STUDIES ON THE ACOUSTIC PROPERTIES OF COASTAL WATERS OF KERALA IN RELATION TO HYDROGRAPHY

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IN
PHYSICAL OCEANOGRAPHY

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CERTIFICATE

This is to certify that this thesis is an authentic record of research work carried out by Ms. A. Geetha Bhasker M.Sc., under my supervision and guidance in the Physical Oceanography and Meteorology Division, School of Marine Sciences in partial fulfillment of the requirements of Ph.D. Degree of the Cochin University of Science and Technology and no part of it has previously formed the basis for the award of any degree in any University.

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CHAPTER I

INTRODUCTION

1.1 General Introduction.

Ph.D thesis under the same title was submitted for adjudication to the Cochin University of Science and Technology in 1991. The thesis is revised in the light of the observations made by the examiners and the present volume comprises the revised version being submitted in 1994. The whole text has been elaborately revised incorporating detailed discussions emanating out of more analyses carried out subsequently. The various suggestions made by the examiners have been kept in mind while preparing this revised thesis. The different questions raised by the examiners are discussed in detail at the respective portions of the ensuing chapters.

Of all forms of radiation known to man, sound, a form of mechanical energy, travels the best through the turbid, saline sea. Because of its relative ease of propagation, under water sound has been applied by man to a variety of purposes including the exploration of the sea.

Underwater sound, as a specialised branch of Science and Technology had been used in the two world wars. Although it has deep roots in the past, underwater sound, as a quantitative subject, may be said to be only a quarter of a century old. Its modern era began with the precise quantitative studies undertaken with great vigour during the days of World War-II. In subsequent years, there has been considerable progress in ocean acoustic research, particularly in the western countries, because of its immense importance in such activities as mineral and oil exploration, marine surveys, fish finding, navigation, underwater communication, telemetry, etc. Much of the research now deals with the more complicated propagation picture that emerges when more realistic conditions are allowed. Attempts are directed to understand the effects of physical ocean processes and the boundaries on sound transmission. Numerical and analytical methods of modelling acoustic propagation are also receiving considerable attention. In the vast literature available on the subject, Indian contribution has been meager.

The coastal waters of Kerala present unique hydrographical features which would require detailed investigations on their sound propagation characteristics. The sea surrounding the peninsular India are subjected to spectacular variations in hydrography in response to the changing seasons. The climate in this region is controlled by the two monsoons. The southwest monsoon breaks over Kerala usually during the first week of June and continues till early September. During this period, the wind blows roughly from the south-west and cloudy conditions and frequent rains are experienced. During December and January, the general wind blow in from the worth-easterly direction and there are occasional thunderstorms. During February the weather is fine and March, April and May are the months when summer conditions are experienced in this area. October and November form a transition period between the two monsoons. The coastal hydrography shows striking variations in response to the changing seasons.

Another remarkable phenomena encountered in these coastal waters in association with the south-west monsoon, is the occurrence of upwelling. Under its influence, the coastal waters experience sudden lowering of temperature, decrease in dissolved oxygen content and increase in nutrients. The upwelling is associated with increase in productivity which accounts for the high yield of fishery.

These hydrographic processes and variations influence the characteristic of the coastal waters as an acoustic propagation medium. The influence of hydrographic parameters on the propagation of sound in sea have been discussed by many authors (Matthews, 1934; Kuwahara, 1939). The velocity of sound in the sea increases with temperature, salinity and depth. In the open ocean temperature and pressure are the dominant parameters for the determination of sound velocity. In the coastal waters, however, salinity also may play a major part. Present thesis aims to bring out the nature of variability in the acoustical propagation characteristics of the coastal waters of Kerala and its relation to some important ocean processes.

1.2 THE STATE OF THE ART

1.2.1 Methods of Sound Velocity measurement

The velocity of sound in the sea is an oceanographic parameter that determines many of the peculiarities of sound transmission in the medium. It varies with depth, the seasons, geographic locations and with time at a fixed location.

The sound velocity is a function of oceanographic parameters such as temperature, salinity and pressure. A relationship between sound velocity and these parameters can be established either theoretically or experimentally. Tables of sound velocity were prepared long ago using theoretical methods by Heck and Service (1924), Mathews (1934) and Kuwahara (1939), the last mentioned serving as standard table for nearly 20 years. By the experimental method, tables of sound velocity were prepared by different authors like Weissler and Del Grosso (1951), Del Grosso (1952) and Wilson (1960), the last receiving general acceptance till recent times. The empirical formula of Chen and Millero (1977) has now superseded Wilson's formula because the former is more accurate (UNESCO, 1983). Direct measurement of the velocity of sound is accomplished by a device called the velocimeter, first developed by Greenspan and Tschiegg (1957). It measures sound velocity directly in terms of the travel time of sound over a constant fixed path.

1.2.2 Sound Velocity profile

The velocity profile in deep water can be generally divided into three layers. Just below the sea surface is the surface layer in which the velocity of sound is susceptible to daily changes in heating, cooling and wind action. The surface layer may contain a mixed layer of isothermal water in which sound tends to be trapped or channeled and sound velocity increases as depth increases in the layer. Below the surface layer is the thermocline, where the temperature and hence sound velocity decrease rapidly. Underlying the thermocline and extending to the sea bottom is the deep isothermal layer having nearly constant temperature. In this layer sound velocity increases with depth due to the effect of pressure. Between the negative velocity gradient of the thermocline and positive gradient of the deep isothermal layer there is a velocity minimum towards which sound tends to be bend or focused by refraction.

In the shallow waters of coastal regions and on the continental shelves, the velocity profile tends to be irregular and unpredictable and is greatly influenced by surface heating and cooling, changes in salinity and water currents. The shallow water profile is complicated by the effect of salinity variations caused by nearby sources of fresh water and contains numerous layers of different sound velocity gradients which have little temporal or spatial stability.

1.2.3 Wave theory and Ray theory

The propagation of sound in an elastic medium can be described mathematically by solutions of the wave equation using the appropriate boundary and medium conditions for a particular problem. The wave equation is a partial differential equation relating the acoustic pressure P to the co-ordinates x,y,z and the time t, and may be written as

$$\frac{\partial^2 P}{\partial t^2} = C^2\left(\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} + \frac{\partial^2 P}{\partial z^2}\right)$$

where C is a quantity that has the general significance of sound velocity and may vary with the co-ordinates. There are two theoretical approaches to solve the wave equation. One is called the ray theory, and the body of results and conclusions therefrom is called ray acoustics. The essence of ray theory is the postulate of wave fronts, along which the phase or time function of the solution is constant and the existence of rays that describe where the sound emanating from the source is being sent to. Like its analogy in optics, ray acoustics has considerable intuitive appeal and presents a picture of the propagation in the form of the ray diagram. Ray theory has certain shortcomings. It does not provide a good solution under conditions where the radius of curvature of the rays or the pressure amplitude changes appreciably over the distance of one wave length. Practically speaking, ray theory is restricted to high frequencies or short wavelengths.

The other form of solution of the equation is normal mode theory, in which the propagation is described in terms of characteristic functions called normal modes, each of which is a solution of the wave equation. The normal modes are combined additively to satisfy the boundary and source conditions of interest. The result is a complicated mathematical function which, though adequate for computations on a digital computer, gives little insight, compared to ray theory, on the distribution of the energy of the source in space and time. However, normal mode theory is particularly suited for a description of sound propagation in shallow water. Eventhough normal mode theory can give a complete solution of the wave equation applicable to all conditions of frequency and sound speed gradient, unless simplifying assumptions are made, full solutions of the wave equation including the effects of surface and bottom boundaries, as well as range dependent variation in the sound speed profile are difficult to obtain numerically or anlytically. One such simplifying assumption is WKB approximation applicable to a stratified medium, where the sound velocity varies slowly in the vertical. The solution in this case will be in terms of normal modes. Yet another is the parabolic approximation applicable to a stratified medium where the sound velocity varies slowly in the horizontal also (Tappert, 1977). The condition that the propagation path should remain close to thee horizontal is a disadvantage of the latter approximation (Spindel, 1985).

There have been several attempts to modify ray theory (Bucker, 1971; Cornyn, 1973; Weinberg and Zabalgogeazcoa, 1977) and normal mode theory (Kanabis, 1972; William, 1981) to accommodate range dependent characteristics of the medium with varied success.

1.2.4. Attenuation

Attenuation of sound in sea water is due to spherical spreading, absorption in the medium and scattering by irregular boundaries, suspended particles, thermal microcells and regions of turbulence. Absorption can be expressed in terms of an absorption coefficient defined as

$$k = (10 \log I_1 - 10 \log I_2)/r$$

where I_1 and I_2 are intensities at the source and the receiver separated by a distance r.

The surface as well as the bottom of the sea are both a reflector and a scatterer of sound. The degree of scattering depends on the roughness of the surface. A criterion for the roughness is given by Rayleigh's parameter defined as

$$R = kH \operatorname{Sin} \theta$$

where k is the wave number, H is the rms wave height and θ is the grazing angle.

Extensive measurement of bottom roughness were made in order to characterise scattering regimes (Mackenzie, 1960; Clay, 1966; Hampton, 1974), and models were developed to characterise acoustic scattering from the time varying surface of the sea (Eckart, 1953; Fortuin, 1970). Also there have been several studies on the attenuation characteristics of the boundaries in a shallow water environment (Kuperman and Ingenito, 1977; Louis, 1980; Beebe et al, 1982; Mitchel and Facko, 1983). But theoretical estimation of the attenuation constant requires a detailed knowledge of the medium. Hence the attenuation constant in a region is usually determined by fitting the solution of wave equation to experimental data (Clay and Medwin, 1977).

1.2.5 Other areas of active research

The other areas of active research in underwater acoustics include the acoustic effects of oceanic eddies (Vastano and Owens, 1973; Weinberg and Clark, 1980; Henrick et al, 1980) and fronts (Speindel and Spiesberger, 1981) and the inverse technique to obtain information on bottom parameters (Schwetlick, 1983; Bleistein and Cohen, 1979) and on the mesoscale variations in the ocean (Munk and Wunsch, 1979; Cornuelle, 1983).

1.3 LITERATURE SURVEY

Except for studies carried out in Defence Laboratories, which are of classified nature and pertain to specific objectives, studies on the acoustic characteristics of the seas around the Indian sub-continent particularly coastal waters, have been few in number. There were some studies on the sound velocity structure of certain areas of the Indian Ocean. Fenner and Bucca (1972) studied the sound velocity structure of the northwest Indian Ocean by analysing the historical temperature - salinity data north of 10°S latitude and west of 80°E longitude. He found that the cause of the complex and irregular sound velocity structure and extremely broad primary sound channel found throughout the Northwest Indian Ocean was due to the intensive mixing between the water masses.

Seshagiri Rao and Sundaranan (1974) studied sound velocity structure in the upper 500m of the Arabian sea during September to December by analysis of the data for the Arabian sea along certain meridional and zonal sections. They found negative velocity gradient in the shallow thermocline, the occasional positive gradients in the surface layer and perturbations in the sound velocity structure in the surface layers especially in the northern sections. Methods for plotting sound ray paths in the potential layers obtained from bathy thermograms have been discussed by Rao (1977). The vertical distribution of temperature influences the sound propagation, particularly in bending the rays from straight line paths. The changes in temperature structure contribute to the formation of several layers with different temperature gradients and plotting of sound ray paths for these bathythermograms becomes difficult. He found a method which reduces the layers in potential layer to a maximum of 3 layers. The small scale features of sound velocity structure in the northern Arabian Sea during February - May (1974) were studied by Somayajulu et al (1980). They have found that the relatively warm and saline Persian Gulf water which intrude into the Arabian sea at 200-400m influence the sound velocity structure and cause formation of an upper sound channel.

Microstructure of sound velocity in the upper 500m of Northern Arabian Sea based on STD data has also been presented by them. The intra-annual variability of the acoustic characteristics of Cochin has been studied by Geetha Bhasker et al (1988). They found sharp negative sound velocity gradients in the surface layers up to 20m depth and almost negligible gradients in the deeper layers during monsoon and post-monsoon seasons suggesting very small horizontal detection ranges in the surface layers and long ranges below 20m. The positive and slightly negative sound velocity gradients found during winter and summer respectively indicate the possibility of comparatively larger range of detection during these seasons, the former season being more favourable. Ramamurthy et al (1990) detailed methods to compute geometric path, travel time and intensity of sound rays and their variability in the Bay of Bengal utilising sound speed data derived from CTD profiles. The results indicated the independent nature of the rays for a given source receiver pair.

The present study comprises of an attempt to elucidate the long range propagation characteristics in shallow waters. There have been various investigations of similar nature in various parts of the world. Kuperman and Ingenito (1977) studied the attenuation of the coherent component of sound propagating in shallow water with rough boundaries. Normal mode theory was used in conjunction with a perturbation method. Numerical results were presented for sample shallow water environment with depth dependent sound speed profiles and loosy bottom sediments. Graves et al (1978) used the adiabatic range variation method to perform an approximate separation into normal modes of the wave equation to study underwater sound propagation in stratified ocean channel and obtained a solution for the isovelocity ocean wedge with rigid ocean floor.

The upslope propagation characteristics in a wedge shaped ocean by the method of normal mode was also studied by Coppens and Sanders (1978). Jensen and Kuperman (1979) presented an environmental acoustic model with an emphasis on application to coastal waters. They presented simulation studies of propagation over a sloping bottom, seismic propagation and the spatial distribution of surface generated noise. Jensen and Kuperman (1980) studied model cut off during upslope propagation in a wedge shaped ocean using the parabolic equation method. The studies showed that there was very little conversion of energy to the next lower mode and that the propagation in a wedge must include coupling into the continuum. Jensen (1981) studied the sound propagation in shallow water with a detailed description of the acoustic field close to surface and bottom. He compared the data with normal mode prediction for an isovelocity shallow water propagation channel overlying a complicated layered bottom. Excellent agreement was obtained over the range 50-3200Hz for range up to 30km. Beebe Mc Daniel and Rubano (1982) carried out the shallow water transmission loss prediction using the Biot sediment model. Experimental data and predicted propagation loss from the shallow sediments are compared for frequencies from 25 to 800 Hz. Good agreement was obtained between measured 1/3 octave transmission loss values and predicted values for frequencies of 25, 80 and 250Hz.

Propagation of acoustic signals in the sea is influenced by the physical properties of sea water viz. temperature, salinity and pressure. The results of investigations on the acoustic properties of the coastal waters of Kerala are presented in this thesis. The hydrographical features of the coastal waters of Kerala have been studied by various authors. Ramasastry (1959) investigated the distribution of sea water characteristics in the upper layers of the south eastern Arabia Sea and found that though the seasonal variations below 20m are not very prominent, processes like upwelling and local variations are very important. During upwelling the surface water gets completely replaced by the subsurface waters. Consequently very low temperature and high salinities are encountered at all levels. Ramasastry and Myrland (1959) investigated the distribution of temperature, salinity and density along the south Malabar Coast during the post monsoon season. The hydrographical features of the continental shelf waters of Cochin were studied by Ramamritham and Jayaraman (1960) and Patil et al (1964). They found that under the influence of the prevailing current system the influx of freshwater extends as a tongue of low salinity water for considerable distance from the coast. Hydrography of the surface waters of Kerala has also been studied by Darbyshire (1967). She found a sharp thermocline associated with the Arabian Sea water, which occurs immediately below the surface during summer and sinks a depth of about 100m in winter. Sharma (1968) also investigated the seasonal variations of hydrographic properties along west coast. The UNDP/FAO report (1973) described the monthly and seasonal hydrographic conditions along various sections off Kerala coast. While analysing the physical characteristics of water off the west coast of India during late spring, Varadachari et al (1974) observed a tongue of high salinity water (>36%) extending from the off shore region towards the coast during late spring. Purushan and Rao (1974) Gopinathan (1974) and Murty and Vishunudatta (1976) also observed vertical movement of isolines in association with upwelling which commences in February along the south west coast of India. In his M.Sc dissertation submitted to the Cochin University, Nandakumar (1983) carried out a study of the hydrological features of the shelf waters along the west coast of India with an attempt to explain their influence upon the living resources of region. He has analyzed the distribution of temperature, salinity and dissolved oxygen along various sections of the Kerala coast during 1972-73 utilising UNDP/FAO data. His studies brought out the influence of upwelling on the hydrographic conditions and fishery in the coastal waters of Kerala. Satish (1984) studied the seasonal variability of the temperature field off the south-west coast of India. He found that though weak during November-March, the monthly mean longshore component of the wind stress is always conducive to coastal upwelling and follows a pattern similar to that of the isotherm tilt. Murthy (1985) analysed the variations in temperature and salinity in relation to upwelling and sinking utilising the UNDP/FAO report data. Hareesh Kumar (1987) presented diurnal scale variability in vertical thermal structure of coastal waters off south west coast of India during May 1985. Heating and cooling cycles observed in the surface layer are qualitatively discussed in terms of surface heat exchange processes.

