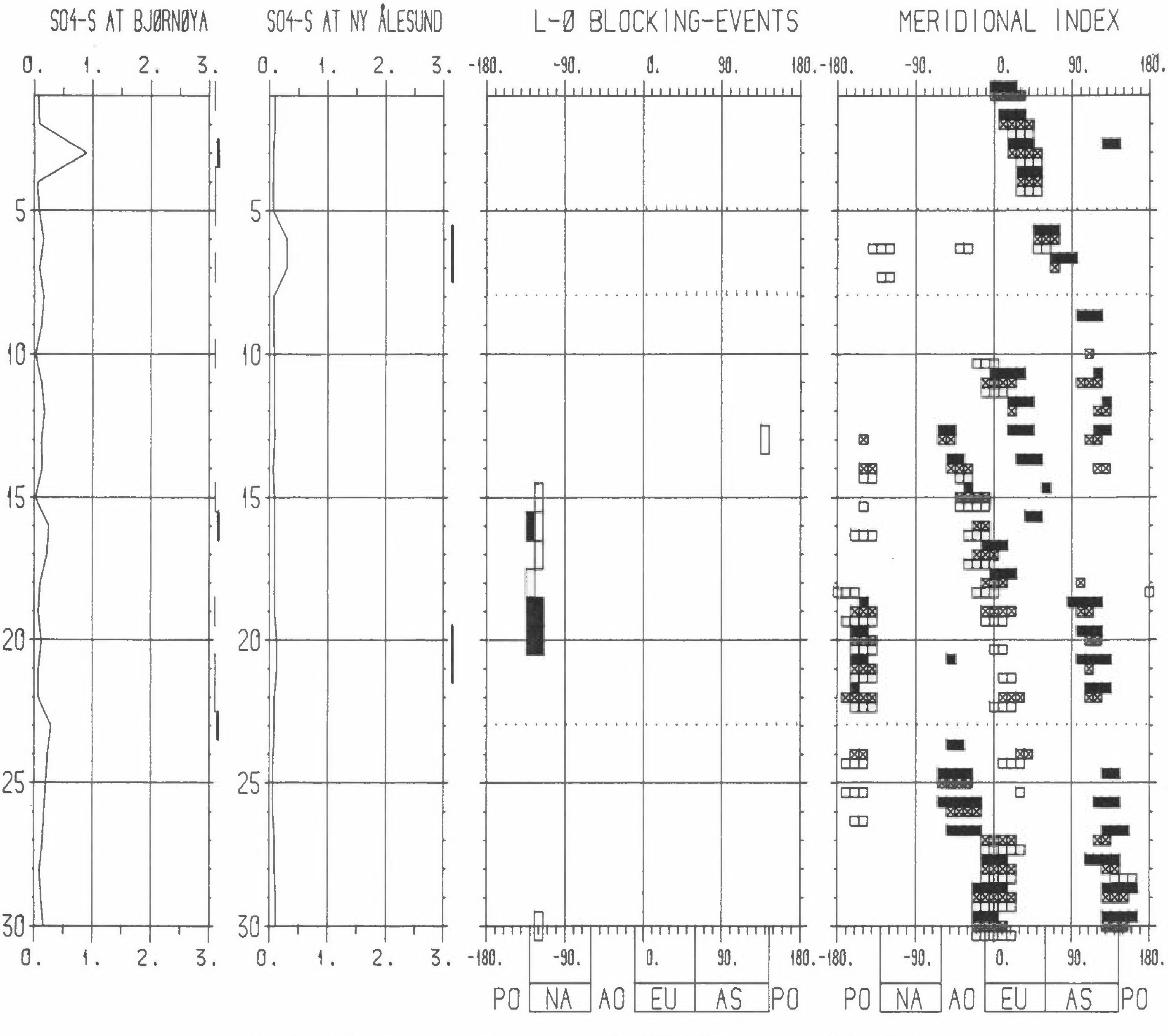

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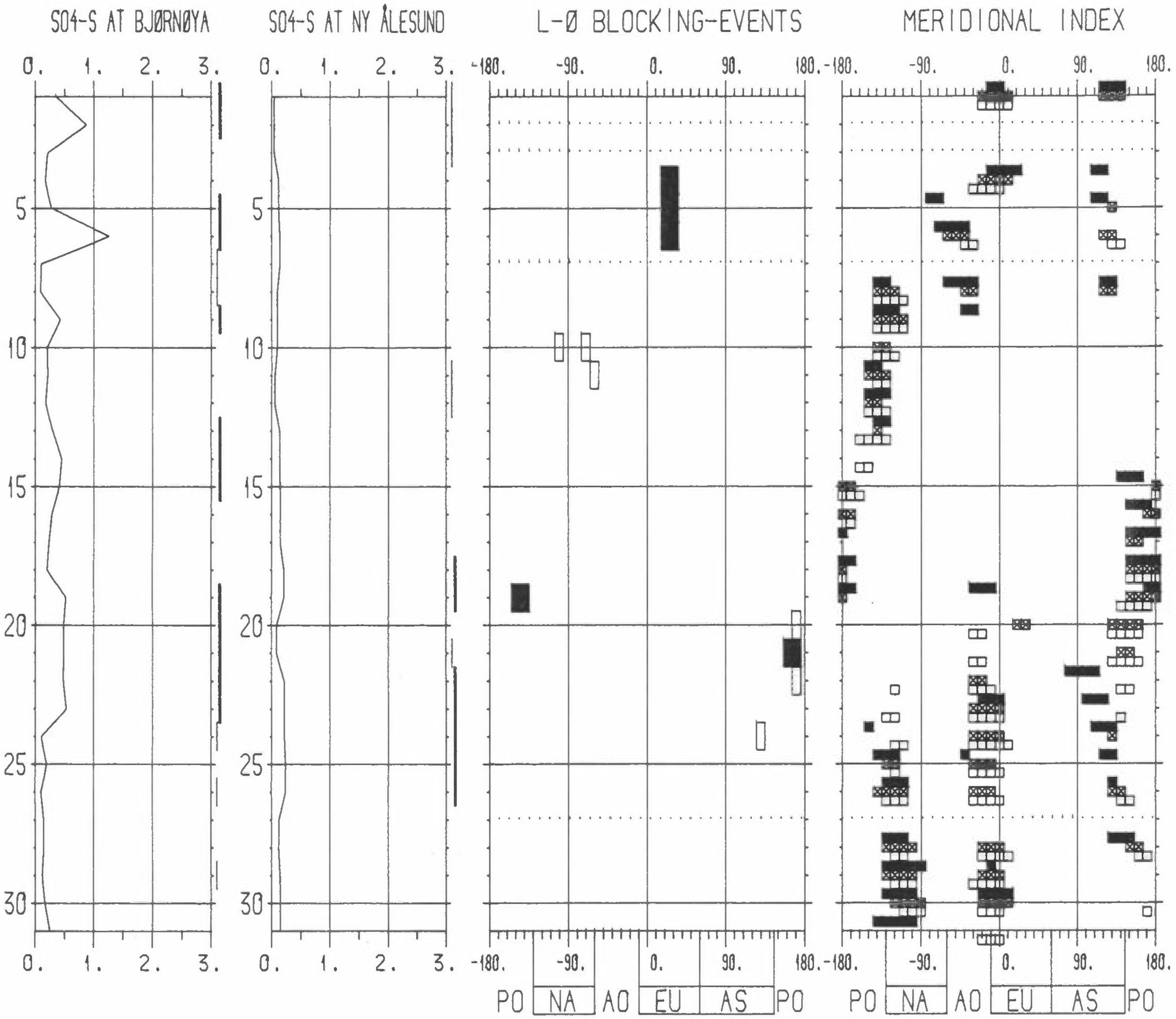
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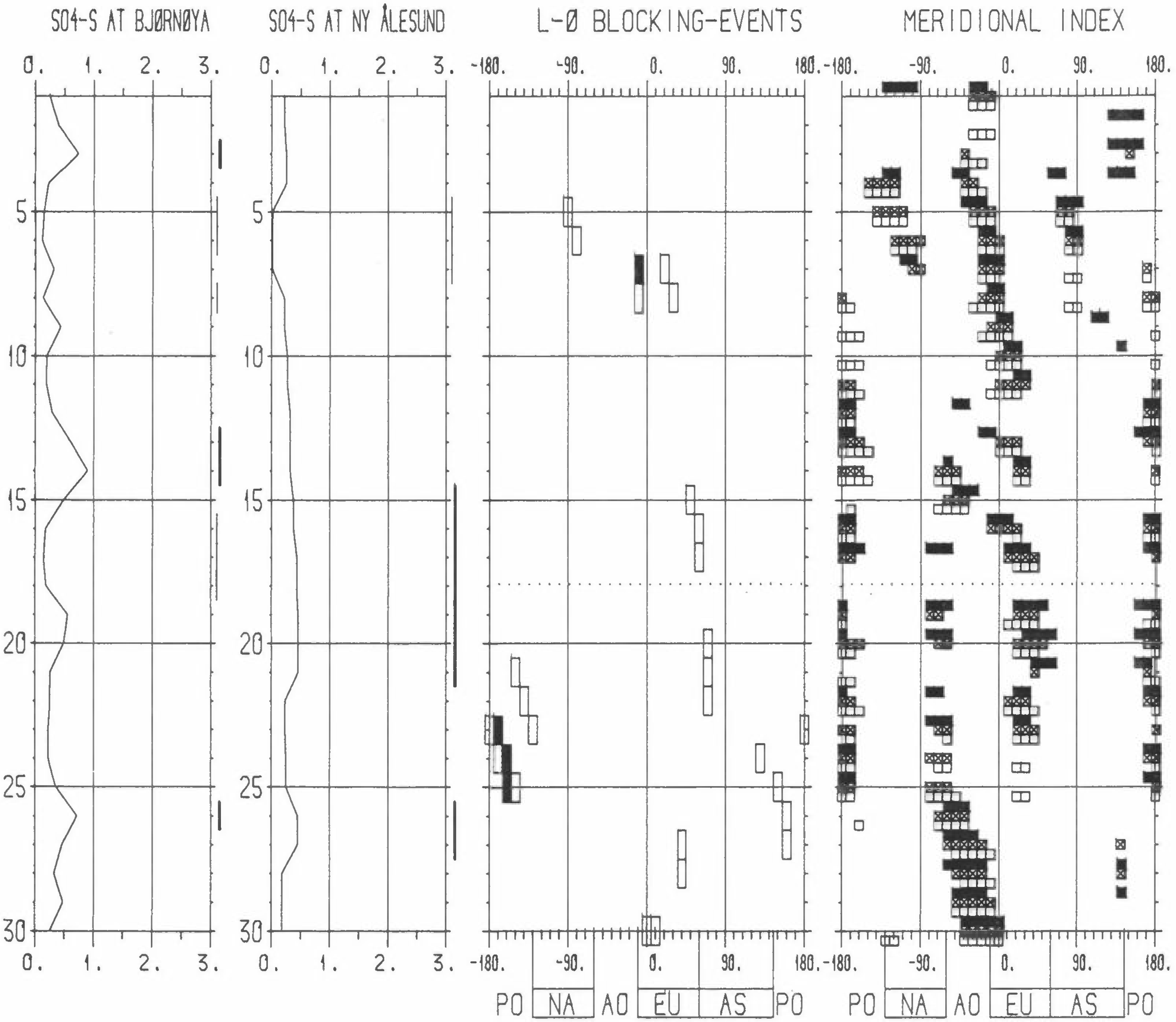
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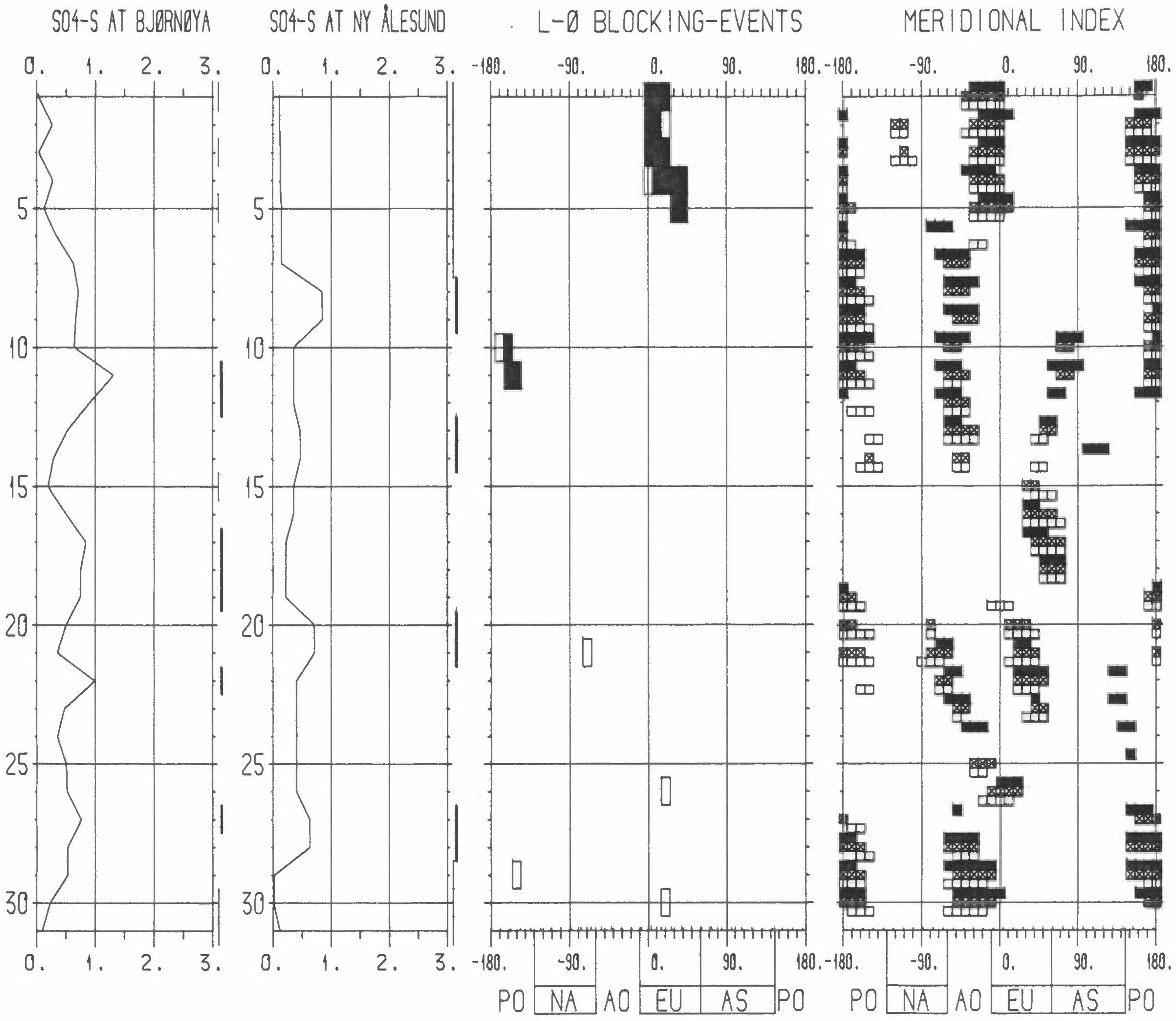