In addition to the hydrographic parameters, the characteristics of the bottom also influence the propagation of sound in shallow water through absorption, reflection etc. The distribution and characteristics of the sediments along the Kerala coast have been discussed by various authors. Kurian (1967) has identified the four zones of bottom deposits in the shelf off Kerala coast. A detailed investigation on the topography of sediments of the western and eastern continental shelves around Cape Comorin has been presented by Hashimi et al (1981). The region between Cochin and Quilon was found to be topographically smooth with sediments characterised by a high percentage of fine grained sediments.

1.4 Scheme of the present work

Results of investigations on the inter-annual and intra - annual variability of acoustic propagation characteristics of the coastal waters of Kerala in relation to hydrography and distribution and characteristics of bottom sediments are presented in this thesis.

The thesis is presented in five chapters including the introductory chapter. Chapter-2 discusses the relevant details of data used for the study, the processing method adopted and the method used for the computation of sound velocity in water. The theoretical details of the computational aspects used for the study of long range propagation characteristics are also presented in this chapter. The results of the investigation on the inter-annual and intra-annual variations of temperature, salinity and sound velocity in the coastal waters of Kerala are discussed in Chapter-3. A discussion on the variability of high frequency propagation characteristics in the region is presented in Chapter-4. Chapter-5 presents the methodology used for the computation of transmission loss in a wedge-shaped ocean.. It also discusses the results of the investigation on the long range propagation characteristics of the coastal waters of Kerala. A summary of the thesis and conclusions drawn from the present study are presented in Chapter-6.

CHAPTER II

DATA AND MATHEMATICAL FORMULATIONS

The primary purpose of this thesis is to investigate the fundamental acoustic property of the coastal water of Kerala to elucidate its capabilities and limitations as a medium for transmitting sound waves. Sound propagation in the sea is subjected to various phenomena such as divergence, absorption, reflection, refraction, scattering, diffraction etc. Velocity of sound in sea water is a function of temperature, salinity and changes in pressure associated with changes in depth. The spatial and temporal variations of acoustic characteristics of an oceanic area can thus be studies on the basis of the information on temperature and salinity variations in the region. The data used and the methodology adopted for the above purpose are presented in this chapter.

2.1 Data

The area of study is the coastal water of Kerala within the approximate limit of 50m isobath. The data on temperature and salinity along three sections westward of Quilon, Cochin and Kasargode, collected during 1972 and 1973 by the research vessels "Varuna", "Sardinella" and "Rastrelliger" of the erstwhile Pelagic Fishery Project have been obtained from Central Marine Fisheries Research Institute, Cochin. The location map of the sections is give in fig.1. The date of occupation on the different sections are shown in table 1. The distance between stations is nearly 10 nautical miles in all sections which extend to about 30 nautical miles from the shore. The basic requirement of hydrographic data to carry out a study on acoustic properties

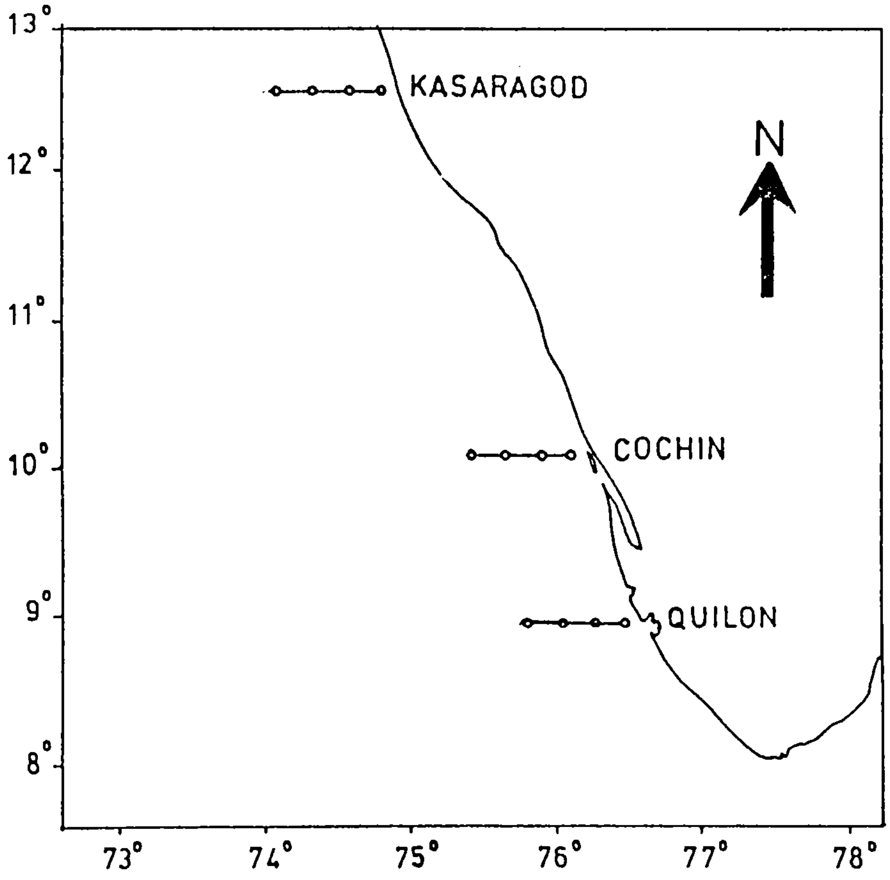

Fig. 1. Station position for the sections off Kasargode, Cochin and Quilon in 1972 and 1973.

TABLE-1: Dates of occupation of the different sections from March 1972 to November 1973.

	1 9 7 2												1 9 7 3											
	J	F	M	A	M	J	Jy	A	S	O	N	D	J	F	M	A	M	J	Jy	A	S	O	N	D
Quilon	-	-	16	27	21	-	11	-	19	-	28	-	16	-	14	17	-	4	-	19	-	16	-	-
Cochin	-	-	15	17	19	-	12	-	18	23	27	-	29	-	26	-	31	-	2	-	-	29	26	-
Kasargode	-	-	21	19	-	27	--	30	24	-	-	3	-	11	30	-	15	21	--	3	1	-	1	-

is repeated observations along fixed sections at regular intervals of time. Data fulfilling this requirement are scanty. The ship and manpower requirements to collect the required data are enormous and beyond the realm of the present work. Hence archive data are the sole possible alternative.

The analysis have now been extended to include one more deeper section in all the sections. The results emanating from the present investigations can in no ways be improved by extending the sections further into deeper waters, for the larger number of modes in deeper water will only decrease the energy contained in the first mode.

Use of archive data for hydrographic studies is widely practised in oceanography. Individual investigators cannot collect his or her own data on seasonally and spatially varying parameters in the sea because of reasons indicated above. Newer data add on to existing data archives to be utilised by later investigations. Usefulness of a set of data collected by an investigator does not terminate with a single application.

In view of what has been said above, the use of the data for a specific purpose, not applied earlier, is justified. The present investigations relate to acoustic properties of the water body. Nandakumar (1983) carried out investigations on the hydrological features of this region with an attempt to explain their influence on the living resources.

In all, coastal hydrographic data of 152 stations were utilised in the present study. The temperature and salinity data have been collected using Nansen reversing bottles equipped with two protected thermometers. Temperature data have been recorded from both main and auxiliary thermometers and corrections have been incorporated using correction charts provided with the thermometers. The salinity value have been determined using a salinometer which has been calibrated using the titration method.

The data were processed by drawing curves for each station for temperature versus depth and salinity versus depth. The guiding principle has been to use all the data and achieve consistency in data. After preliminary drawing of all curves, the graph of each station was superposed on the graphs of the two adjacent stations and the curves were adjusted to give as much continuity from stations as was permitted by the observed points. Comparison was also made with curves of the stations that were obtained on the previous and subsequent dates. Thus outliers were eliminated. The final values of temperature and salinity were tabulated which were subsequently used to draw vertical sections and also to compute sound velocity.

2.2 Computation of Sound Velocity.

The sound velocity is computed using the formula developed by Chen and Millero (1977). This formula is more accurate than the one given by Wilson (1960) (UNESCO, 1983). The formula and the function subprogram used for the computation (UNESCO, 1983) of sound velocity are given in Appendix-1. The computed values are used for drawing the vertical sound velocity sections presented in Chapter.3, the vertical sound velocity profiles presented in chapter 4 and also in the computation of long range acoustic propagation characteristics discussed in chapter 5.

2.3 Mathematical formulation for the study of long range acoustic propagation characteristics

2.3.1. Introduction.

The following symbols are used in the present discussion

θ_c	the critical angle
C_{bw}	the sound velocity in water at bottom
C_b	the sound velocity in sediment
C_z	the velocity of sound at depth z
C_0	the sound velocity at source depth
r	range
h	water depth
λ	wave length
$R(r)$	range dependent function
$Z(z)$	mode amplitude function
k	propagation constant
K	horizontal component of propagation constant
k_b	propagation constant in sediment
γ	vertical component of propagation constant
ω	freqency
ω_0	experimental frequency
m	mode number
$Z_{m(z)}$	amplitude function of mode m
ρ_{bw}	density of water at bottom
ρ_b	density of sediment
ρ_0	density at source depth
W	source power

In acoustic propagation, trapped waves and waveguide phenomena are encountered at long ranges. The related mathematical formulations which are rather lengthy are presented in an abridged form in this section. Waves are completely trapped when the reflection coefficients at the upper and lower boundaries have magnitudes close to unity. The reflection coefficient at the ocean surface has a magnitude of unity because it is a pressure release surface. At the ocean bottom, the reflection coefficients will have a magnitude of unity when the angle of incidence is greater the critical angle which is given by

$$\sin \theta_c = \frac{c_{bw}}{c_b} \qquad (1)$$

A criterion for long range given by Weston (1963) is

$$r > \frac{h^2}{\lambda}$$

At long ranges, it is convenient to use solution of the wave equation and boundary conditions to calculate the sound pressure by the normal mode theory. The following discussion is broadly based on Clay and Medwin (1977) and Tolstoy and Clay (1966).

2.3.2. Mathematical formulations.

The classic problem of sound transmission in a layered waveguide consists of solving the cylindrical wave equation, which can be separated into a range-dependent and a depth-dependent equation by separation of variables, viz.,

$$\frac{\partial^2 R(r)}{\partial r^2} + \frac{1}{r}\frac{\partial R(r)}{\partial r} = -K^2 R(r) \qquad (2)$$

$$\frac{\partial^2 Z(z)}{\partial z^2} = \gamma^2 Z(z) \qquad (3)$$

and

$$K^2 + r^2 = k^2 \ . \qquad (4)$$

$$k^2 = \frac{w^2}{c^2} \qquad (5)$$

Since eq. 2 and R (r) are only functions of the range r, the horizontal component of wave number, K is constant throughout the water column in a layered waveguide since C(z) is a function of Z only. Since K is constant, R (r) which is the solution of cylindrical wave equation is the same for all depths, at long range. But eq.3 shows that γ will depend on Z if C is a function of Z. This ordinary, second order partial differential equation, together will appropriate boundary conditions posess an eigen value problem with solution Zm (z) only for a discrete set of γ_m values. The solution requires the assumption that the condition for WKB approximation is satisfied. The solution then will be the characteristic equation for the wave guide.

In the case when the stratification in slightly irregular, that is, the sound velocity varies slowly as a function of distance and the depth is not constant, wave equation can be solved with the additional assumption that the radiation within any particualr mode remains in the mode (Tolstoy and Clay, 1966) and that there are no reflection or appreciable scattering of energy from one mode to another in transition region. Jensen and Kuperman (1980) have experimentally showed that the intermodel transfer or leakage of energy is negligible. So the value of source excitation function can be calculated as

$$\overline{q}_m = \sqrt{q_m(\text{source}) \; q_m(\text{receiver})} \qquad (6)$$

where
$$q_m = 2\pi \frac{(\rho_0 C_0 W)^{1/2}}{\gamma_m \sqrt{K_m}}$$
$$\gamma_m = \int_0^h \bar{\rho}\, Z_m^2(z)\, dz$$

2.3.3. Calculation of the horizontal and vertical components of propogation constants.

From the characteristic equation, the frequency is obtained as

$$\omega = \bar{C}\, \frac{\left[(m - 1/2)\pi + \phi_L\right]}{h \cos \theta_m} \qquad (7)$$

where
$$\phi_L = \tan^{-1} \frac{a_1 \rho_{bw} C_{bw}}{\rho_b C_b \cos \theta_m}$$
$$a_1 = \left[\frac{C_b}{C_{bw}} \sin^2 \theta_m - 1\right]^{1/2}$$

θ_m is obtained by graphical interpolation. Once the value of θ_m is obtained for each mode the horizontal component of propagation constant, K_m at the bottom is obtained from

$$K_m(h) = \frac{\omega_0}{C_{bw}} \sin^2 \theta_m \qquad (8)$$

This will be constant throughout the water column at the station, but will be different at other stations if the stratification or depth varies with range. Now $\gamma_m(h)$ is obtained from

$$\gamma_m(h) = \frac{\omega_0 \cos \theta_m}{C_{bw}} \qquad (9)$$

and
$$\gamma_m^2 = k_m^2 - K_m^2$$
$$= \frac{\omega_0^2}{C^2(z)} - \frac{\omega_0^2}{C_{bw}^2} \sin^2 \theta_m \qquad (10)$$

Assuming that the profile of sound velocity is composed of segment having the form

$$C_{(z)} = \left(\frac{1}{C_{bw}^{2}} - gz\right)^{-1/2}.$$

$$\text{where} \quad g = \frac{2\Delta C}{d\,C_{bw}^{3}}$$

and substituting in equation (10) we get (Tolstoy and Clay, 1966).

$$\gamma_m^{2}(z) = \gamma_m^{2}(h) - g\,\omega_0^{2} Z \qquad (11)$$

Using this expression γm(z) and eigen value at any depth can be computed. If propagation of acoustic energy in a single mode only is considered, the RMS acoustic pressure is given by

$$P = \frac{\rho\,\overline{q_1}}{\sqrt{r}}\, Z_m(z_0)\, Z_m(z) \qquad (12)$$

where q_1 is obtained from eqn. (6). The rms pressure of a unit power source (1 watt) at a distance of 1m is

$$P_0 = \left(\frac{\rho_0 C_0}{4\pi}\right)^{1/2}$$

The source level is

SL=20 log Po/Pr dB reference Pr

If Pr is taken as 1 Pascal

SL=20 log Po dB.

The sound presume level at the receiver is

SPL = 20 log P/Pr dB, reference Pr

and if Pr is taken as 1 Pascal,

SPL = 20 log PdB

The transmission loss is given by

TL = SL-SPL (13).

Using eqn. (13) the tranmission loss can be computed for different souce depths.

CHAPTER III

TEMPORAL AND SPATIAL VARIABILITY OF SOUND VELOCITY IN THE COASTAL WATERS OF KERALA

3.1 Introduction

The influence of temperature salinity and depth on sound velocity has already been discussed in detail in the preceding chapter. In response to the changing monsoons, the coastal waters of Kerala exhibit considerable temporal and spatial variability in temperature and salinity. Under its influence, the sound velocity also exhibits large variations both in space and time. This chapter attempts to bring out the nature of variations in sound velocity and their dependence on hydrographic conditions in the coastal waters of Kerala. The parametric variability has been studied along the three sections, off Quilon, Cochin and Kasargode, during 1972 and 1973 on the basis of monthly distribution of the parameters.

3.2. MATERIAL AND METHODS

The data on temperature and salinity collected in different months during 1972-73 are used in this study. The details of the data have already been discussed in the previous chapter. The processing of temperature and salinity data has also detailed in the earlier chapter. Sound velocities are computed using the method discussed in section 2.3.

Vertical sections of temperature, salinity and sound velocity are drawn for different months during, both the years. They are presented as fig. 2 to 18.

3.3 RESULTS AND DISCUSSION

3.3.1 Spatial and Temporal variations of vertical profiles of sound velocity in relation to temperature and salinity.

Vertical profiles of sound velocity have been prepared for three sections namely Quilon, Cochin and Kasargode during different months of 1972 and 1973. 1972 has been a conspicuously drought year, while 1973 experienced normal rainfall. During March 1972, the maximum value of sound velocity at the surface is above 1542m/s off Quilon and Cochin while off Kasargode, very near the coast, values above 1544 m/s are observed (fig. 2). The overall vertical sound velocity gradient is negative in most of the regions with values around 0.06 m/s/m off Quilon and 0.01 m/s/m off Kasargode. Off Cochin, however local positive gradients are also observed with a value around 0.03 m/s/m.

During this month the overall vertical temperature gradient is negative (around 0.04°c/m off Quilon and Kasargode 0.04°c/m off Cochin). The isotherms show slight downward slope towards the coast indicating a weak sinking process. (Geetha Bhasker et al. 1988), comparatively low values of salinity (33.5 to 34.5) are observed in all the sections in the surface layers. However, salinity values above 35 are seen below 45m off Cochin and Kasargode. The positive gradient in sound velocity observed locally off Cochin irrespective of the negative temperature gradient may be attributed to the larger vertical variations in salinity which swamps the effect of the small negative temperature gradient. The effect of large vertical variation in salinity is clearly seen off Kasargode also where the negative sound veloci-

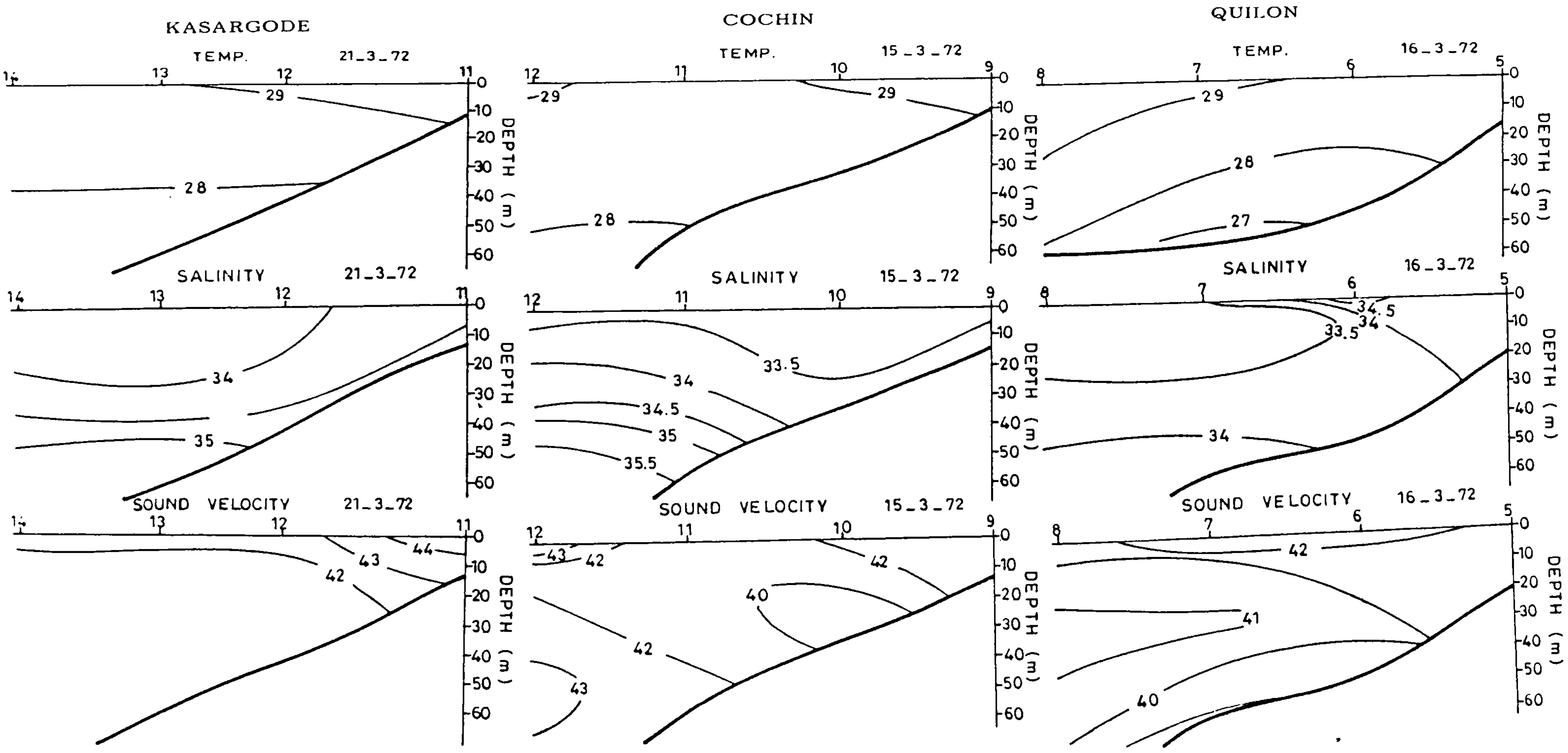

Fig.2 Vertical profiles of temperature (^{0}C), salinity (S.I. Units), sound velocity (values in m/s - 1500) during March 1972.

ty gradient is extremely small eventhough the negative temperature gradient is comparatively large.

It is interesting to note that the influence of the conspicuously drought conditions of 1972 is clearly indicated in the vertical profiles of 1973 as can be seen by comparing fig.2 (March 1972) and fig.3 (March 1973). During March 1973, the surface sound velocity increases to value above 1543 m/s off Quilon and to values above 1546 m/s in the other two sections in response to increasing temperatures. Both the temperature and salinity values are substantially larger in 1973 compared to 1972. Weak monsoon condition result in less evaporation and consequently less heat energy loss. Hence the heat energy stored in the ocean, normally in the mixed layer increases after a monsoon failure (George and Ramasastry, 1975). This increase in stored heat energy manifests itself as a temperature increase in the mixed layer. Thermal stratification is better in March 1972 compared to 1973 March, when well formed mixed layers are observed in all the three sections. Off Quilon the vertical sound velocity gradient is slightly positive, but it is negative off Cochin and Kasargode. Off Quilon the vertical temperature gradient is marginally negative up to about 20m depth and marginally positive below. Off Cochin and Kasargode, the temperature gradients are negative and of small magnitude. The isolines slope down towards the coast indicating coastal sinking.

During April 1972 (fig. 4) the overall vertical gradient of sound velocity is 0.1 m/s/m in the sections. The maximum value of sound velocity at the surface has increased from the March value to 1545 m/s. Summer heating increases the surface temperature to

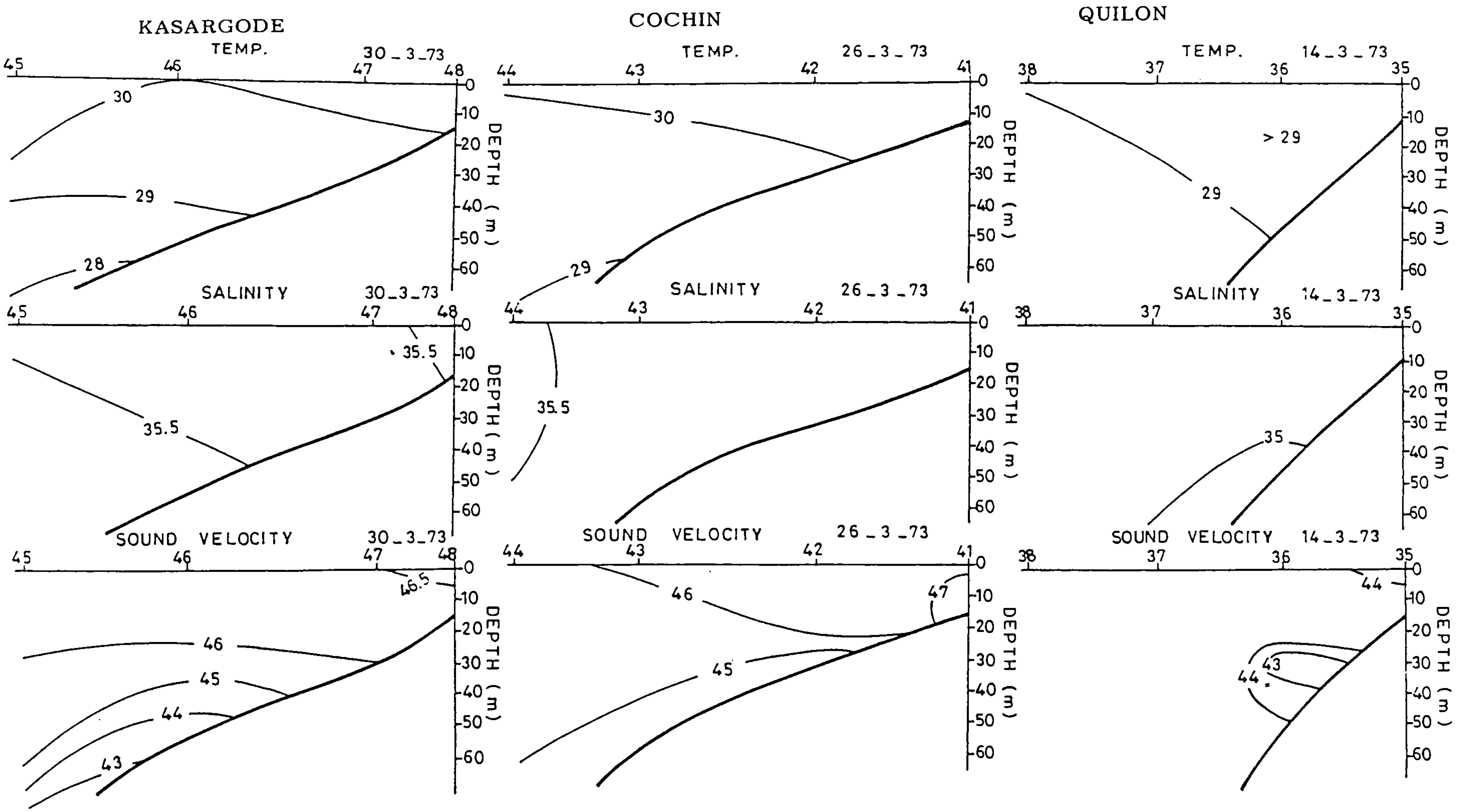

Fig. 3 Vertical profiles of temperature (^{o}C), salinity (S.I.Units), sound velocity (values in m/s-1500) during March 1973.

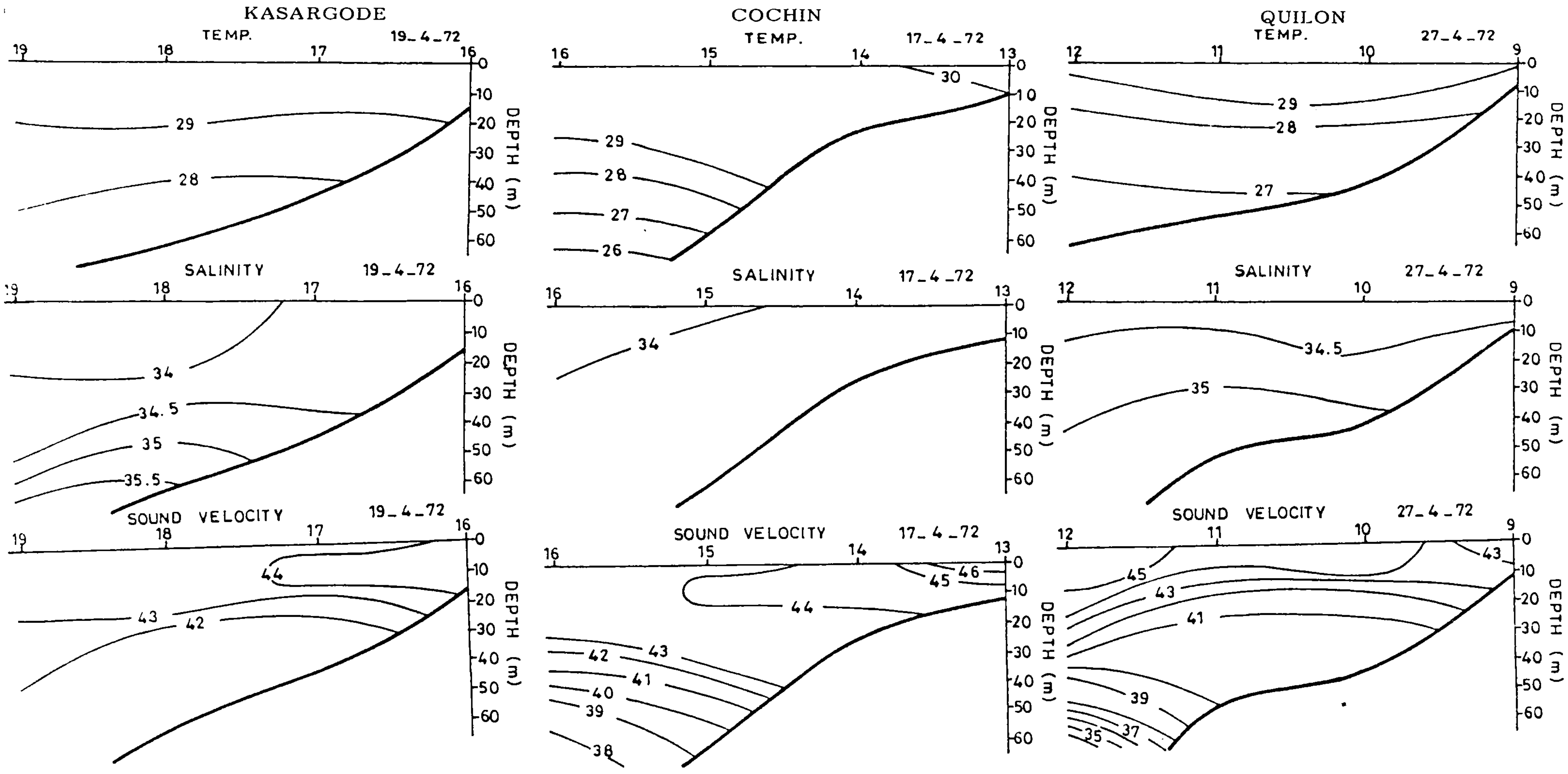

Fig. 4 Vertical profiles of temperature (^{o}C), salinity (S.I. Units), sound velocity (values in m/s-1500) during April 1972.

about 30° in the three sections with maximum vertical temperature gradient of about 0.05° c/m. There is a general increase in salinity compared to the previous month in the three sections, particularly off Quilon, probably due to the weak upwelling as indicated by the slight slope of the isolines up towards the coast (UNDP/FAO report, 1973). The salinity decreases away from the coast as a result of the diverging flow associated with upwelling.

Fig.5 depicts the vertical profiles of sound velocity temperature and salinity during April 1973 in the section off Quilon. It has not been possible to illustrate the profiles off Cochin and Kasargode due to paucity of data. Compared to the previous month, the surface sound velocity increases to a value above 1546 m/s as a result of the increase in surface temperature to values above 30°c. The sound velocity decreases with depth and the magnitude of gradient is around 0.09 m/s/m. The magnitude of temperature gradients is about 0.05°c/m. The salinity is nearly uniform but indicates marginal increase from the previour month. Both temperature and salinity values are higher compared to corresponding month in the previous year. The isoline slope up towards the coast indicating coastal upwelling.