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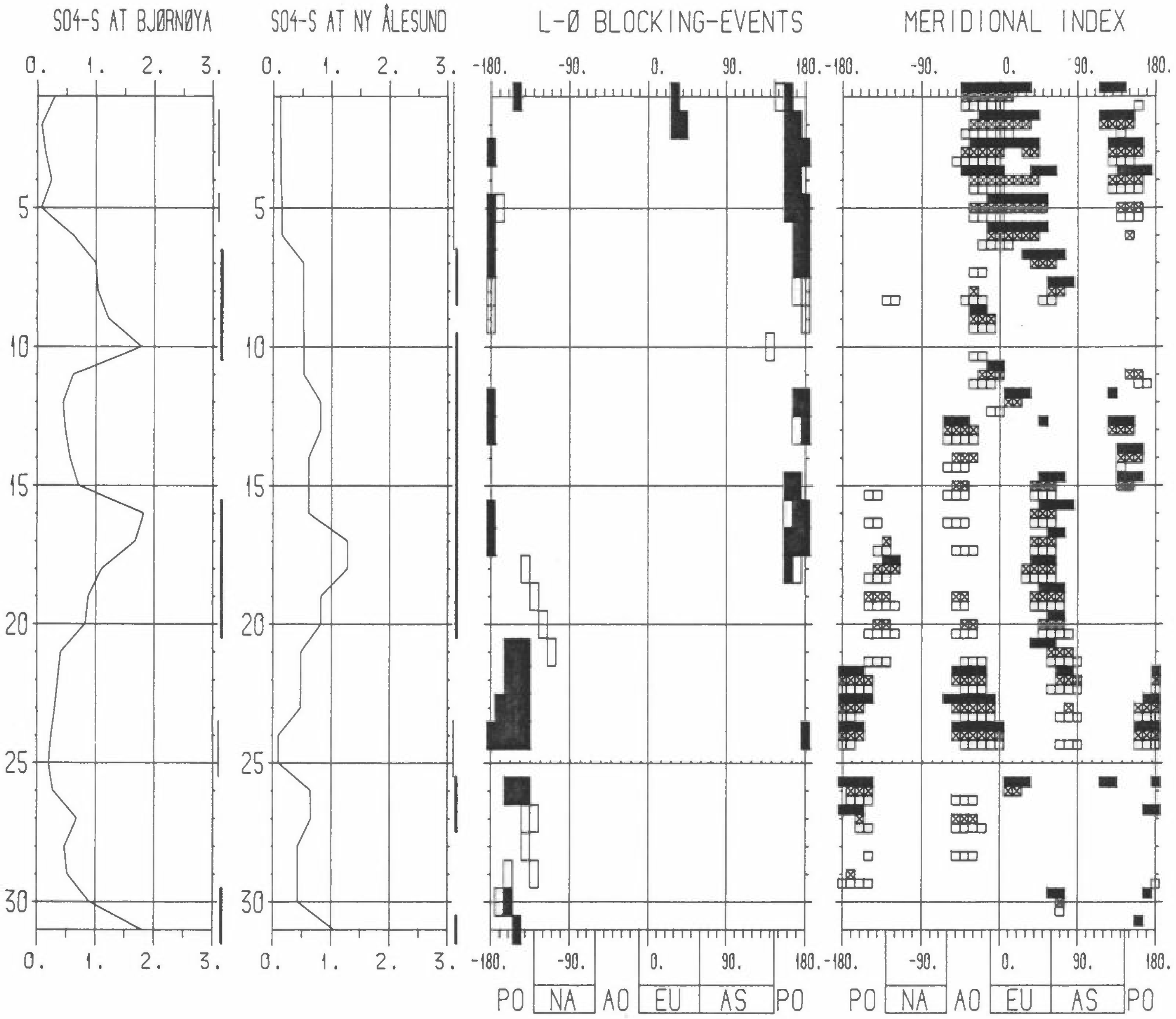
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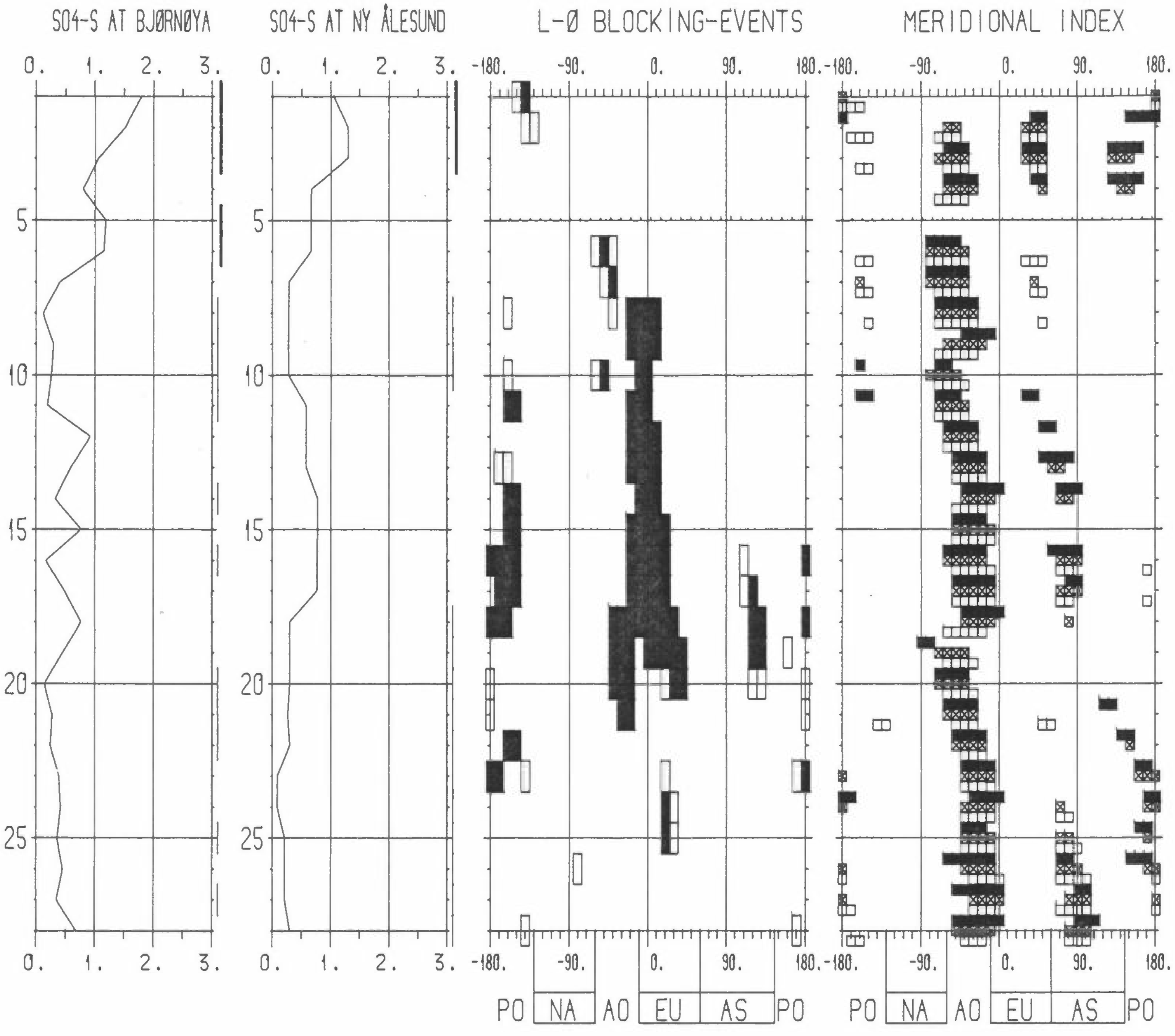
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SO4-S AT NY ÅLESUND