Fig. 6 & 7. show the vertical profiles of sound velocity, salinity and temperature off Cochin and Quilon during May 1972 and 1973. Profiles of Kasargode have not been depicted due to paucity of data along this section. The sound velocity in the surface layers shows lower values compared to April 1972, in response to decrease in surface temperature and salinity. The maximum value of sound velocity in the surface is around 1543 m/s. Off Cochin, the surface sound velocity doesn't indicate

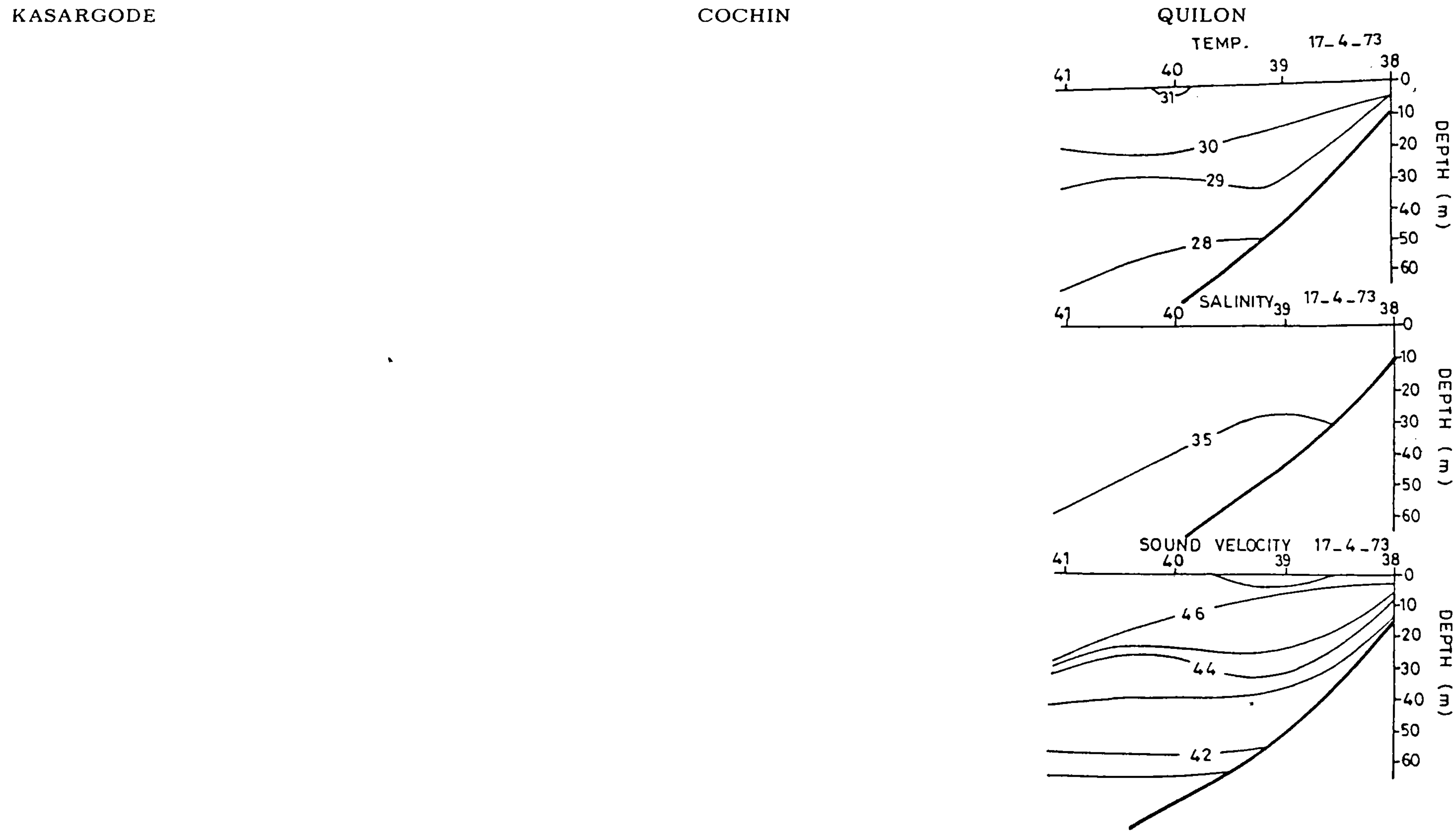

Fig.5 Vertical profiles of temperature (^{o}C), salinity (S.I.Units), sound velocity (values in m/s-1500) during April 1973.

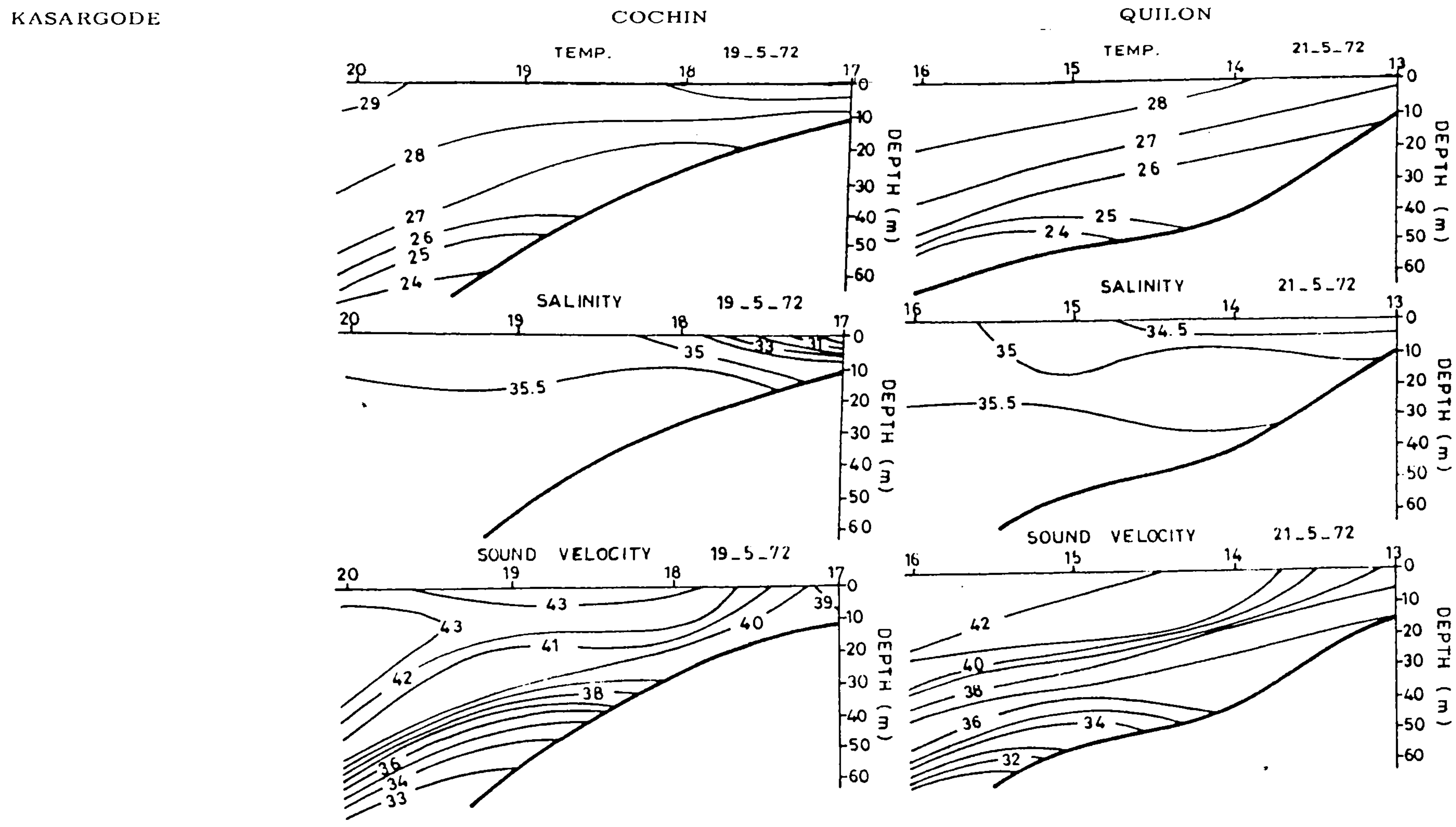

Fig. 6 Vertical profiles of temperature (^{0}C), salinity (S.I.Units), sound velocity (values in m/s-1500). during May 1972.

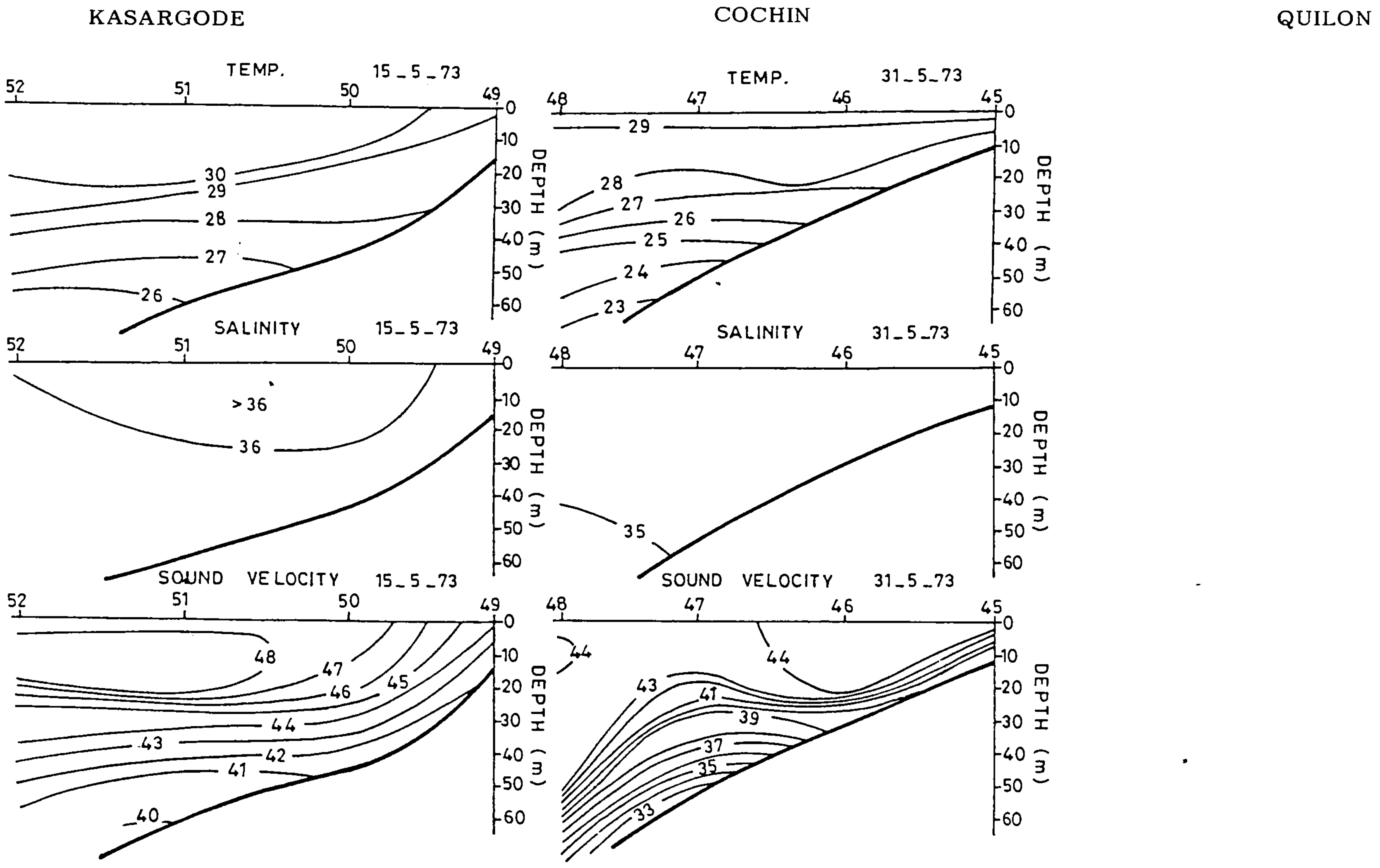

Fig.7 Vertical profiles of temperature (oC), salinity (S.I. Units), sound velocity (values in m/s-1500) during May 1973.

increase eventhough there is an increase in surface temperature. This can be attributed to the large reduction in the values of salinity in this region as a result of the large run off from land caused by the temporary onset of monsoon over Kerala on May 13, 1972 (George and Ramasastry, 1975). The sloping of the isotherms indicate comparatively stronger upwelling than during the preceding month. The upwelling causes the salinity in the area to increase to a value above 35 except very near the coast where the surface salinity is lowered due to run off from the land.

Off Quilon, the surface sound velocity decreases towards the coast as a result of large reduction in salinity in this region. Near the coast, off Cochin and Quilon, the maximum value of sound velocity at surface is less than 1539 m/s. The maximum overall sound velocity gradient off these stations is as high as 0.2 m/s/m consequent to increase in the overall vertical temperature gradient. However upwelling maintains large vertical gradients in temperature below about 10m off both Quilon and Cochin.

Owing to the rough sea conditions that exist during the monsoon season, data on hydrographic parameters are highly scarce during June, July and August. Off Kasargode, during June 1972 (fig.8) the sound velocity at the surface varies between 1534 m/s and 1543 m/s. The surface sound velocity shows conspicuous decrease towards the coast in association with the large shoreward decrease of surface salinity. Salinity is generally above 35, except very near the coast values less than 31 are observed, which may be due to mixing of run off from land. The overall vertical sound velocity gradient is about 0.15 m/s/m. The

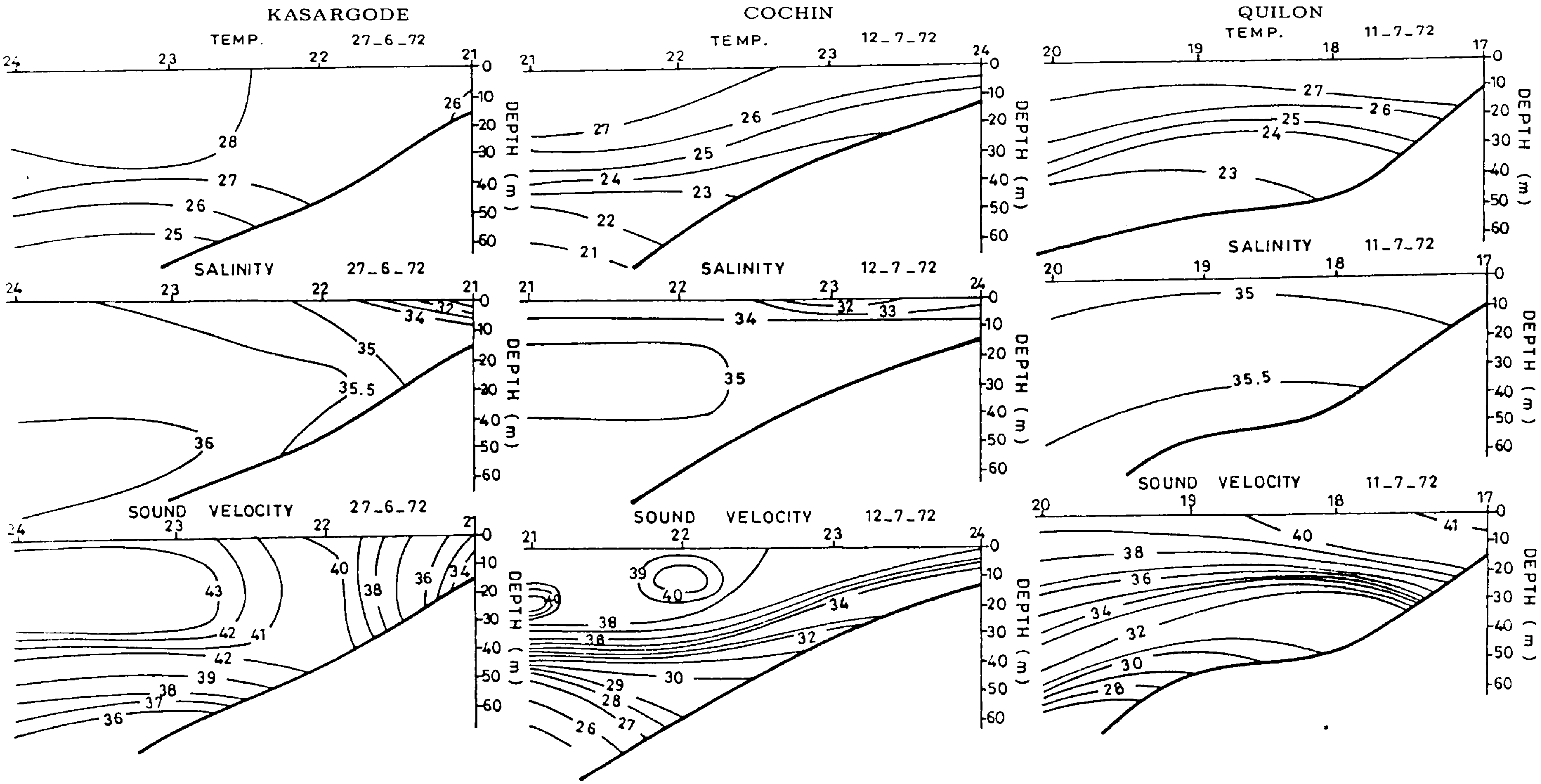

Fig. 8 Vertical profiles of temperature (^{o}C), salinity (S.I. Units), sound velocity (values in m/s-1500) during June and July 1972.

surface temperature near the coast is below 28°C and increases towards offshore. The entire water column up to about 40m depth shows isothermal conditions below which the temperature decreases rapidly.