L-0 BLOCKING-EVENTS

MERIDIONAL INDEX

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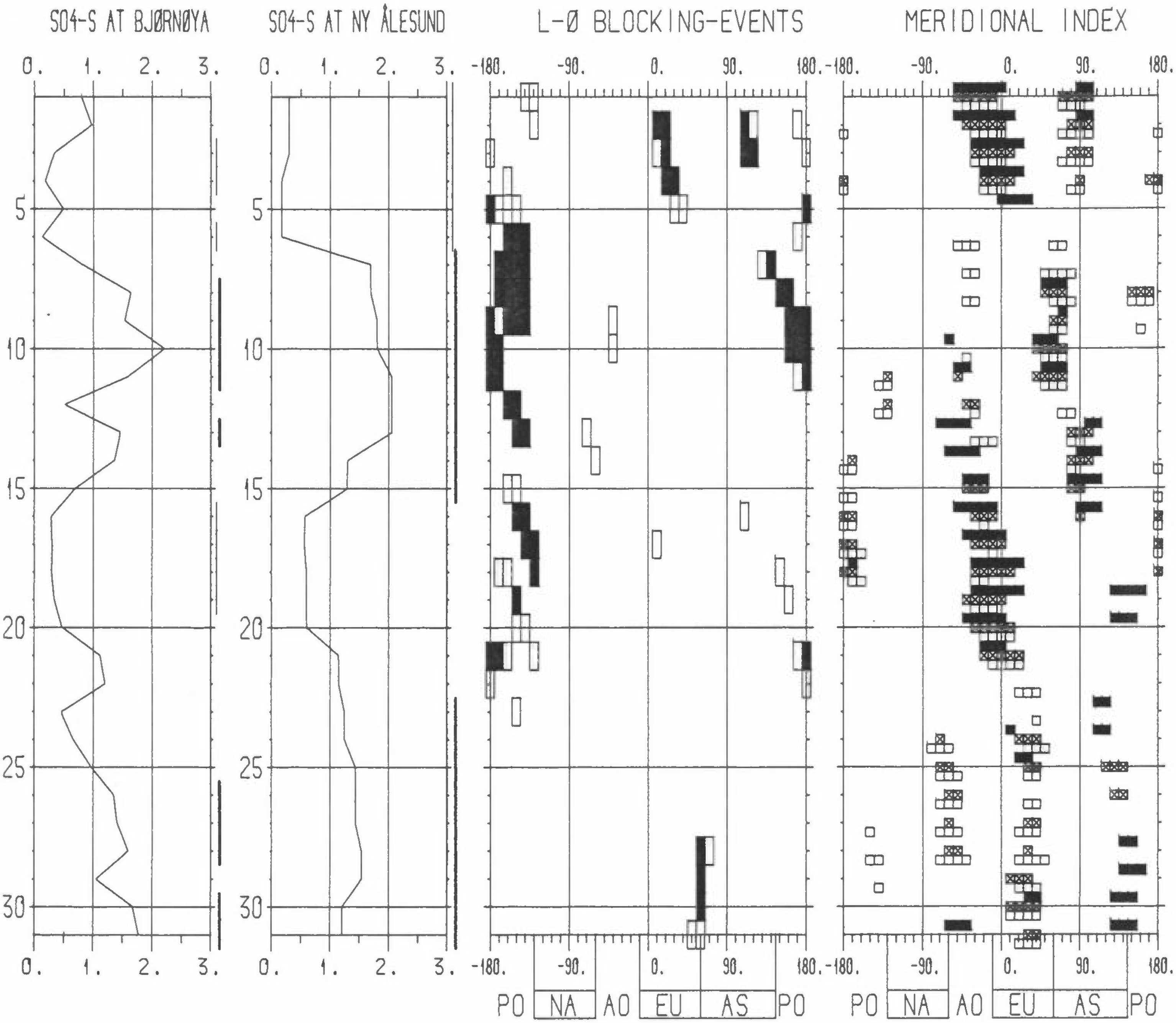
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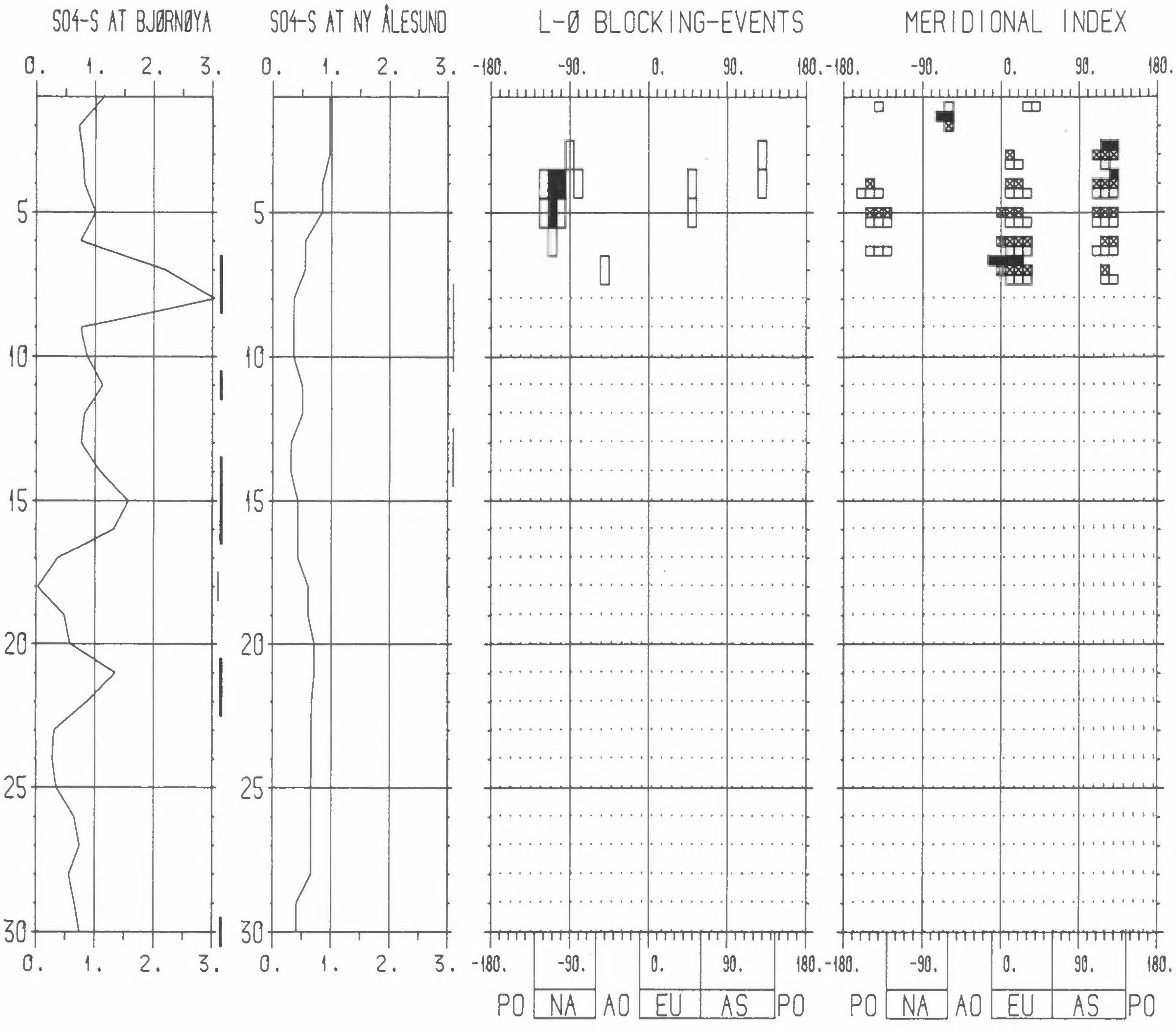
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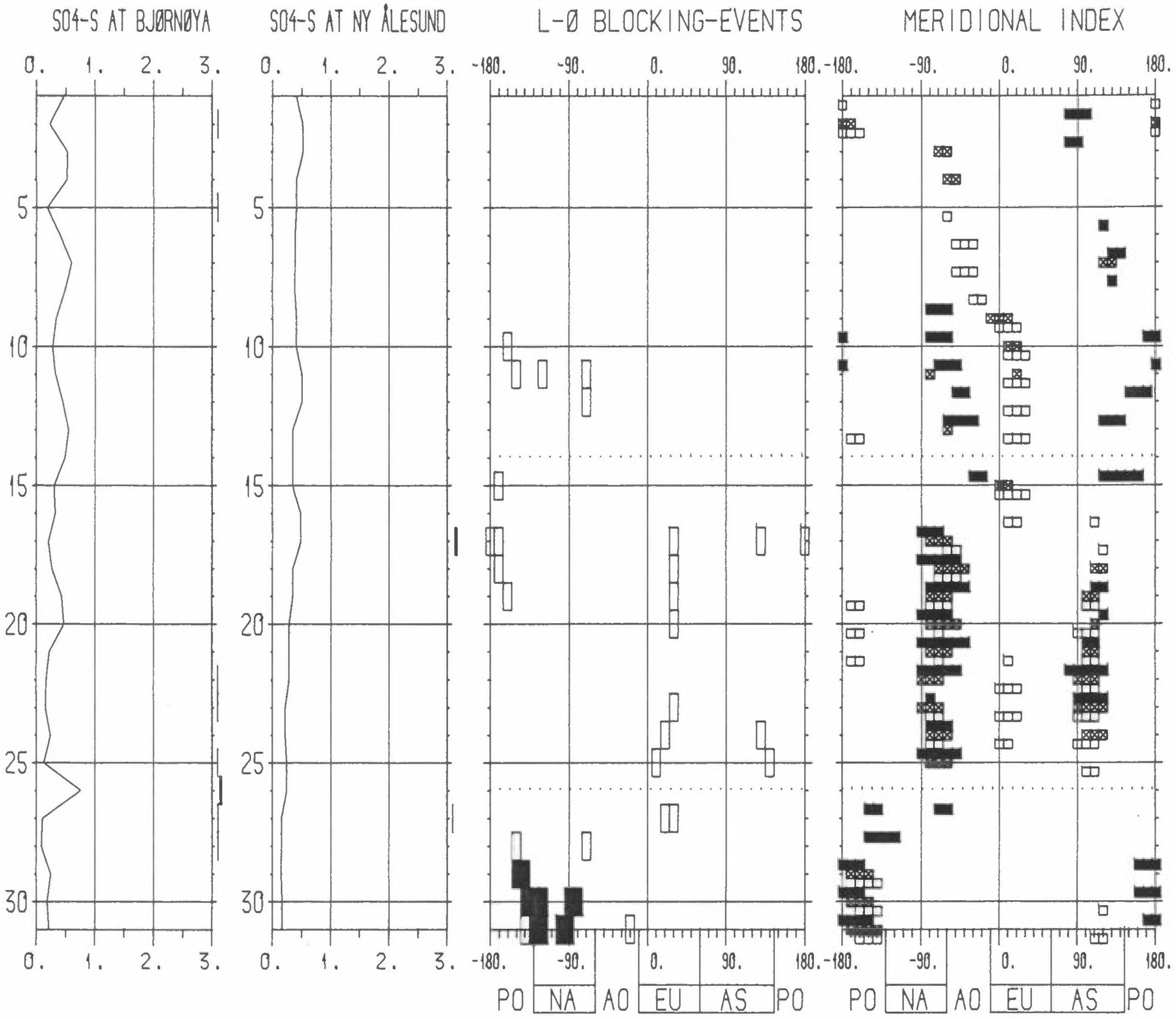
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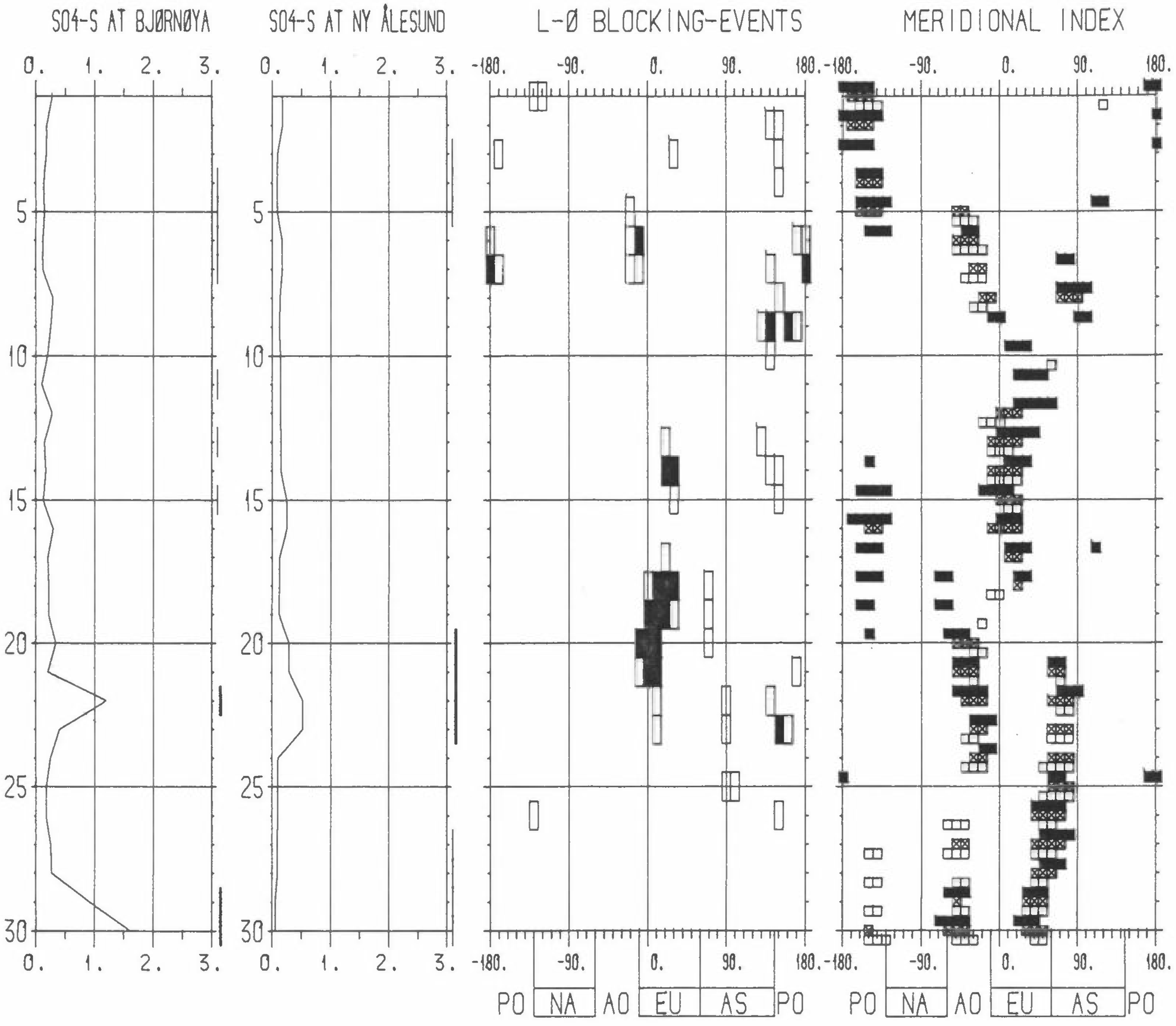
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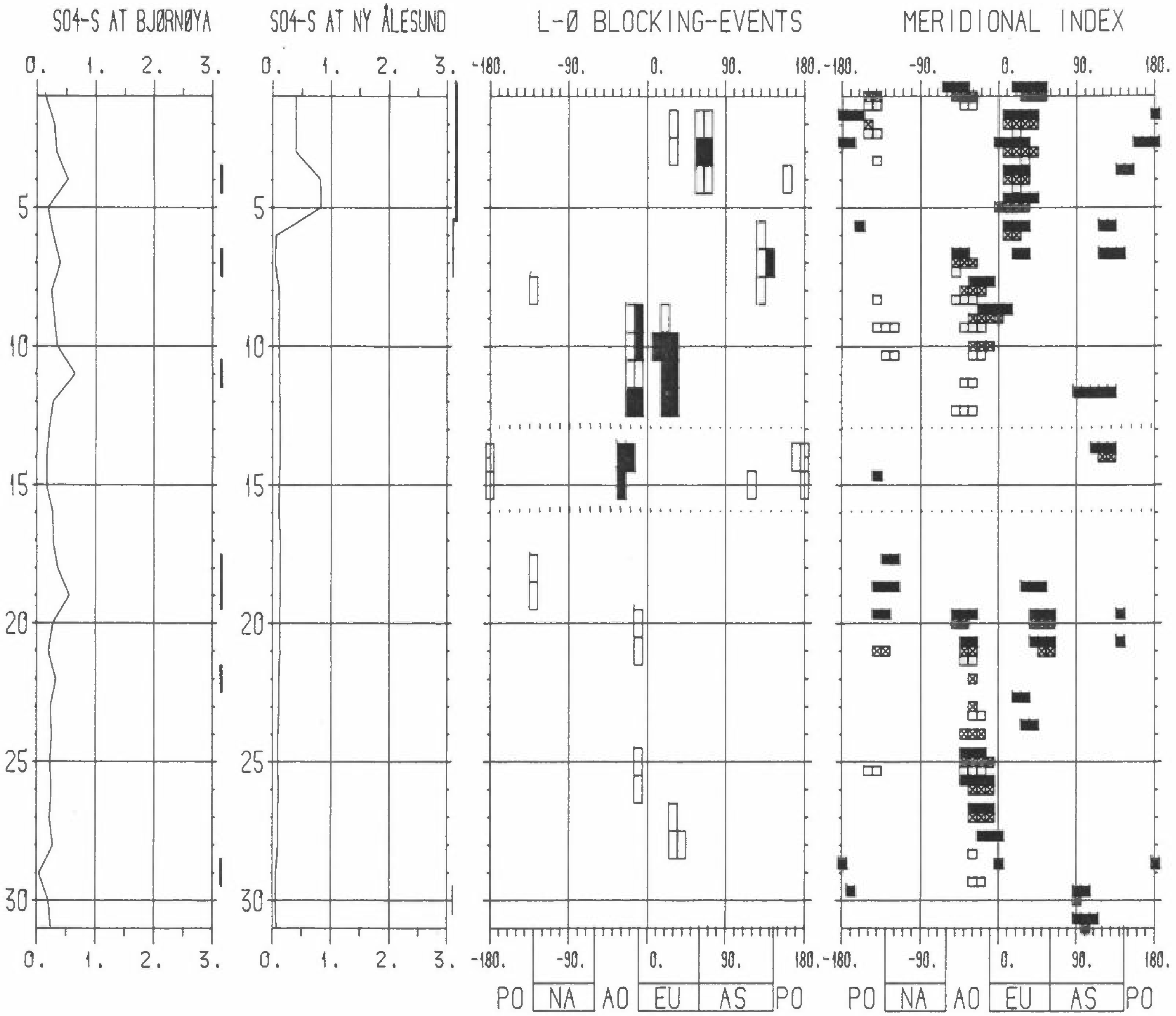
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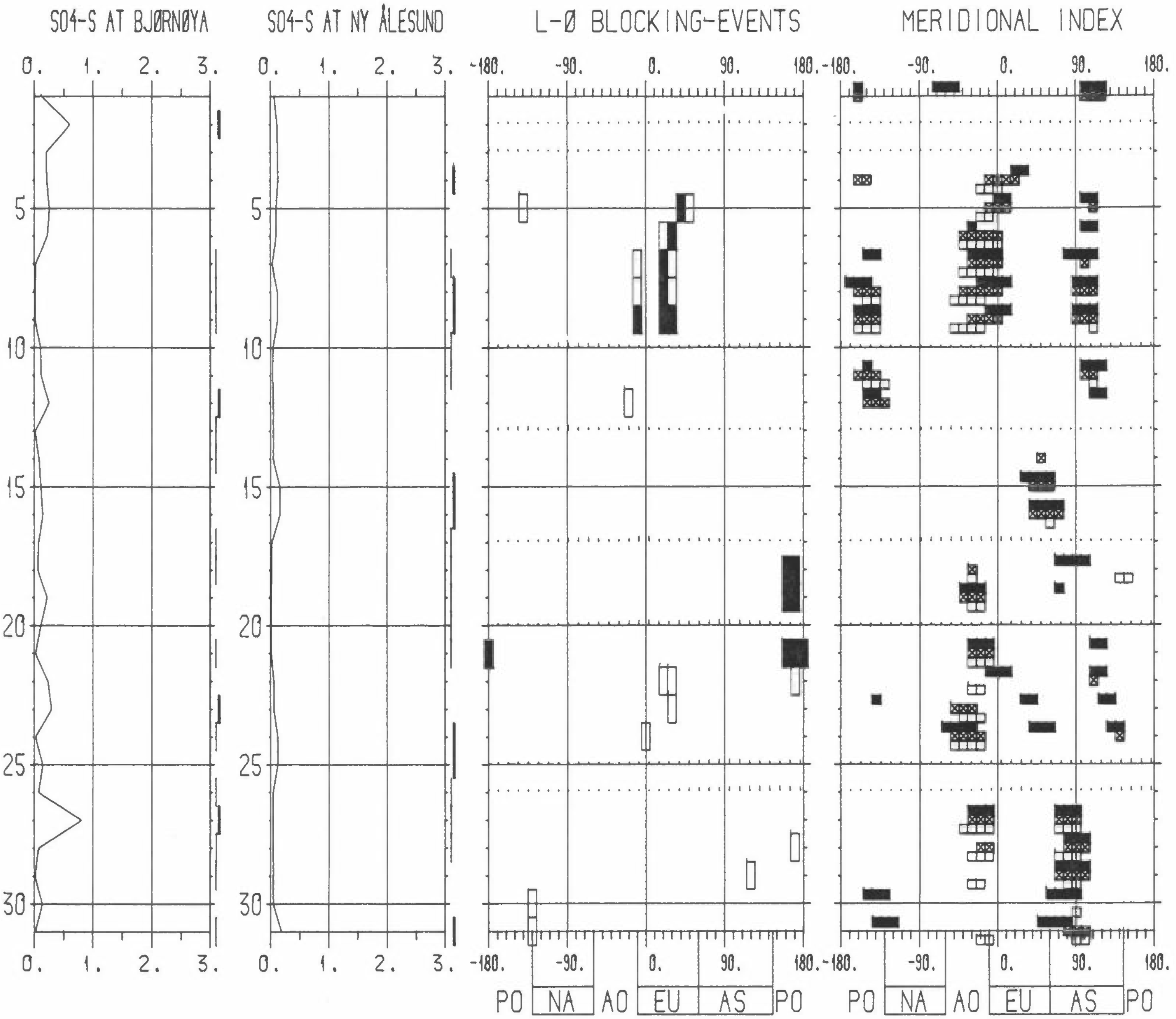
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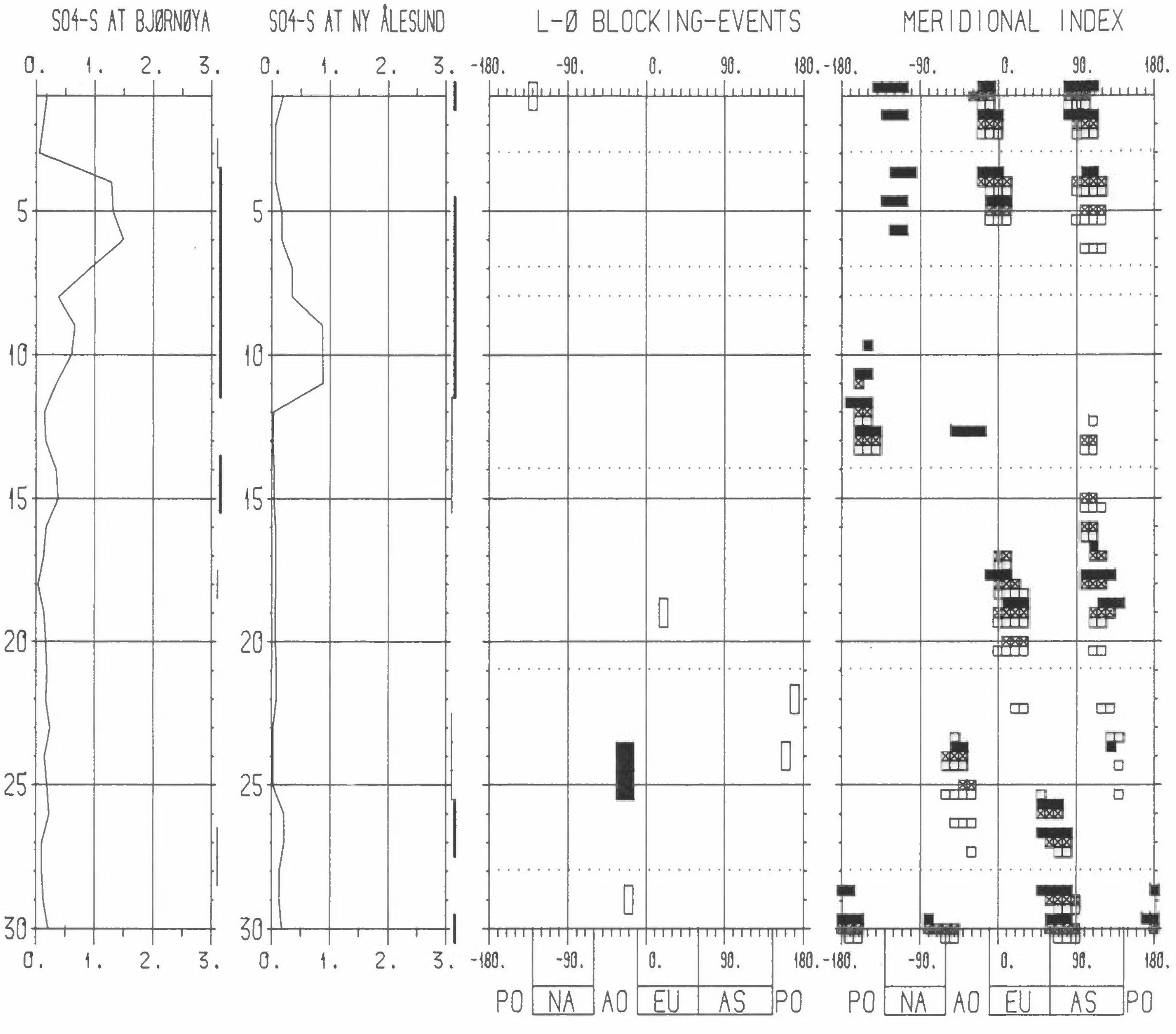