It is interesting to note that the surface sound velocity during June 1973 (fig. 9) shows marked decrease compared to the previous months off Quilon and Kasargode the maximum being about 1544 m/s. The overall vertical temperature gradients show an increase in both the sections, the values being 0.09 °C/m and 0.14°C/m for the sections off Quilon and Kasargode respectively. The isotherms slope up towards the coast indicating coastal upwelling. Consequent to this increase in temperature gradient, sound velocity gradient also increases showing overall values of 0.16 m/s/m and 0.32 m/s/m off along these sections. Off Kasargode surface sound velocity shows decrease towards the shore in association with corresponding decrease in salinity.

Comparison with the June conditions in 1972 shows an increase in the surface sound velocity values during June 1973. There is a sharp increase in the sound velocity gradient compared to the corresponding month of the preceding year. The temperature values in the mixed layer are higher in 1973 than in 1972. The temperature gradients, however, are much sharper in 1973. The salinity values are generally higher in 1973. The hydrographic conditions clearly indicate influence of the monsoon failure during the preceding year and comparatively good monsoon conditions in 1973. (Abbi et al 1974).

Off Cochin, during July 1972, (fig.8) the maximum surface sound velocity is around 1539 m/s. Off Quilon, the maximum surface

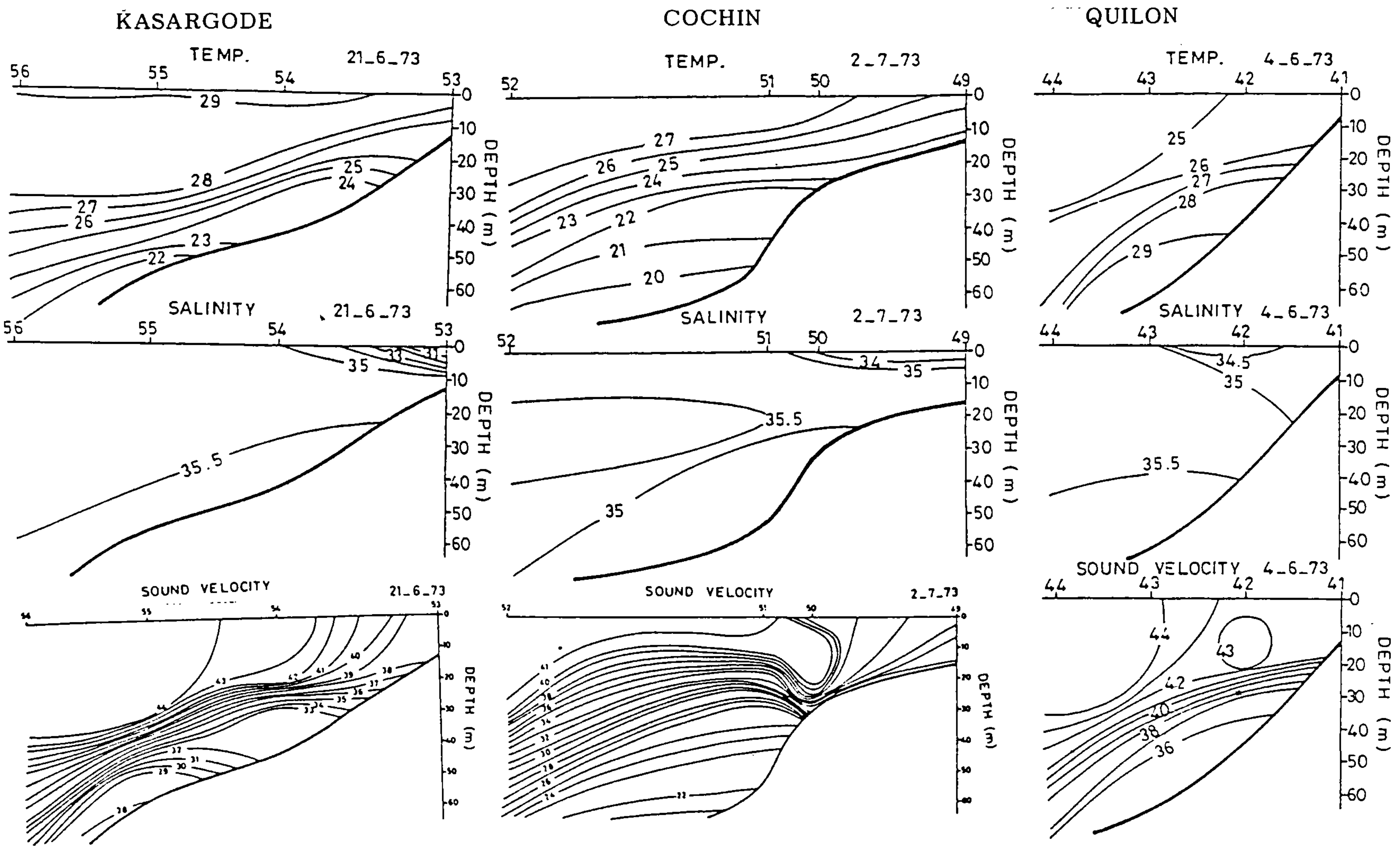

Fig. 9 Vertical profiles of temperature (^{o}C), salinity (S.I.Units), sound velocity (values in m/s - 1500) during June and July 1973.

sound velocity is found to have reduced to 1541 m/s, consequent to reduction in surface temperature. In both the sections, the overall sound velocity gradient is found to be 0.2 m/s/m. Larger values of gradients are observed only below 10m. The overall sound velocity gradient doesn't indicate any variation compared to May 1972.

Off Cochin during July 73 (Fig. 9) surface sound velocity shows decrease to about 1541 m/s in association with decrease in the surface temperature. Very near the coast surface sound velocity is as low as 1535 m/s. The overall vertical temperature gradient has increased to 0.17° c/m. The temperature gradient below the surface layer is much sharper compared to the May conditions as a result of the intense upwelling indicated by the upward tilt of the isotherms. Consequent to the increase in temperature gradient, the sound velocity gradient also increase to an overall value of 0.38 m/s/m. The salinity values decrease particularly in the surface layers as a result of the monsoon rainfall.

Comparison with the July conditions in 1972 shows that during 1973 the surface sound velocity is higher consequent to the higher temperature induced by the drought conditions of the previous year. The sound velocity gradient is however sharper during 1973 than the preceding year. The salinity values are also generally higher in 1973.

Fig. 10 shows the conditions that existed off Kasargode in August 1972. The value of sound velocity at the surface is generally less than 1540 m/s. The minimum value of sound velocity at the surface (less than 1538 m/s) is associated with the minimum salinity. The temperature gradient is very strong in the surface layer up to 30m. Here the velocline is also very sharp with a

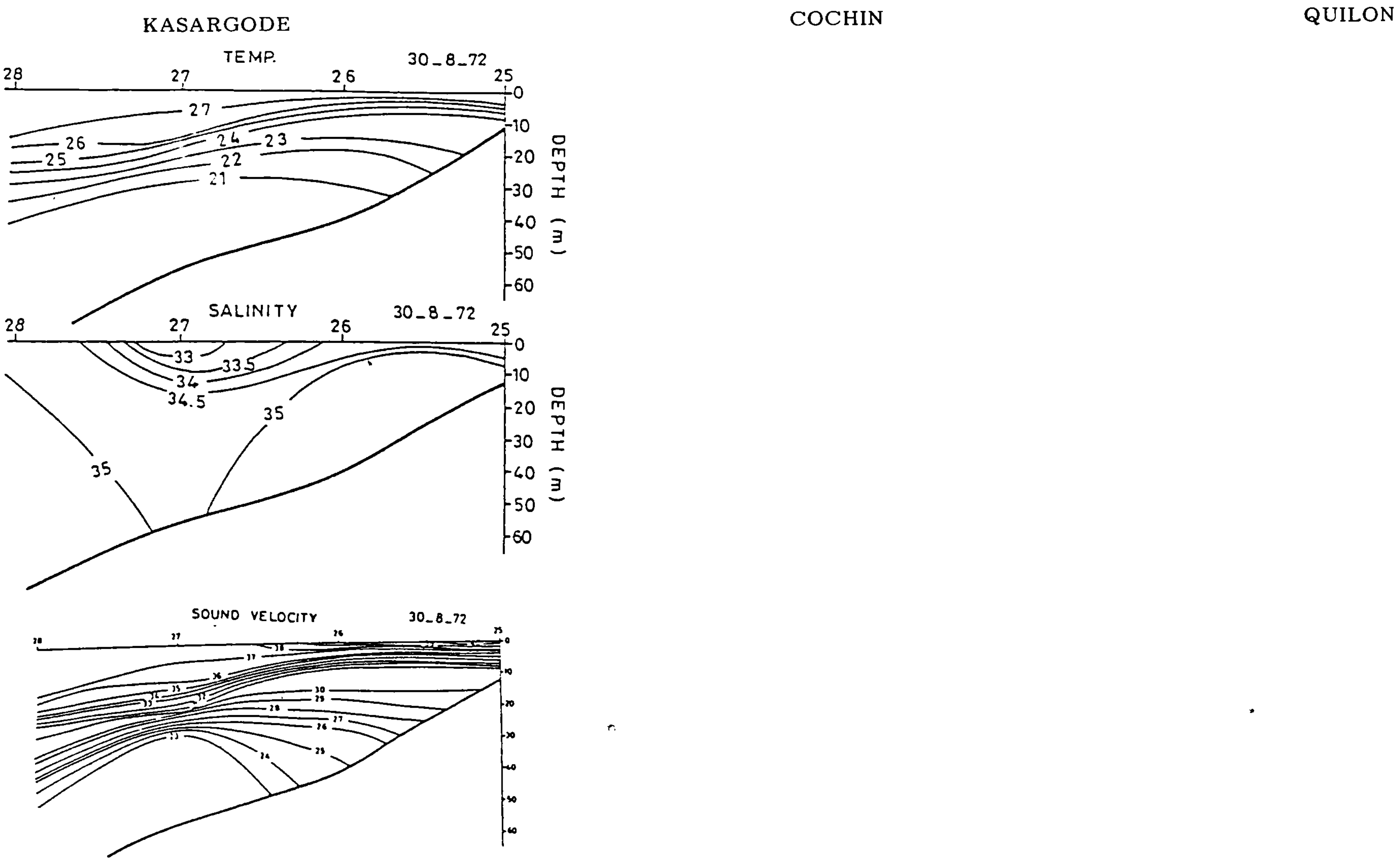

Fig.10 Vertical profiles of temperature (^{o}C), salinity (S.I.Units), sound velocity (values in m/s-1500) during August 1972.

gradient of about 0.5 m/s/m. Below 30 m (where isothermal watermass is observed) the sound velocity gradient is extremely small. Ramasastry and Myrland (1960) have attributed the formation of this watermass to the mixing of upwelled water with the bottom current. A similar condition with sharp temperature gradient in the surface layers and isothermal watermass near the bottom has been reported in a section off Cochin during August 1958 by Geetha Bhasker et al (1988). Salinity values are generally lower than 35 and very low values less than 33 are found in the surface layers.

Fig. 11 presents the vertical profiles of sound velocity, temperature and salinity during August 1973 off Quilon and Kasargode. Corresponding to the general decrease in surface temperature, the surface sound velocity also shows a decrease compared to the earlier months. Off Quilon, the surface sound velocity increases towards the coast (from 1539 m/s at 16 km offshore to 1542 m/s nearshore). Off Kasargode, the surface sound velocity decreases towards the coast (from 1532 m/s 32 km offshore to 1528 m/s near the shore). This is due to increase of surface temperature towards the coast off Quilon and decrease of surface temperature towards the coast off Kasargode. The overall value of vertical temperature gradient off Quilon has increased approximately to 0.13° c/m compared to the earlier observations. Consequently the sound velocity gradient also increases to about 0.3 m/s/m. Off Kasargode, however, the overall value of temperature gradient has decreased to 0.1°c/m and consequently the sound velocity gradient also decreases to 0.2 m/s/m compared to the earlier observations. Off both Quilon and Kasargode, the sharpest gradient are found below about 10m. Off Kasargode, the gradient are less sharp

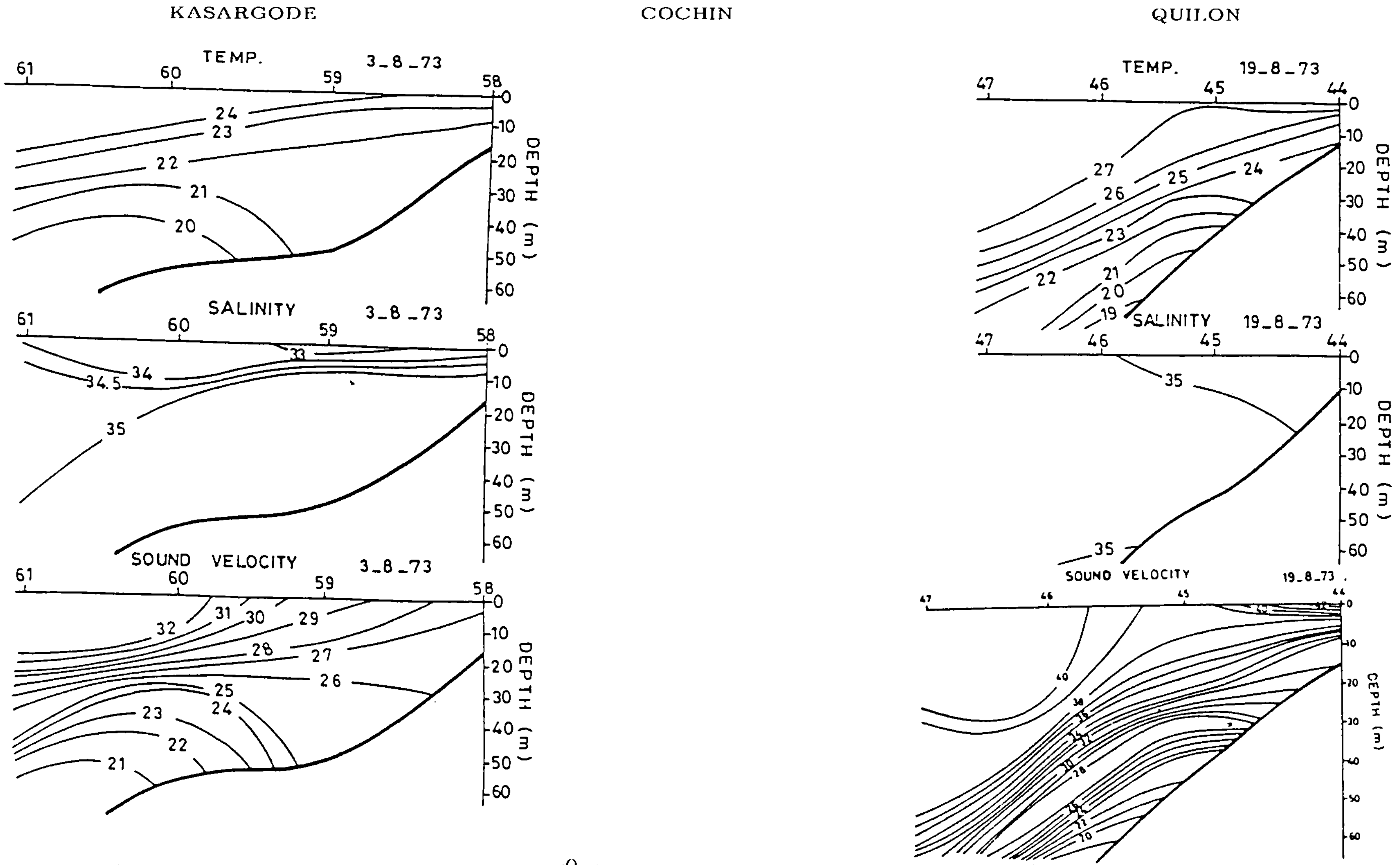

Fig.11 Vertical profiles of temperature (^{o}C), salinity (S.I.Units), sound velocity (values in m/s -1500 during August 1973.

compared to June value. While the values of salinity off Quilon have slightly reduced, the reduction in salinity off Kasargode is considerable, particularly in the surface layers.

A comparison of the vertical profiles off Kasargode between August conditions of 1972 and 1973 bring out the influence of the stronger monsoon during 1973 on sound velocity and hydrography. The intense upwelling has resulted in considerable lower surface temperatures with smaller gradients. Accordingly the sound velocity shows comparatively lower surface values during 1973 with smaller vertical gradients.