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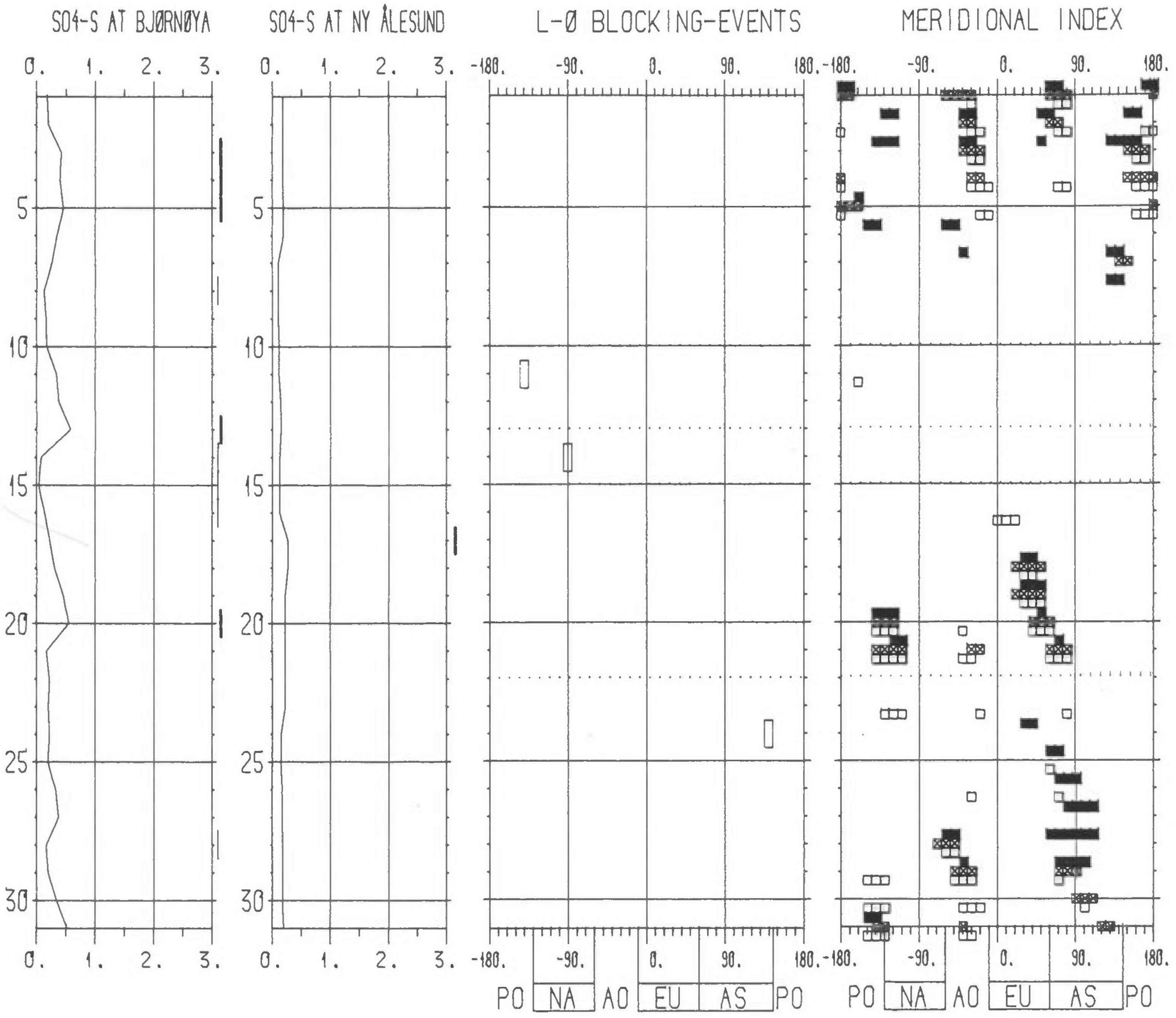
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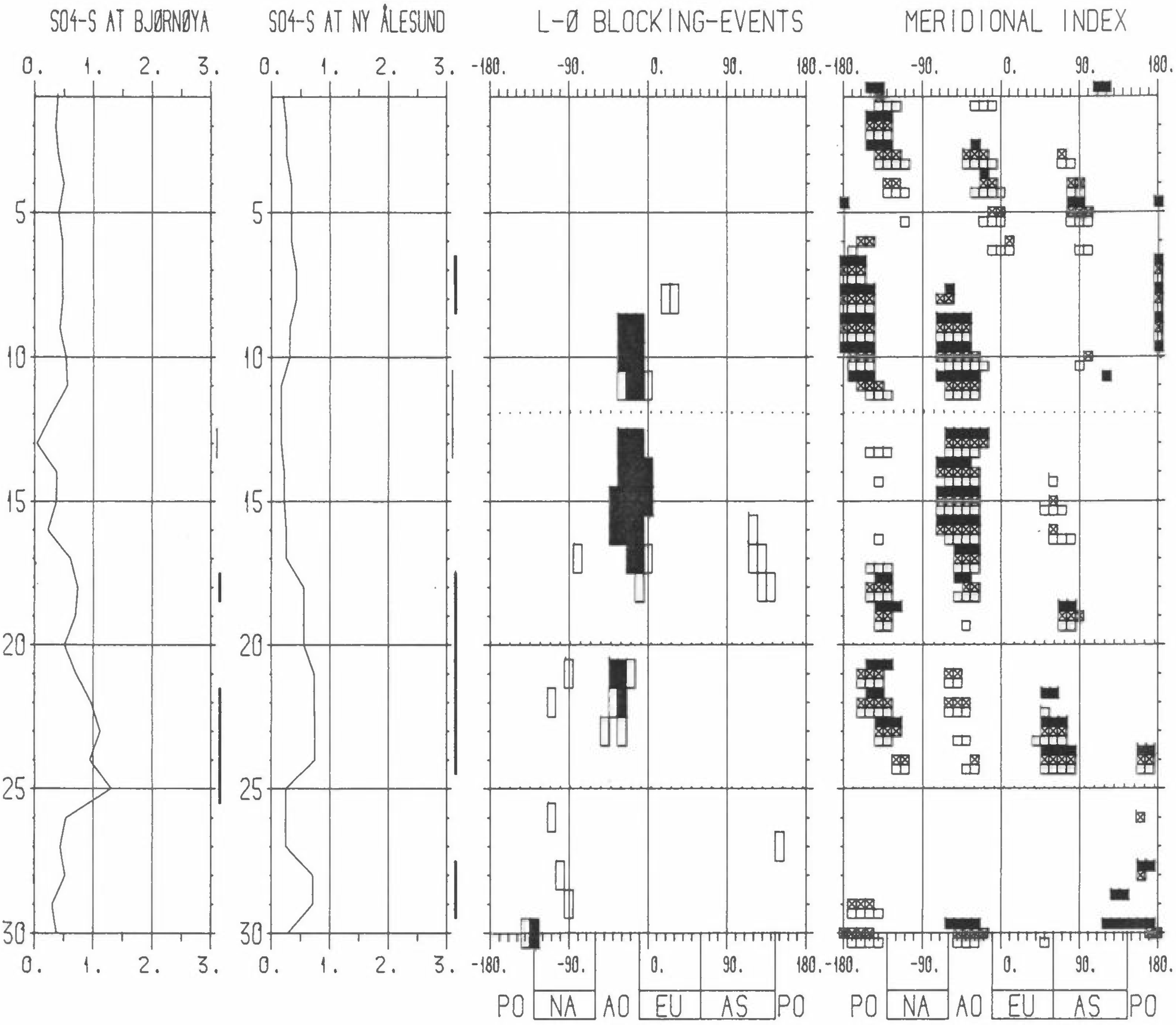

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SO4-S AT NY ÅLESUND

L-Ø BLOCKING-EVENTS

MERIDIONAL INDEX

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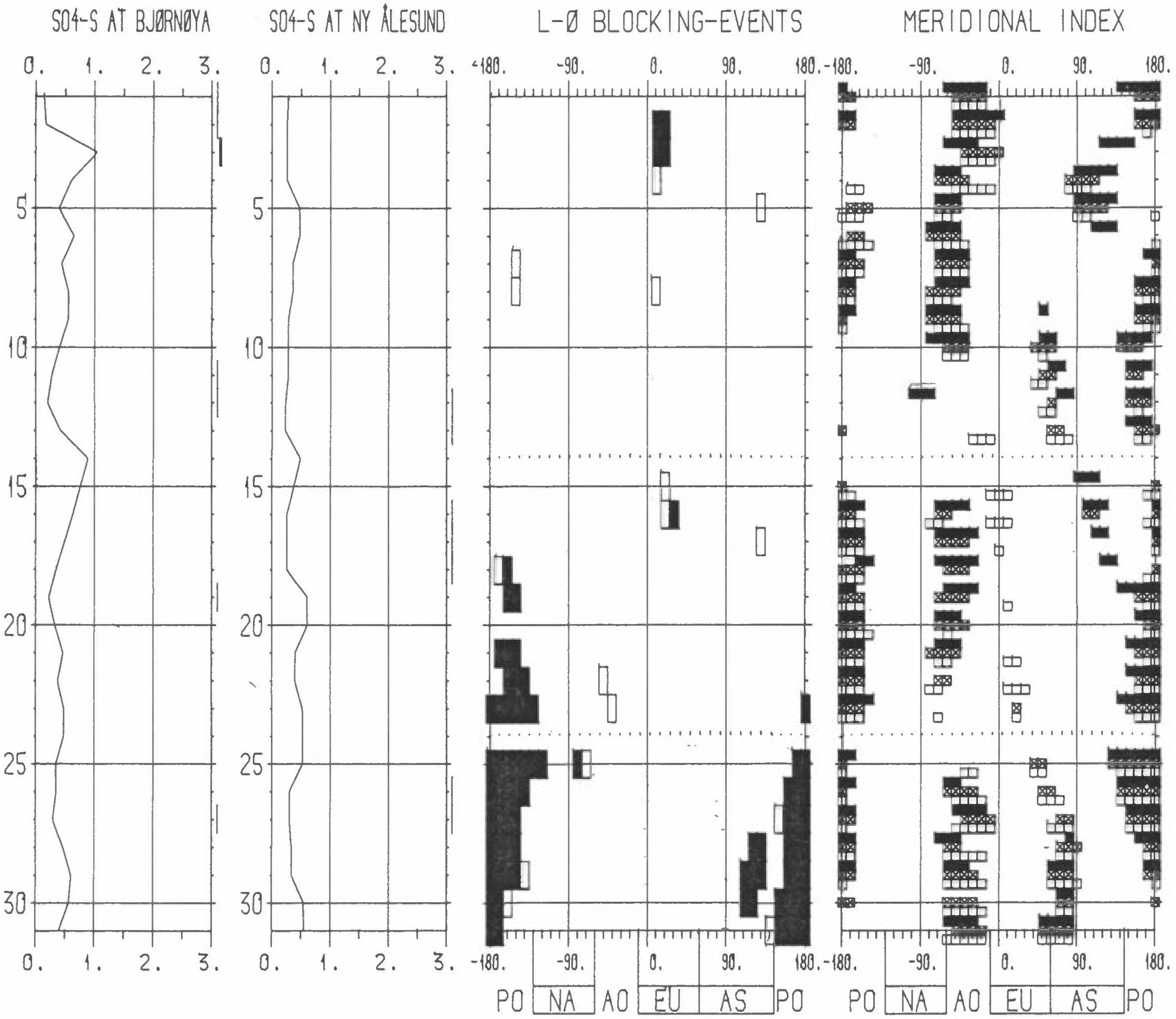
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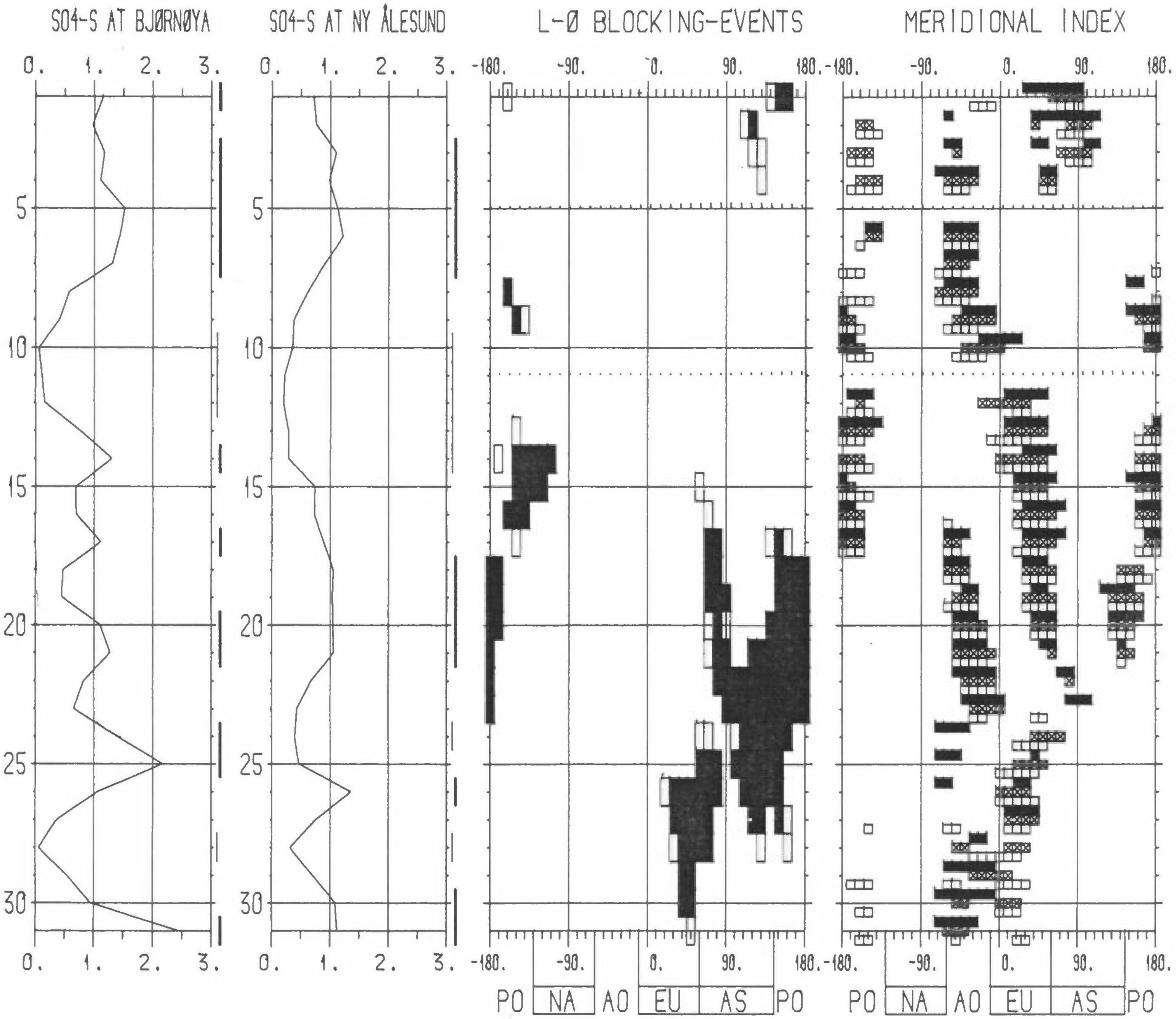
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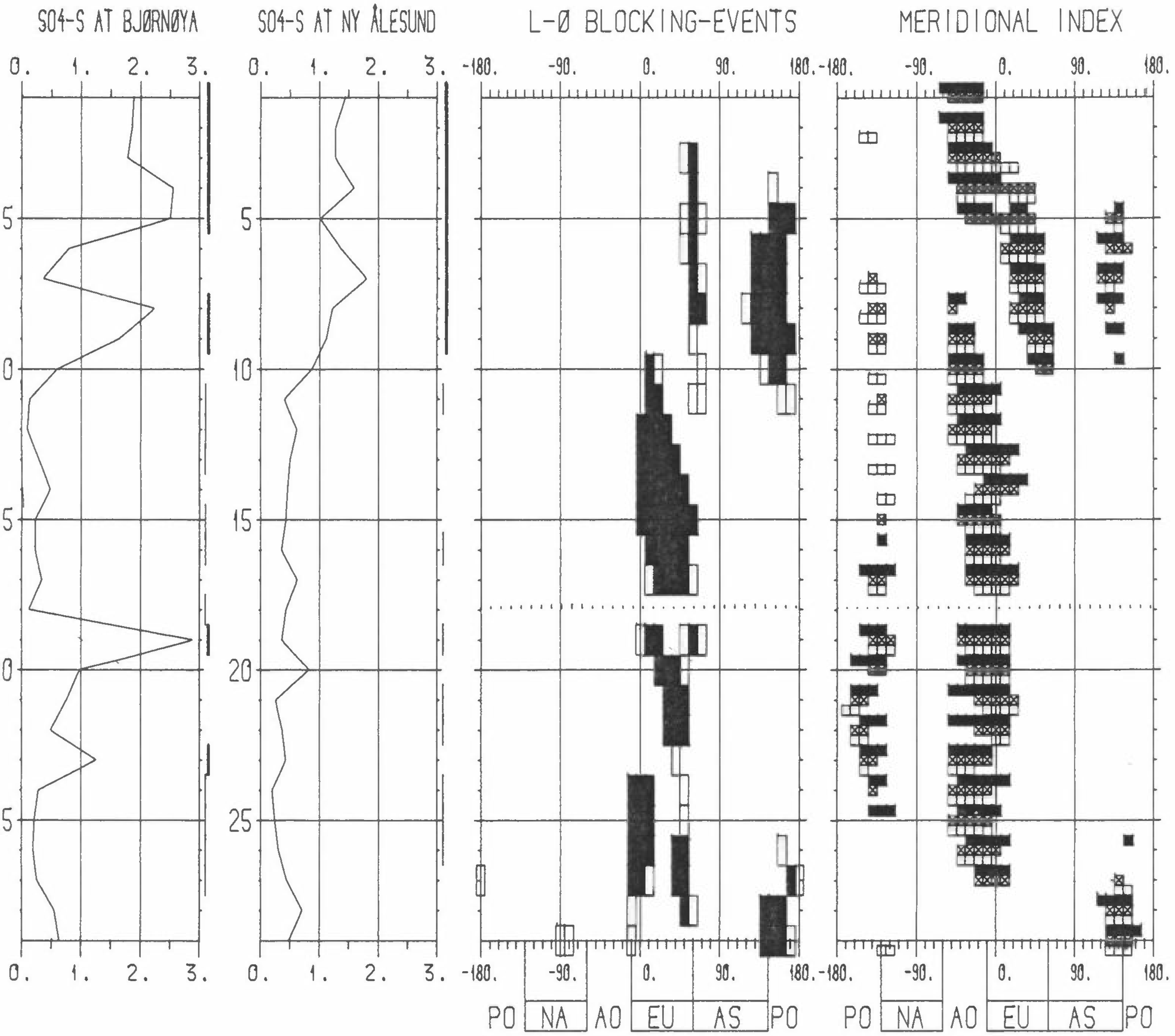
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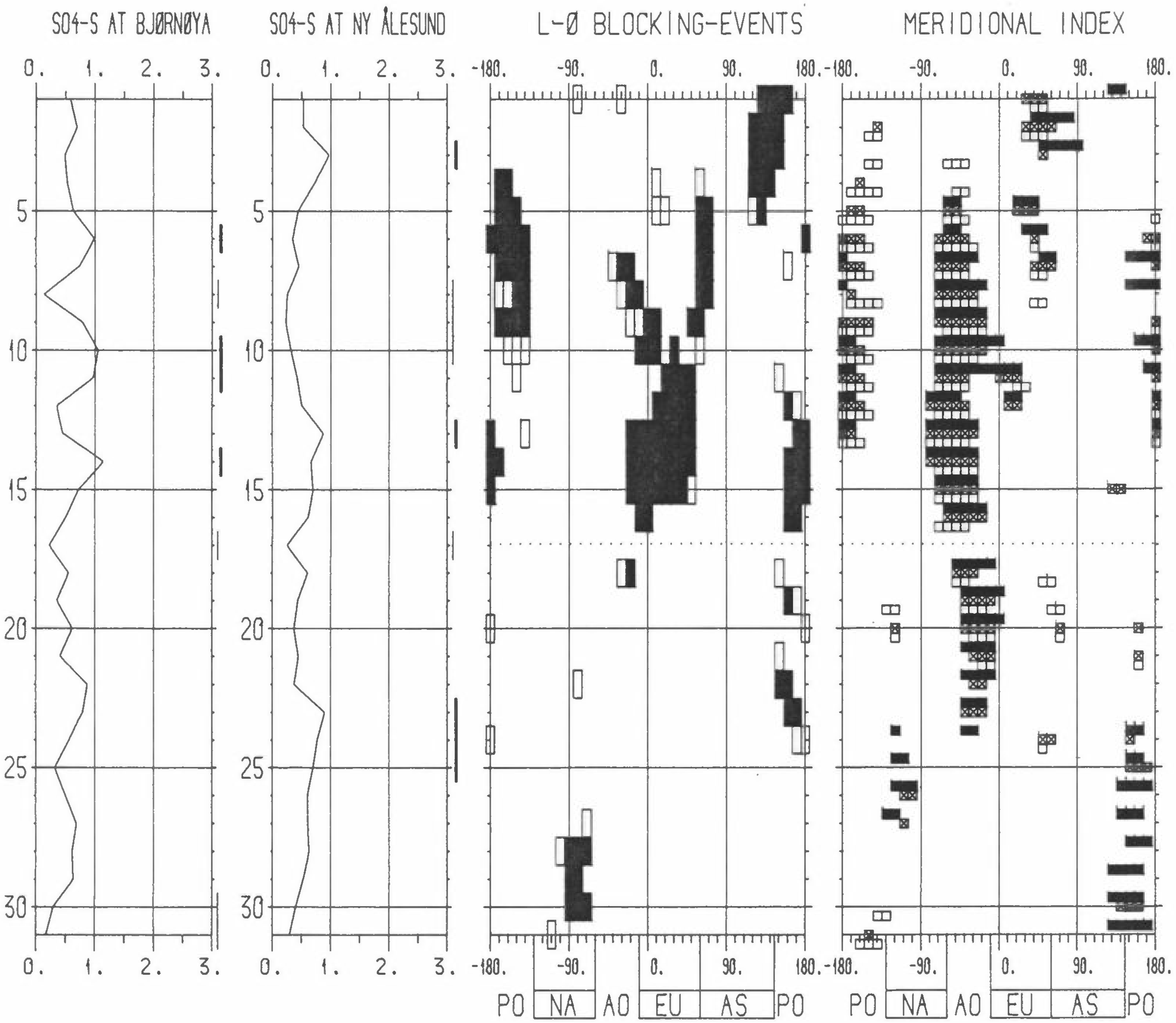