During September 1972 (fig. 12), the surface sound velocity increases to a value around 1541 m/s off Quilon, Cochin and Kasargode consequent to increase in the surface temperature. Sharp thermocline and velocline near the surface and nearly isothermal water below are observed in these region. Off Quilon the thermocline and velocline become sharper towards the coast and near the coast,, they are limited to within 20m from the surface. The maximum values of sound velocity gradient and temperature gradient are 0.55 m/s/m and 0.25° c/m respectively. Off Cochin and Kasargode, both thermocline and velocline are limited to a depth of about 10m from the surface. The maximum values of sound velocity gradients and temperature gradients are 1.1 m/s/m and 0.5° c/m respectively. Both thermocline and velocline are the sharpest during the month of September. There is an increase in salinity due to decrease in rainfall and the continued upwelling indicated by the upward slope of the is lines towards the coast.

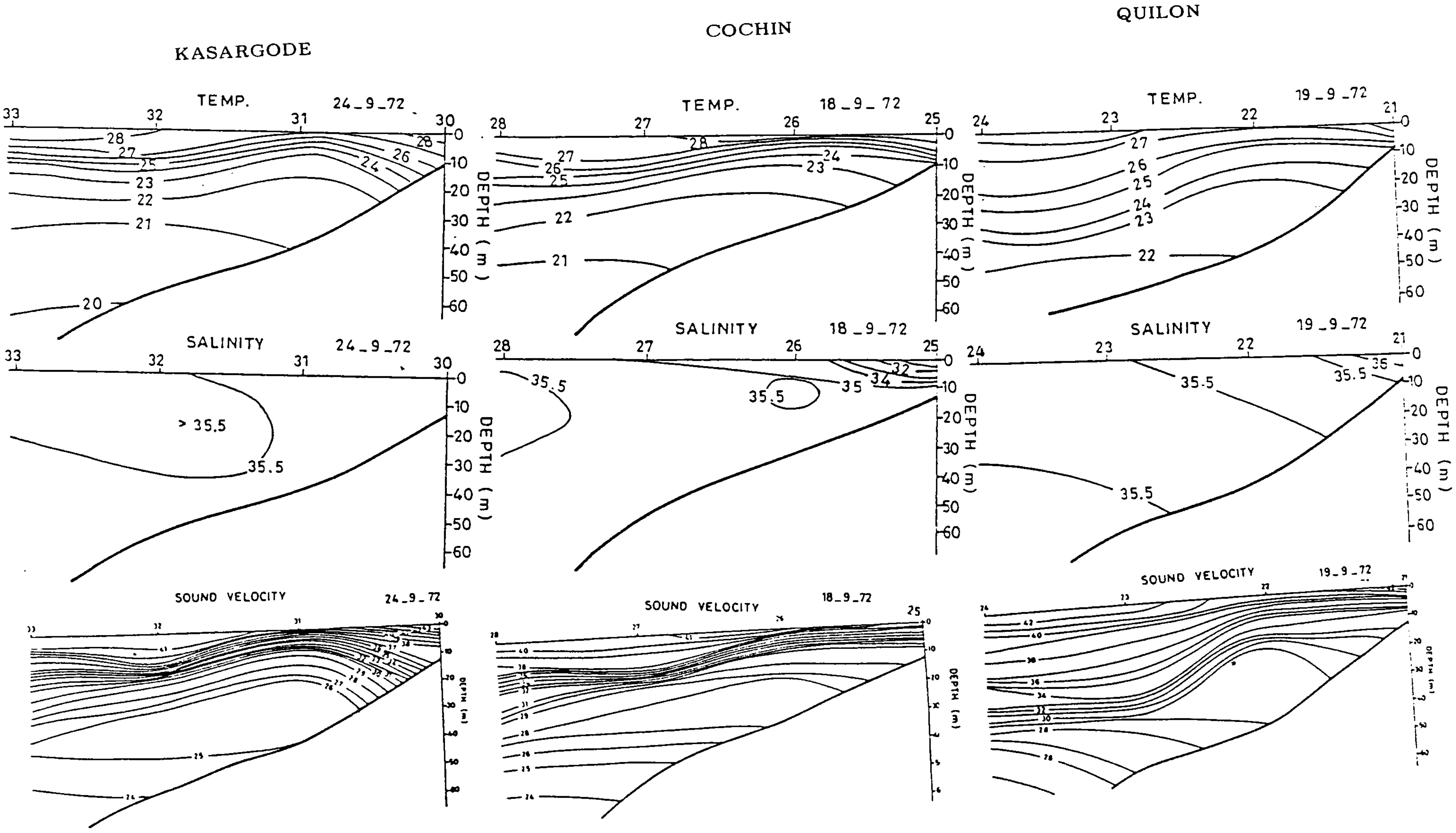

Fig.12 Vertical profiles of temperature (^{o}C), salinity (S.I.Units), sound velocity (values in m/s-1500) during September 1972.

The vertical sections of sound velocity and hydrography off Kasargode during September 1973 are illustrated in (fig. 13). The surface sound velocity increases from the August values to nearly 1534 m/s. Along the surface,sound velocity decreases towards the coast to values as low as 1530 m/s. This is due to shoreward decrease of salinity caused by surface dilution. Compared to the earlier month, the overall values of sound velocity gradient and temperature gradient have increased to 0.30 m/s/m and 0.15° c/m. The largest gradient is found very near the surface and up to a depth of around 15, below which a nearly isothermal water is observed, indicating that both thermocline and velocline are close to the surface during this month. Salinity values have generally reduced from their previous values in August.

Comparing the vertical distributions during September of 1972 and 1973, it can be found that the surface sound velocity is considerably lower during 1973 consequent to the hydrographic conditions. The vertical sound velocity gradient is also considerably lower in 1973.

During October 1972, the section off Cochin (Fig. 14) shows that the surface value of sound velocity has increased to about 1543 m/s consequent to increase of the surface temperature to values above 29°C, compared to the previous month. The thermocline and velocline are observed about 10m below the surface with their sharpness considerably reduced compared to September 72. The sound velocity gradients and temperature gradients have overall values of 0.25 m/s/m and 12°c/m respectively. The isothermal water observed during September 72

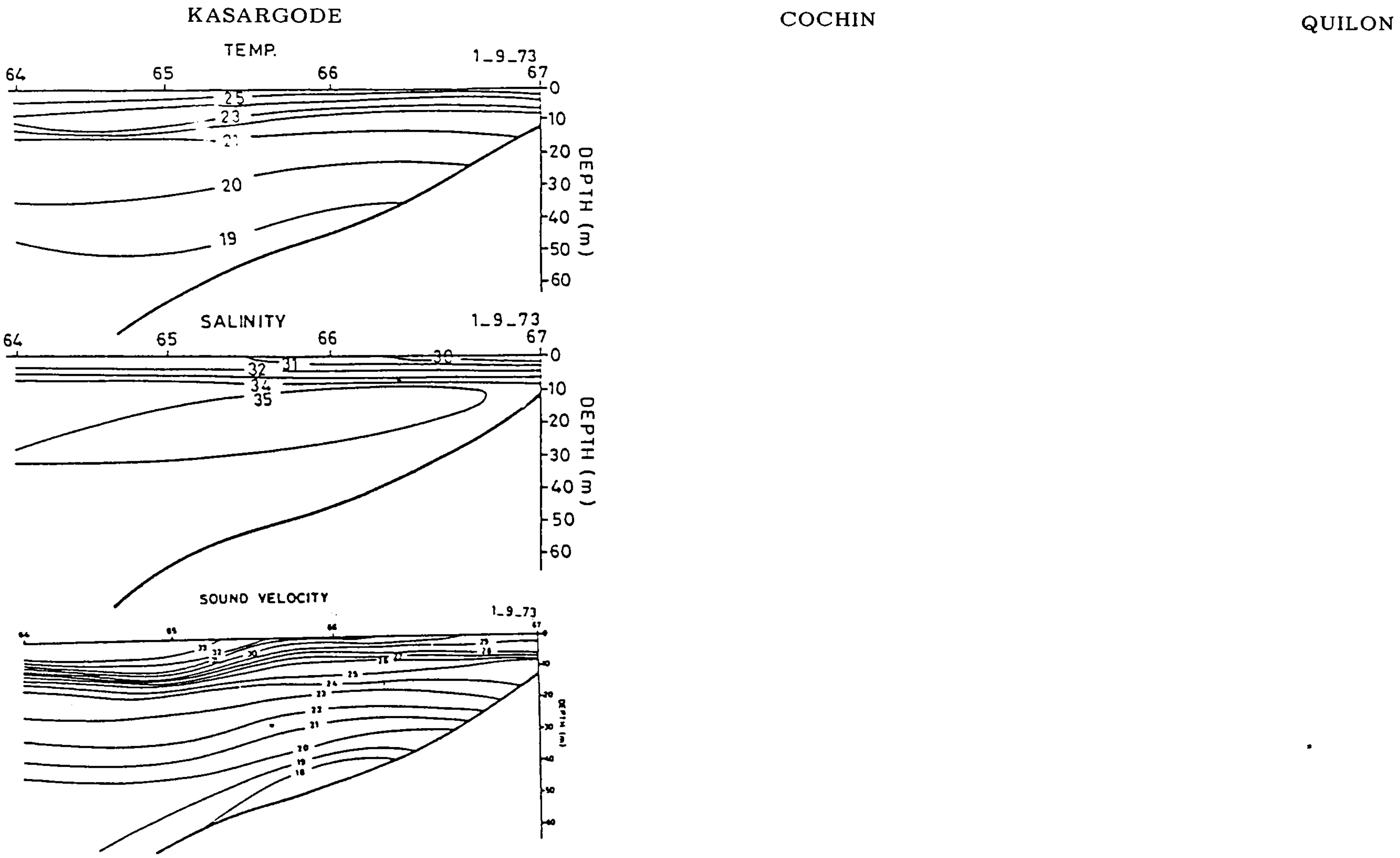

Fig. 13 Vertical profiles of temperature (^{o}C), salinity (S.I.Units), sound velocity (values in m/s-1500) during September 1973.

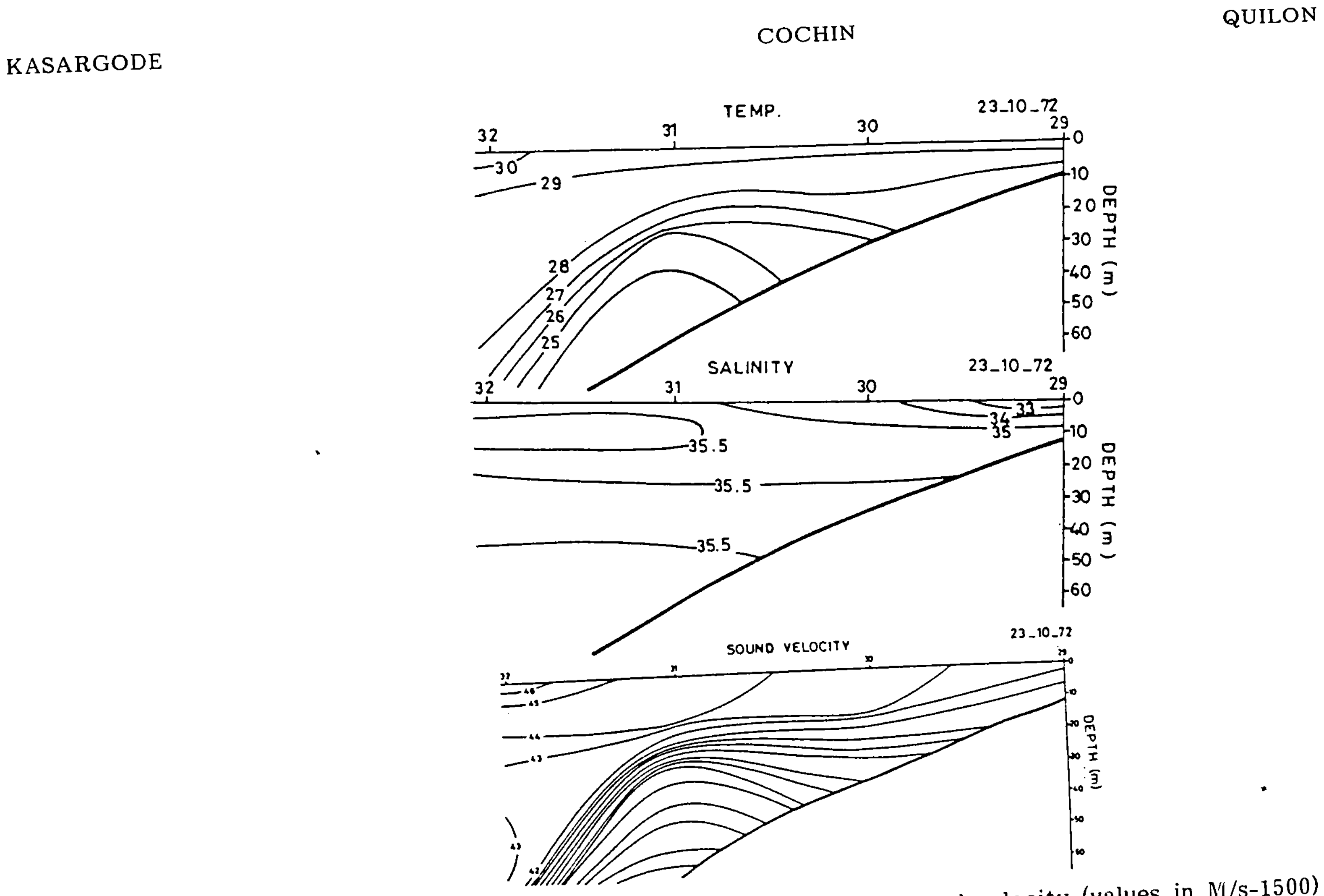

Fig. 14 Vertical profiles of temperature (^{o}C), salinity (S.I.Units), sound velocity (values in M/s-1500) during October 1972.

in the bottom layers in this region is now practically absent as a result of sinking indicated by the downward slope of the isotherms towards the coast. This sinking is initiated by the change in wind direction and the consequent changes in coastal circulation normally observed during this period of the year. (Geetha Bhasker et al (1988). Salinity distribution remains more or less the same as in September 1972. Generally, values above 35 are observed except very near the coast where salinity is less than 33.

The vertical profiles of sound velocity, temperature and salinity off Quilon and Cochin during October 1973 are depicted in fig. 15. Sound velocity at the surface is found to increase compared to the previous month, both off Quilon and Cochin, reaching maximum values above 1542 m/s. Off Quilon, sound velocity decreases towards the coast reaching minimum value of around 1538 m/s very near the coast, in association with shoreward decrease in surface temperature. The vertical gradients in sound velocity also shows a decreasing trend temporally with values around 0.2 m/s/m off Quilon and 0.06 m/s/m off Cochin. Salinity values show a general increase in both the sections.

Comparing with the conditions that existed during the corresponding month of the previour year, it can be seen that surface temperature, surface salinity and the sound velocity at the surface are lower in October 1973. The vertical gradients of the parameters are also lower during this year.

The vertical profiles of the parameter during 1972 November off Quilon and off Cochin are illustrated in Fig. 16. The maximum

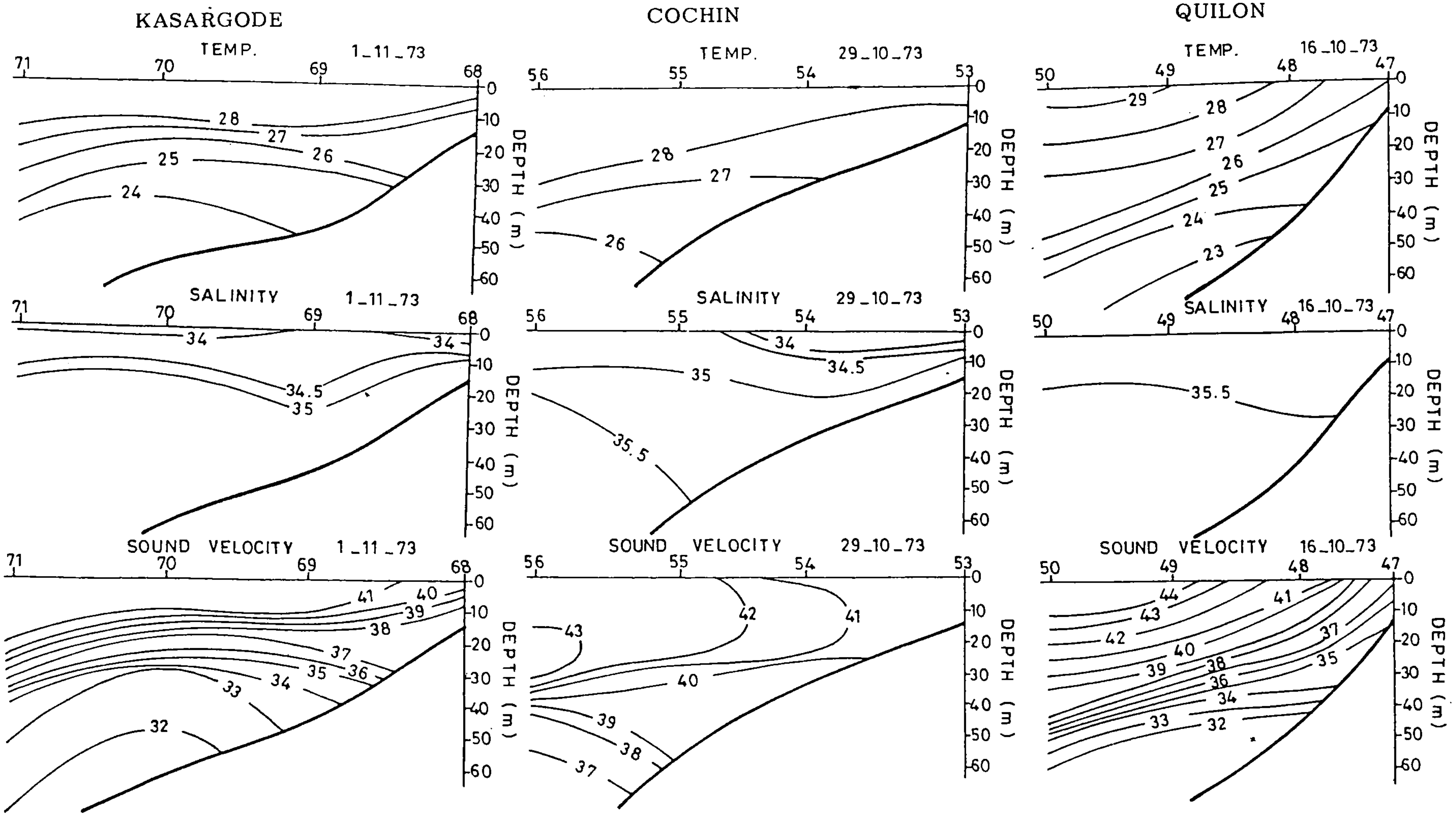

Fig. 15 Vertical profiles of temperature (^{o}C), salinity (S.I.Units), sound velocity (values in m/s-1500) during October and November 1973.

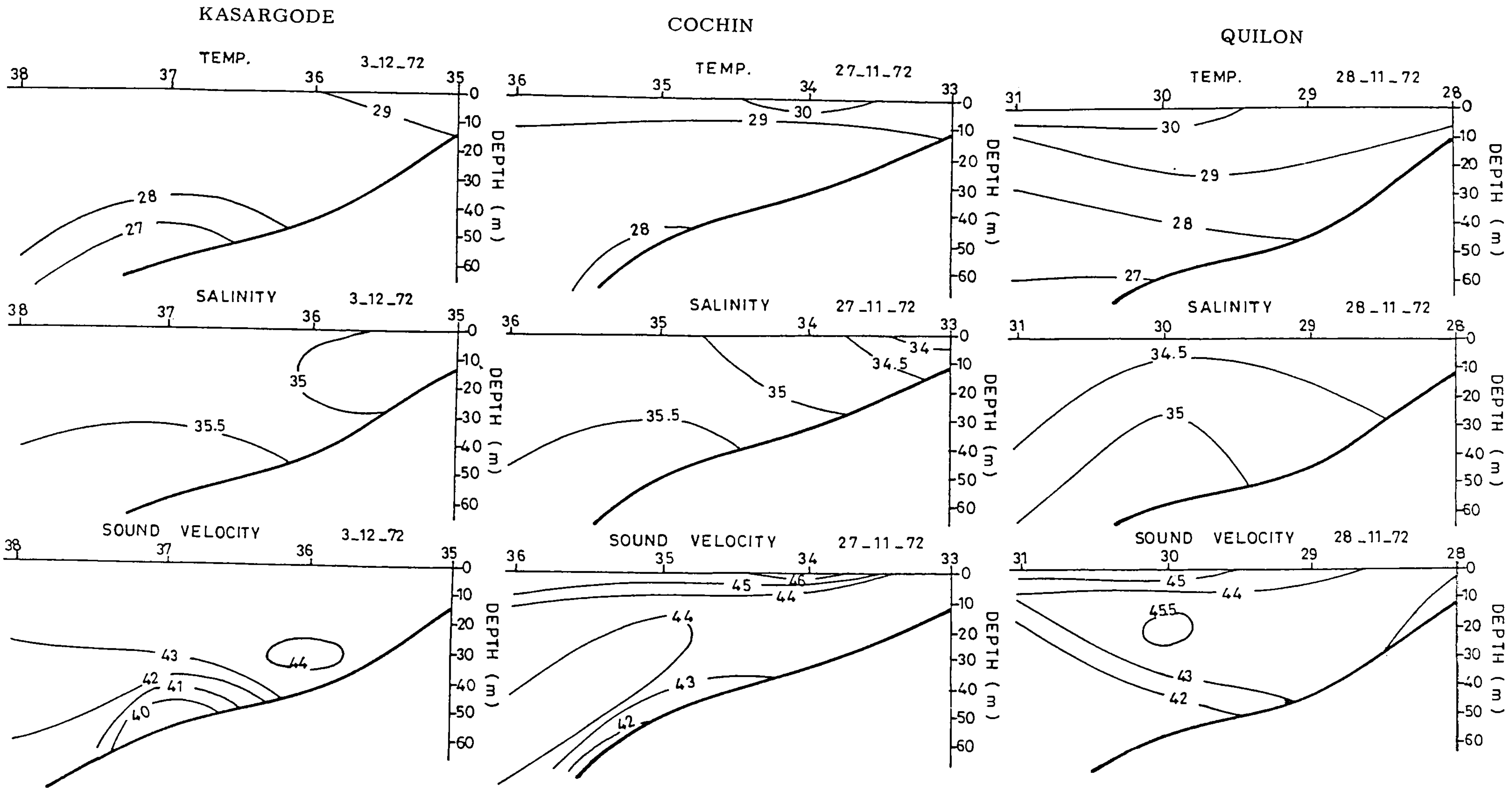

Fig. 16 Vertical profiles of temperature (oC), salinity (S.I. Units), sound velocity (values in m/s-1500) during November and December 1972.

values of surface sound velocity have increased to values around 1546 m/s in the section off Quilon and off Cochin as a result of increase in surface temperature to above 30°c. No sharp gradients in temperature and sound velocity are observed. In sections off Quilon the overall values of vertical gradients of sound velocity and temperature are 0.08 m/s/m and 0.05°c/m respectively. However, off Cochin nearly isothermal water is observed up to a depth of 40m with negligible gradient in sound velocity caused by sinking of the surface water. The salinity values are also reduced to below 35 as a result of this sinking process.

Fig. 15 and 17 presents the vertical profiles of temperature salinity and sound velocity that prevailed during 1973 November. The surface sound velocity shows a temporal increase reaching 1544 m/s off Cochin and 1541 m/s off Kasargode, consequent to the increase in surface temperature to above 29°c and 28°c respectively. Corresponding to decrease in temperature gradients the sound velocity gradient also decreases to 0.04 m/s/m and 0.2 m/s/m off Cochin and Kasargode respectively. The vertical profiles show that salinity continues to increase off Kasargode while it decreases off Cochin under the influence of sinking.

Comparison with the conditions that observed during the previous year shows that the sound velocity and the hydrographic parameter are lower during 1973. The vertical gradients are also lower during the latter year.

During December 1972, the surface sound velocity continues to show the increasing trend reaching values above 1543 m/s off Kasargode with very small vertical gradient (fig.16). Nearly

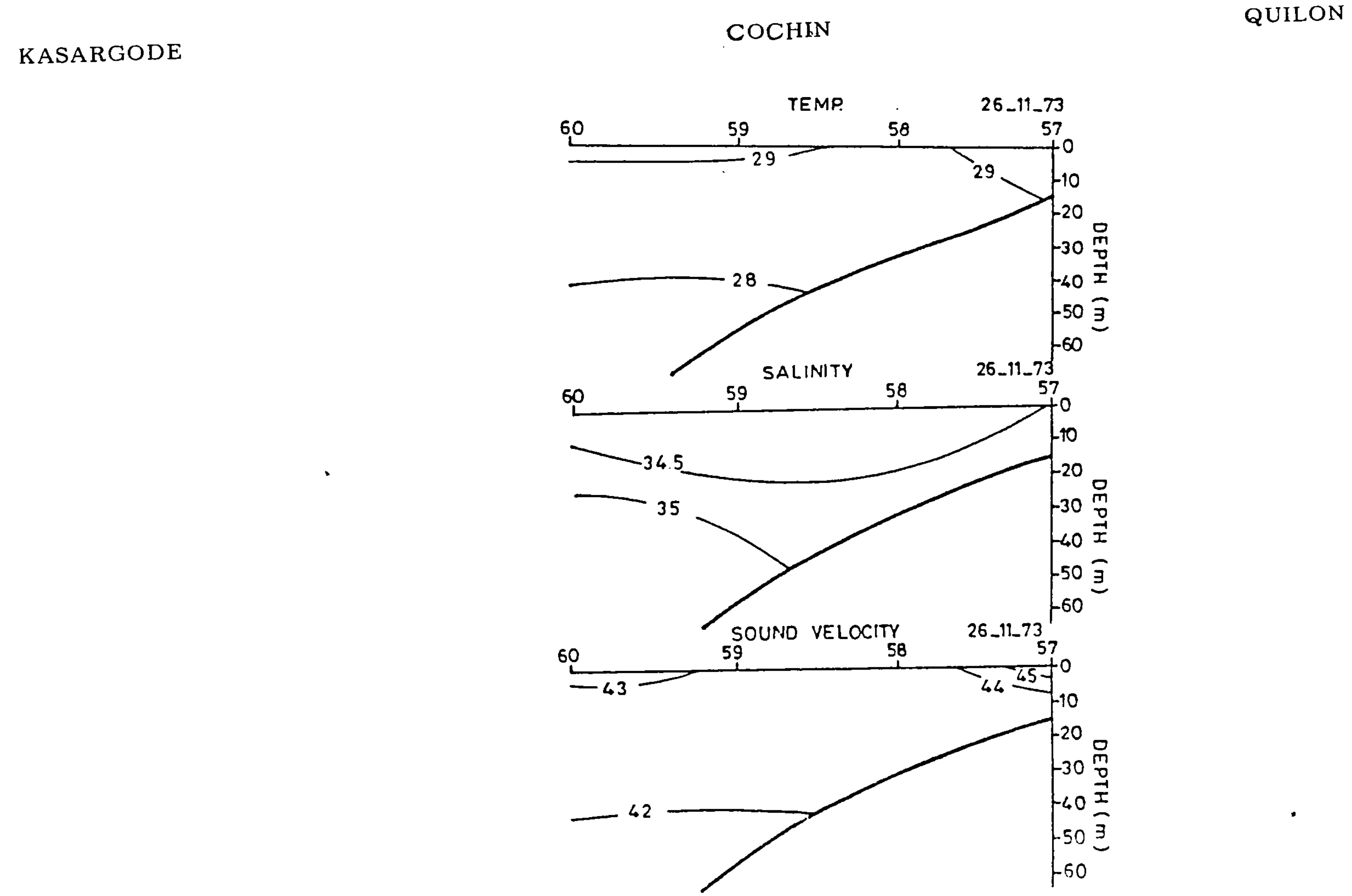

Fig. 17 Vertical profiles of temperature (^{o}C), salinity (S.I.Units), sound velocity (values in m/s-1500) during November 1973.

isothermal water is observed up to a depth of 40m. The thermocline and velocline are no longer observed close to the surface. The complete breaking up of the profiles which existed till October has been brought by the sinking process, indicated by the downward slope of the isotherms. Salinity shows a decreasing trend under the influence of the sinking process.

The vertical profiles off Quilon and Cochin during January 1973 (fig. 18) show decrease in surface sound velocity brought about by the winter cooling to values around 1541 m/s (off Quilon) and 1545 m/s (off Cochin). A well formed mixed layer is seen with an overall positive vertical temperature gradient of about $0.01^{o}C/m$ off Quilon. Off Cochin the temperature gradient is comparatively large and negative up to a depth of 30m below which a weak positive gradient is observed. Because of the better thermal stratification in the surface layers off Cochin the magnitude of the overall temperature gradient is larger and is around 0.05°c/m. The salinity decreases slightly from its November value off Quilon and Cochin. In the vertical direction salinity is nearly uniform off Cochin whereas off Quilon salinity increase from about 34 at the surface to about 35 at the bottom. The increase in salinity towards the bottom coupled with the positive temperature gradient causes the sound velocity gradient to the positive and of comparatively larger magnitude of about 0.05 m/s/m. However, during December-January 1958-59, the presence of positive gradients of temperature and sound velocity have been reported off Cochin by Geetha Bhasker et al (1988).

Off Kasargode, during February 1973 (fig. 18) the surface sound velocity is about 1543 m/s. The temperature gradient is negative

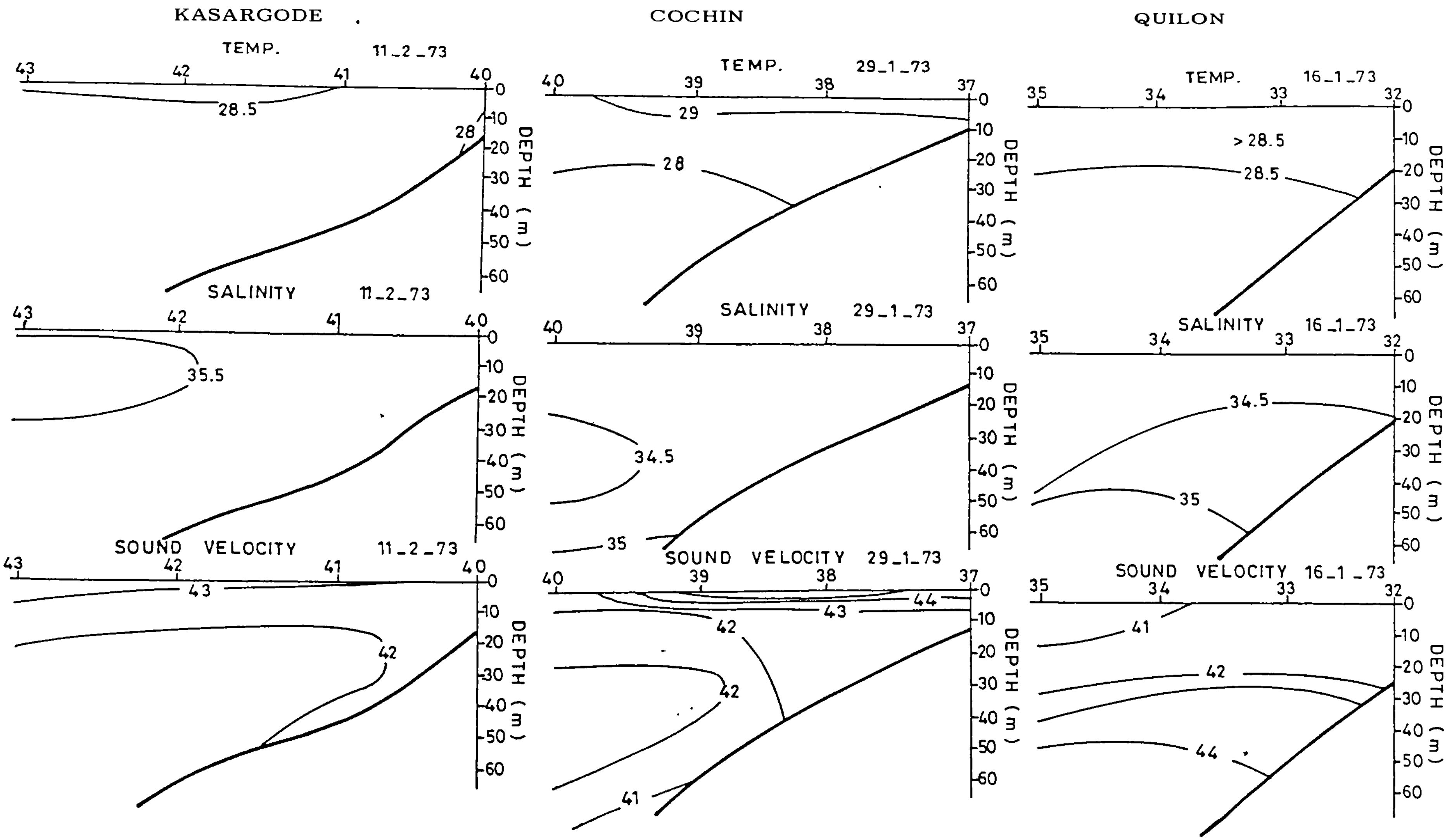

Fig. 18 Vertical profiles of temperature (^{o}C), salinity (S.I.Units), sound velocity (values in m/s-1500) during January and February 1973.

with negligible magnitude. The salinity is nearby uniform in the entire water column the sound velocity gradient found to be positive, despite, the temperature gradient being marginally negative, the magnitude however is negligibly small.