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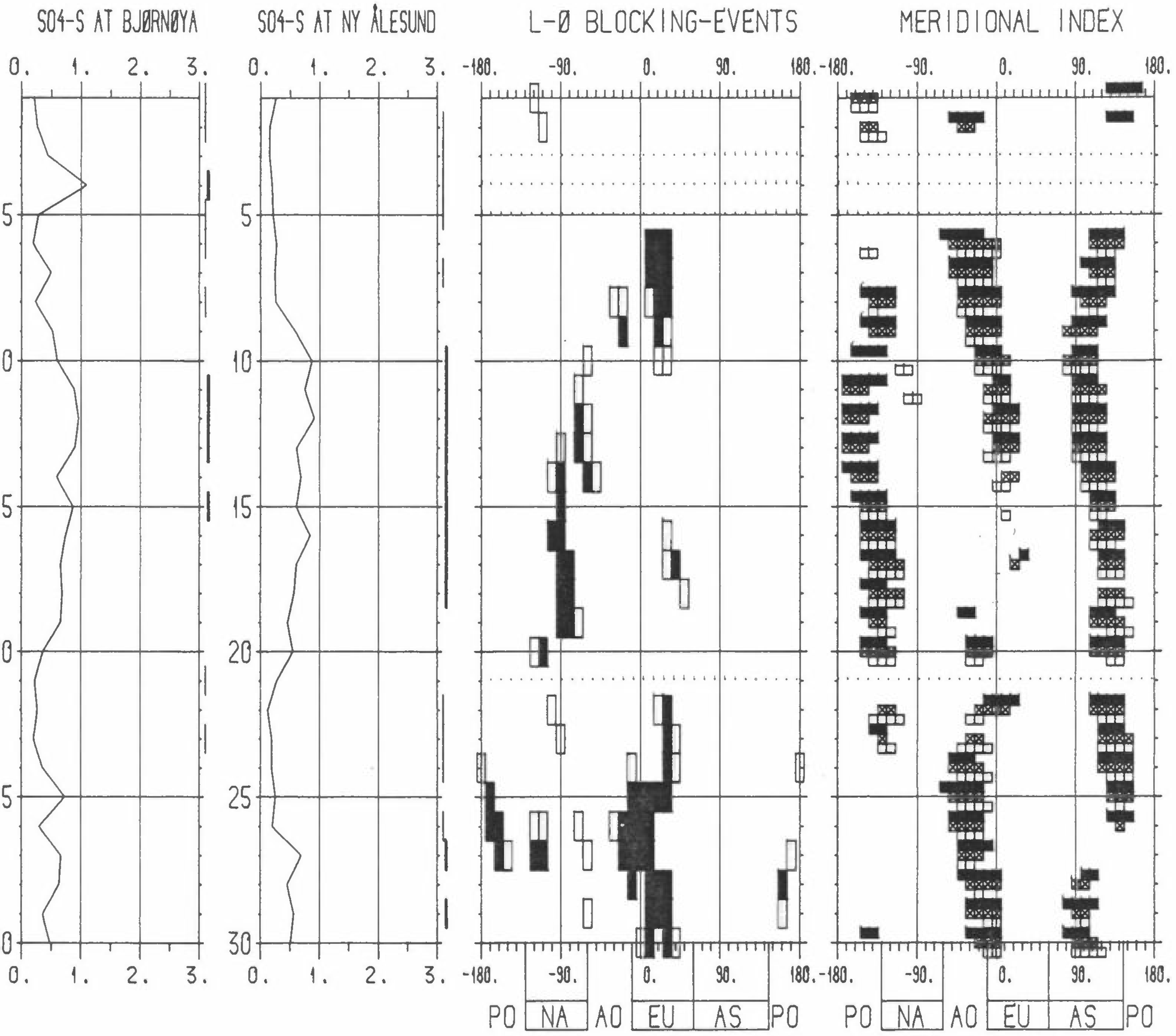
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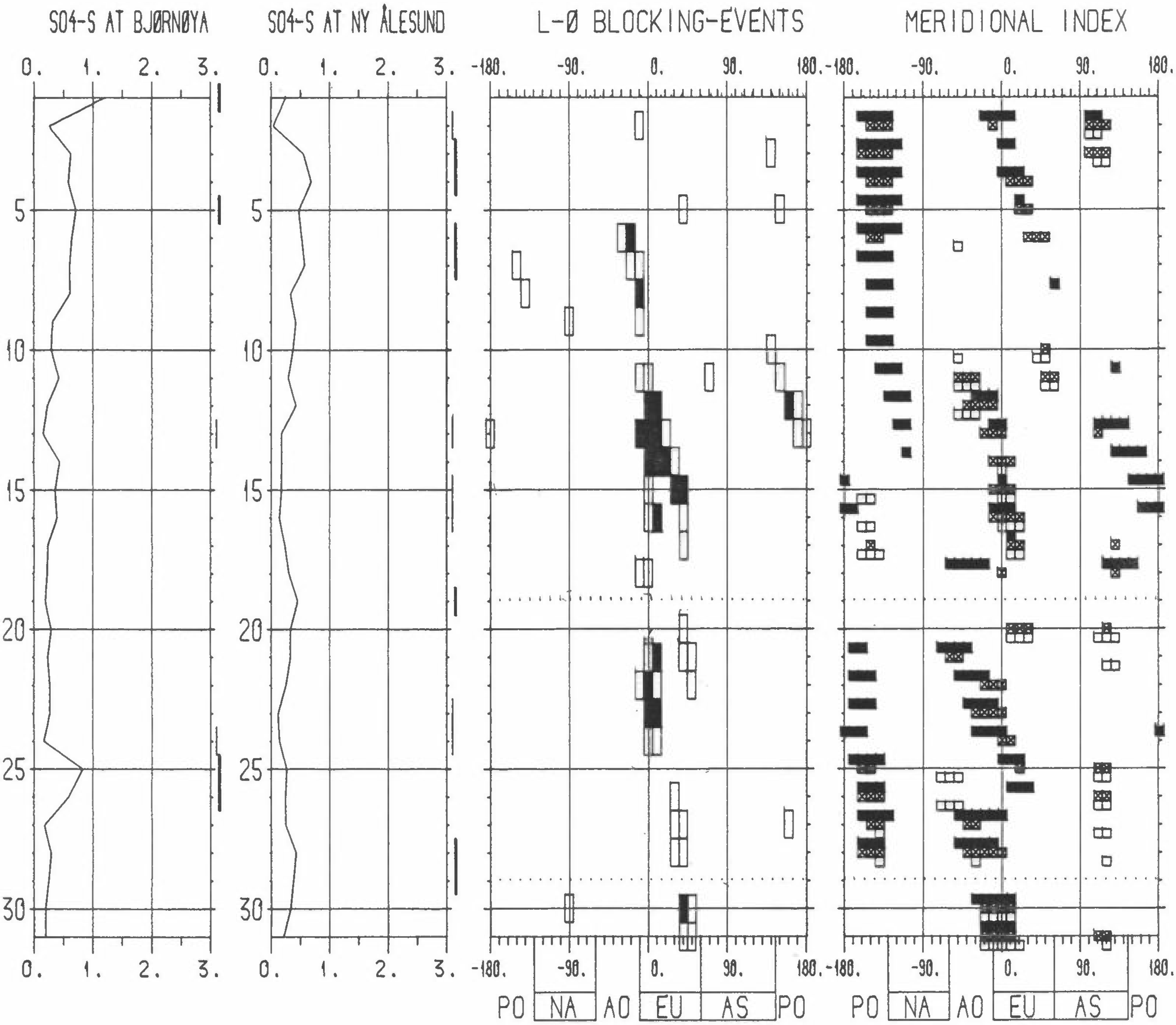
APRIL 84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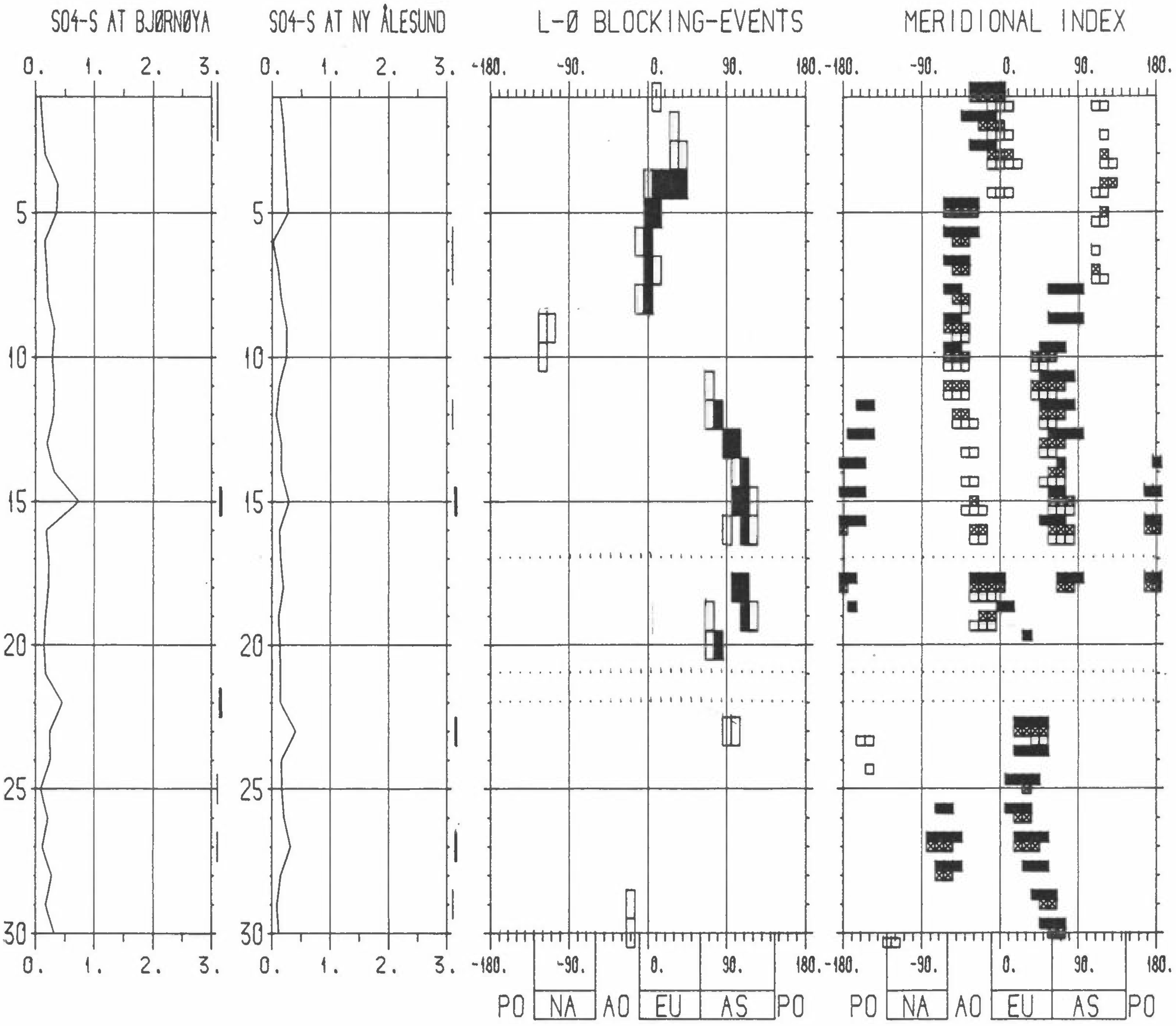
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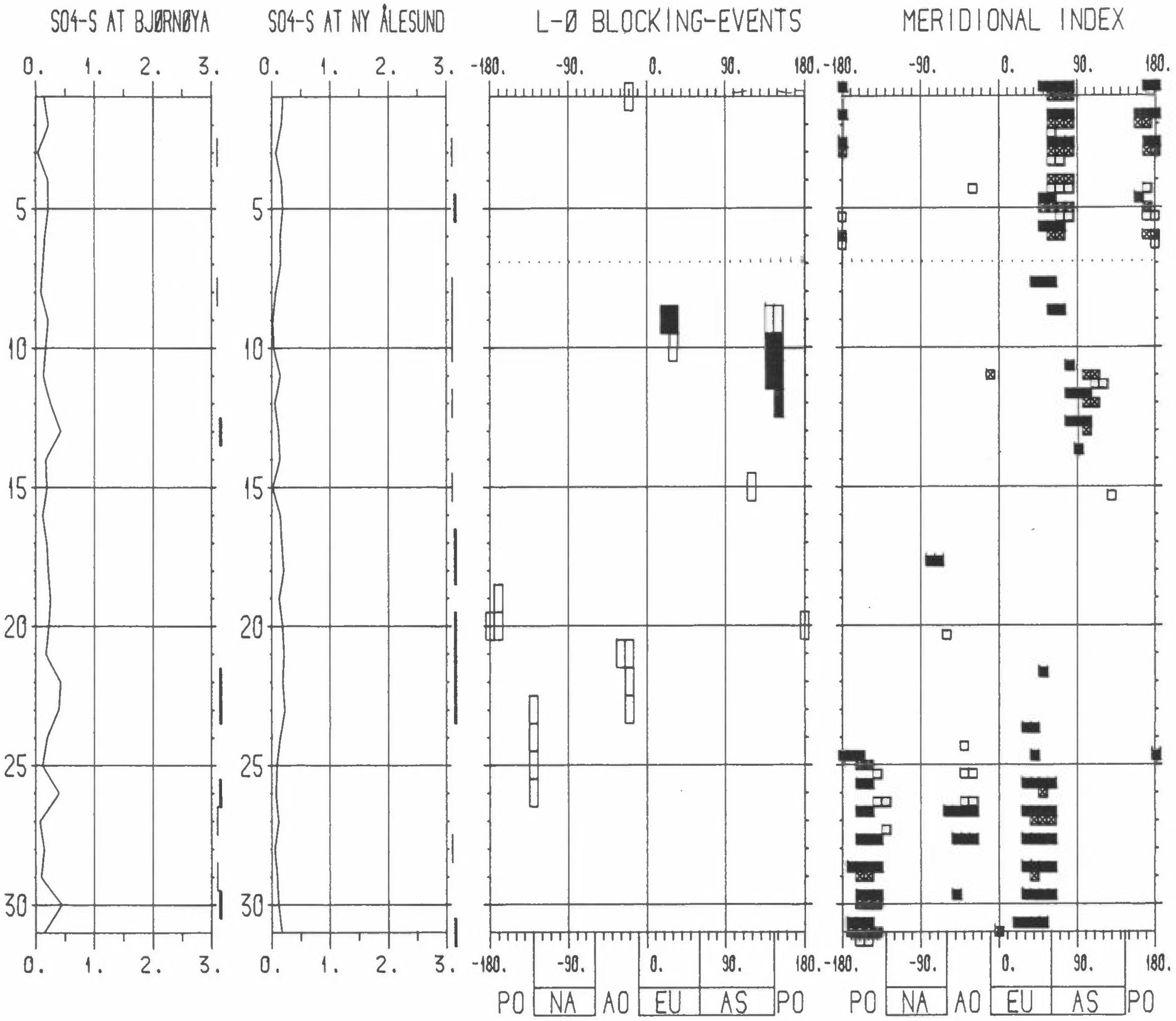
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JULY 84

NORSK INSTITUTT FOR LUFTFORSKNING (NILU)
NORWEGIAN INSTITUTE FOR AIR RESEARCH

(NORGES TEKNISK-NATURVITENSKAPELIGE FORSKNINGSRÅD)

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TITTEL

On air pollution transport to the Norwegian Arctic.

PROSJEKTLEDER
T. Iversen

NILU PROSJEKT NR.
O-8514

FORFATTER(E)

Trond Iversen

TILGJENGELIGHET*
A

OPPDRAGSGIVERS REF.

OPPDRAGSGIVER (NAVN OG ADRESSE)

British Petroleum Ltd.

3 STIKKORD (à maks. 20 anslag)

Arctic Haze	Time series	Planetary waves

REFERAT (maks. 300 anslag, 7 linjer)

TITLE On air pollution transport to the Norwegian Arctic

ABSTRACT (max. 300 characters, 7 lines)
Ground level measurements of sulphate made at Ny Ålesund and Bjørnøya during the period 1979-08-24 through 1984-08-31, has been analysed and used to identify episodes of polluted and clean air in the Norwegian Arctic. By objective criteria, it is shown that large-scale, quasi-stationary atmospheric flow systems, determining the basic conditions for long range transport from mid- to polar-latitudes.

*Kategorier:	Åpen - kan bestilles fra NILU	A
	Må bestilles gjennom oppdragsgiver	B
	Kan ikke utleveres	C