3.3.2 Overall features of variations in sound velocity and hydrography.

The monthly as well as annual variation in the vertical profiles of sound velocity and hydrographic parameters off Quilon, Cochin and Kasargode have been discussed in the forgoing section. It will be interesting to summarise the overall features of the variations in the vertical profiles of these parameters to arrive at the seasonal patterns of the variations. Low values of surface temperature and sound velocity are observed during the monsoon season and high values in the summer season. The surface temperature and sound velocity show a bimodal distribution with two maxima and two minima in a year. In the section off Quilon and Cochin the maxima occur in April and November and minima in February and August. Off Kasargode, however, the summer maximum occurs in May.

The magnitude of the lowest value of surface temperature and sound velocity are found to depend on the monsoon, the stronger the monsoon the lower the magnitudes. Also the highest values of temperature and sound velocity appear to depend on the monsoon of the previous year, the weaker the monsoon in the previous year, larger the highest values. The maximum and minimum values occurring in November and February also depend on the strength of the monsoon, a weak monsoon resulting in higher maximum in November and higher minimum in February. Similarly, the temperature and sound velocity in the mixed layer above the thermocline is found to be higher after a weak monsoon. The isotherms slope up to wards the coast from April to the end of September indicating coastal upwelling, while they dip towards the coast from October to the end of March indicating coastal sinking.

The nature of variation of salinity is seen to be more complex. The surface salinity variation show two maxima and two minima in a year. The maxima usually occurs in June and by the end of the year, whereas, the minima occurs in March and by the end of Southwest monsoon season. The salinity values are seen to be generally higher after a weak monsoon.

Vertical gradients of temperature and sound velocity are found to be small in magnitude from the beginning of the year up to the end of April. During this period both positive and negative values are observed. Generally negative gradients are seen from May to October. Sharpest gradients are seen in the bottom layer up to July which rise to the surface by August and persists till the end of September. In October the sharpest gradients are at mid depths. By the end of October or early November this temperature and sound velocity structure is completely broken up and the gradients are small in magnitude. Generally their values are negative in November and positive in December. The gradients are seen to depend o the strength of the monsoon, the stronger the monsoon the sharper the gradient.

CHAPTER IV

HIGH FREQUENCY ACOUSTIC PROPAGATION CHARACTERISTICS

4.1 Introduction

For most of the practical applications, high frequency sound waves are employed at sea because of their directional nature. However, high frequency acoustic waves, by virtue of their short wavelength, are subjected to larger absorption and scattering, limiting the useful range of propagation. The distinction between high and low frequency propagation is primarily a matter of scale, defined by the dimensionless parameter kh, k being the horizontal component of the wave number and h the ocean depth. In practice high frequency acoustic concerns with the range $kh>>10$ i.e., usually $kh>10^2$. In shallow waters, frequencies above around 2500Hz can be considered as high frequencies. However, these frequencies find only limited applications such as underwater communications while ultrasonic frequencies are employed for a large number of applications like identification, localisation and fish finding.

The characteristics of high frequency acoustic propagation in an oceanic area are very much influenced by the vertical sound velocity gradient. Since the vertical sound velocity distribution changes with season, the acoustic propagation characteristics also exhibit seasonal variations. In regions where the sound velocity gradient is negative, a horizontal acoustic beam will get refracted downwards forming a surface shadow zone. The sharpness of bending will depend on the magnitude of the gradient, the larger the magnitude, the sharper will be bending. In such situations, the horizontal range of propagation will be very much limited. On the other hand, in a layer where the sound velocity gradient is positive, the beam gets refracted upward forming a bottom shadow zone (Urick, 1975). In this case, the acoustic propagation will be as in a surface duct where the propagation losses tend to be smaller (Camp, 1970). However, in cases where the gradient are very small, large horizontal ranges of propagations are possible irrespective of the sign of the gradient.

4.2 RESULTS

Monthly vertical profile of sound velocity are drawn for the sections off Quilon, Cochin and Kasargode for the years 1972 and 1973. (Fig.19 to 28) The vertical distribution diagrams of sound velocity are discussed for the individual sections grouping corresponding months of both the years with a view to bring out inter-annual variability.

4.2.1 QUILON

Fig. (19) shows the vertical profile of sound velocity off Quilon during March 1972. The vertical profile show a negative gradient up to a depth of 10m and a positive gradient up to about 30m at the third and fourth stations from the coast while at the second station this feature is limited to 20m depth. The first station shows no vertical gradient. This indicates the presence of a surface channel extending up to a depth of 20-30m. Below 30m, the gradient is again negative with small magnitudes up to 75m. Below this depth at the fourth station, the profile shows a larger negative gradient up to the bottom. The negative gradients below 30m indicate that high frequency propagation as in a bottom duct. A horizontal acoustic beam below 30m, where the sound velocity gradient is negative, will refract downwards to form a shadow zone below the surface channel. Small gradients observed during this month indicate large horizontal ranges of propagation. It is interesting to note that the picture is strikingly different during March 1973 (fig. 19) at the three stations where the sound velocity gradients are slightly positive at the second station and nearly zero at the other stations. This indicates possibility of sound propagation as in a surface duct and formation of a bottom shadow zone.

During April 1972 (fig. 20) the profile show negligible gradient up to 10m at all stations except the fourth station, where the gradient is negligible up to 20m. Below these depths, the gradient is negative up to bottom at all stations. This sound velocity structure indicates possibility of sound propagation as in a bottom duct. During April 1973 (fig. 20) all stations show slightly negative gradients in the entire water column indicating again sound propagation as in a bottom duct.

During May 1972 (fig. 21), the vertical profiles show negative gradient at the first station. At the second and fourth stations, small positive gradients are observed in the surface layers up to 10m and 20m respectively. Below these depths, the gradients are negative. However, at the third station the gradient is small and negative in the surface layers up to 20m and comparatively large and negative below. The above distribution indicates the sound propagation as in a surface duct above 10-20m depth and as in a bottom duct below. Similar vertical distribution is observed during June 1973 also (fig. 22).

During July 1972 (fig. 23) the gradients are small and negative in the surface layers up to 20m and comparatively large and negative below that depth. The gradient of the vertical profile of sound velocity during August 1973 (fig. 24) indicate similar features in the surface layers, except at the first station where the gradient is large and negative whereas in deeper layers the gradients are smaller. The above feature indicates sound propagation as in a bottom duct.

During September 1972 (fig. 25), the vertical gradients are negative and large in the entire water column indicating possibility of formation of strong shadow zone just below the surface. The larger velocity gradients indicate lower ranges of propagation. Identical situation is presented in fig.26, for October 1973 except that the gradients are considerably lower indicating larger ranges of propagation.

Fig. 27 illustrates the profile of sound velocity off Quilon during November 1972. The gradient is slightly negative up to the bottom at the first and third stations and up to 20m at the second station. At this station, below 20m, the gradient shows larger negative values. The possibility of propagation as in a bottom duct with larger horizontal range and formation of a surface shadow zone is indicated during November.

January 1973 (fig. 28) presents a different picture with nearly zero gradient at the first station and slightly positive gradients at the second and third stations from the surface to the bottom. This indicate that the sound propagations is as in a surface duct with very large range of propagation and possibility of formation of a bottom shadow zone.

4.2.2 Cochin

Fig.(19) illustrates the vertical profiles of sound velocity off Cochin during March 1972. The vertical profiles show small positive gradients at the first and third stations where as it is slightly negative at the second station. The fourth station from the coast, however, shows small negative gradient up to a depth of 10m, slightly positive gradient up to 50m and again negative gradient up to the bottom. This sound velocity structure indicates the possibility of high frequency propagations as in a surface duct and the formation of a bottom shadow zone. The small positive gradients generally observed during the months indicate large horizontal ranges of propagation. The picture is slightly different in March 1973, (fig. 19) where the sound velocity gradients are slightly negative up to the bottom except at the first station where it is slightly positive. This indicates the possibility of high frequency propagation as in a bottom duct, and the formation of a surface shadow zone. The small gradients indicate comparatively larger ranges of propagation.

During April 1972 (fig. 20), the profile show a small negative gradient at the first station and nearly zero gradient at the second station. At the third station, the gradient is small and positive up to a depth of 20m below which the gradient is negative. At the fourth station, however the gradient is slightly negative up to 10m, slightly positive up to 20m, and again negative below. This sound velocity structure indicates the formation of a surface duct above 20m depth and a bottom duct below that depth.

During May 1972 (fig. 21) the profiles show slightly positive gradient at the first station. At the second station the gradient is negative and is of small value up to a depth of 10m below which it is larger. At the third station, however, the gradients is comparatively larger and negative up to the bottom. The fourth station shows a small positive gradient up to 10m below which the gradient is negative and small up to 50m. Below this depth the negative gradient is comparatively larger. This velocity structure indicates the high frequency propagation as is a bottom duct and formation of a surface shadow zone. During 1973 May (fig. 21), the profile show negative gradient at the first station. The second station shows nearly zero gradient up to the bottom. At the third and fourth stations, the gradients are negative and small up to a depth of 10m and 30m respectively, below which the gradients are larger. The above feature indicates a propagation characteristic similar to May 1972.

During July 1972 (fig.23) the profiles show large negative gradient at the first station. The sound velocity gradients are positive at the second and third stations up to a depth of 10m whereas it is positive up to 20m at the fourth station. The gradients are negative and large below 10m depth at second and third stations. At the fourth station, however, it is negative and large up to a depth of 50m, below which the negative gradient is comparatively smaller. The above structure indicates the propagation as in a surface duct above 10 to 20m depth and as in a bottom duct below with the formation of a shadow zone just under the surface duct. It is interesting to not that during

July 1973 (fig 23) also the sound velocity structure is more or less similar except at the third station where the gradient is slightly negative up to 10m.

During September, 1972 (fig. 25), the profiles show large negative gradients at the first station. At the second stations the gradients are large and negative up to a depth of 30m and 50m respectively below which the gradient is smaller. At the third station however, the gradient is negative and comparatively smaller up to a depth of 10m. Below this depth, the gradient is very large up to a depth of 20m. The magnitude of the gradient decreases below 20m. The above features indicate the high frequency propagation as in a bottom duct. The large negative gradients suggest shorter ranges of propagation.

Fig (26) illustrates the sound velocity profiles during October 1972. At the first station, the sound velocity gradient is negative and smaller than during the previour month. At the second and third stations the sound velocity gradients are negative and small up to a depth of 10m below which the values are comparatively larger. However, at the third station, below 30m, comparatively smaller values are encountered. At the fourth section, the gradient is negative and small up to a depth of 30m and slightly positive below up to a depth 50m. Below this depth, the gradient is again slightly negative up to 75m depth. Below 75m the gradient in large and negative. The above features indicate the propagation characteristics similar to September,1972. The sound velocity profiles during October 1973 (fig 26) show a different picture. The sound velocity gradient at the first station is nearly zero. The gradient at the second station is positive and small up to a depth of 10m below which it is slightly negative. At the third station, the gradient has extremely small negative values up to 20m below which it is slightly larger. However, at the fourth station the sound velocity gradient is small and negative up to 10m and slightly positive up to 20m. Below this depth, the gradient is comparatively larger and negative. The conditions as above indicates the propagation as in a surface duct above 10m to 20m and as in a bottom duct below with a shadow zone just below the surface duct.

The sound velocity profiles during November 1972 (fig.27) show that the sound velocity gradient at the first station is nearly zero. At the second station, the gradient is negative up to 10m and nearly zero below this depth. The gradients are negative up to 10m and slightly positive below up to 30m at the third station and up to 50m at the fourth station. The sound velocity gradients are again negative below these depths. The above sound velocity structure indicates the propagation as is a surface channel above 20 to 30m and as in a bottom duct below this depth, with a shadow zone just below the surface channel. November 1973 (fig. 27), however shows negative gradients at the first station and slightly positive gradients at the second station. At the third and fourth stations, the sound velocity gradients are slightly negative up to 10m and slightly positive up to 30m below which the values are again slightly negative. In this case also the propagation characteristics will be more or less similar to that during November 1972.

During January 1973 (fig. 28) the profiles show negative gradient at the first station. At the other stations the gradients are negative in the surface layers and positive below except at the fourth station where it is again negative below 75m. The gradient is negative up to 10m at the second station, 30m at the third station and 50m at the fourth station. The above conditions indicate the high frequency propagation as in a surface channel.

4.2.3 KASARGODE.

Fig. 19 shows the vertical profiles of sound velocity during March 1972. The sound velocity gradients are seen to be negative and small up to the bottom at all the stations. This indicates that the high frequency propagation in this region is as in a bottom duct. Small gradients values indicate large ranges of propagation. Similar propagation characteristics are observed during March 1973 (fig. 19) also when the sound velocity gradients are again negative and small.

During April 1972 (fig.20), the gradients are positive and small at the first station. At the second station, the gradient is positive up to 10m and negative below, the magnitudes being small in both the cases. At the third station, however, the gradient is slightly negative up to 10m, slightly positive up to 20m and again negative is the entire water column. This velocity structure indicates the propagation as in a surface duct above 10 to 20m depth and as in a bottom duct below. The propagation characteristics during May 1973 (fig. 21), June 1972 and June 1973 (fig. 22) are also observed to be similar. During May 1973 small positive gradients are observed in the surface layers at the third and fourth stations, up to 10m and 20m respectively with negative gradients below these depths. During June 1972 and June

1973 positive gradients are observed at these station up to 30m. At the first station the gradient is negative during these three months. At the second station it is nearly zero up to 10m during May 1973, it is positive up to 30m during June 1972 (fig.22). Below these depths, the gradients are negative. During June 1973, the second station shows negative gradients in the surface layers also. The magnitudes of the negative gradients below the surface layers during June 1973 are considerably larger than those during the other two months.

During August 1972 (fig.24), the first and second stations show large negative gradients throughout the water column. At the third and fourth stations, small negative gradients are observed in the surface layers up to a depth of 10m. Below this depth the gradients are large up to 30m at the third station and up to 50 m at the fourth station, below which the gradient is again small and negative. The vertical distribution as above indicates the propagation as in a bottom duct and formation of a surface shadow zone. Larger negative gradients indicates lesser ranges of propagation. The vertical sound velocity distributions during August 1973 September 1972 and September 1973 (figs. 25 and 26) are also similar with slight differences. During August 1973 gradients are smaller at the first and second stations and positive up to 20m at the fourth station. During September 1972, the sound velocity gradient is negative and large in the surface layers at the fourth station. During September 1973, the negative gradients are generally small. These small difference will not however materially affect the nature of propagation in the region which will be similar to that during August 1972.

During November 1973 (fig. 27) the vertical sound velocity distribution shows negative gradient at the first station. At the second and third stations, the gradients are slightly positive up to 10m and comparatively large and negative between 10 and 30m. Below this depth, the gradient is again slightly negative. At the fourth station, small negative gradient is observed in the surface layers up to 30m. Between 30 and 50m the gradient is comparatively large and negative. Below 50m, the gradient has small negative value. The distribution as above indicates propagation as in a surface duct above 10m and as in a bottom duct below 10m.

The vertical profile during December 1972 are shown in fig. 28. The sound velocity gradient is nearly zero at the first section. At the second station, the gradient is slightly negative up to 10m and positive below. At the third station, the gradient is positive up to 30m and negative below. At the fourth station, however, the sound velocity gradient is negative up to 20m, positive up to 50m and negative below. The above distribution indicates sound propagation as in a surface channel above 30m depth and as in a bottom duct below.

During February 1973 (Fig. 28) the gradient is nearly zero at the first station and slightly positive at the second station. At the third and fourth stations small negative gradients are observed in the surface layers up to 10m below which the gradients are slightly positive in the entire water column. The above indicates the propagation as in a surface duct and formation of a bottom shadow zone.

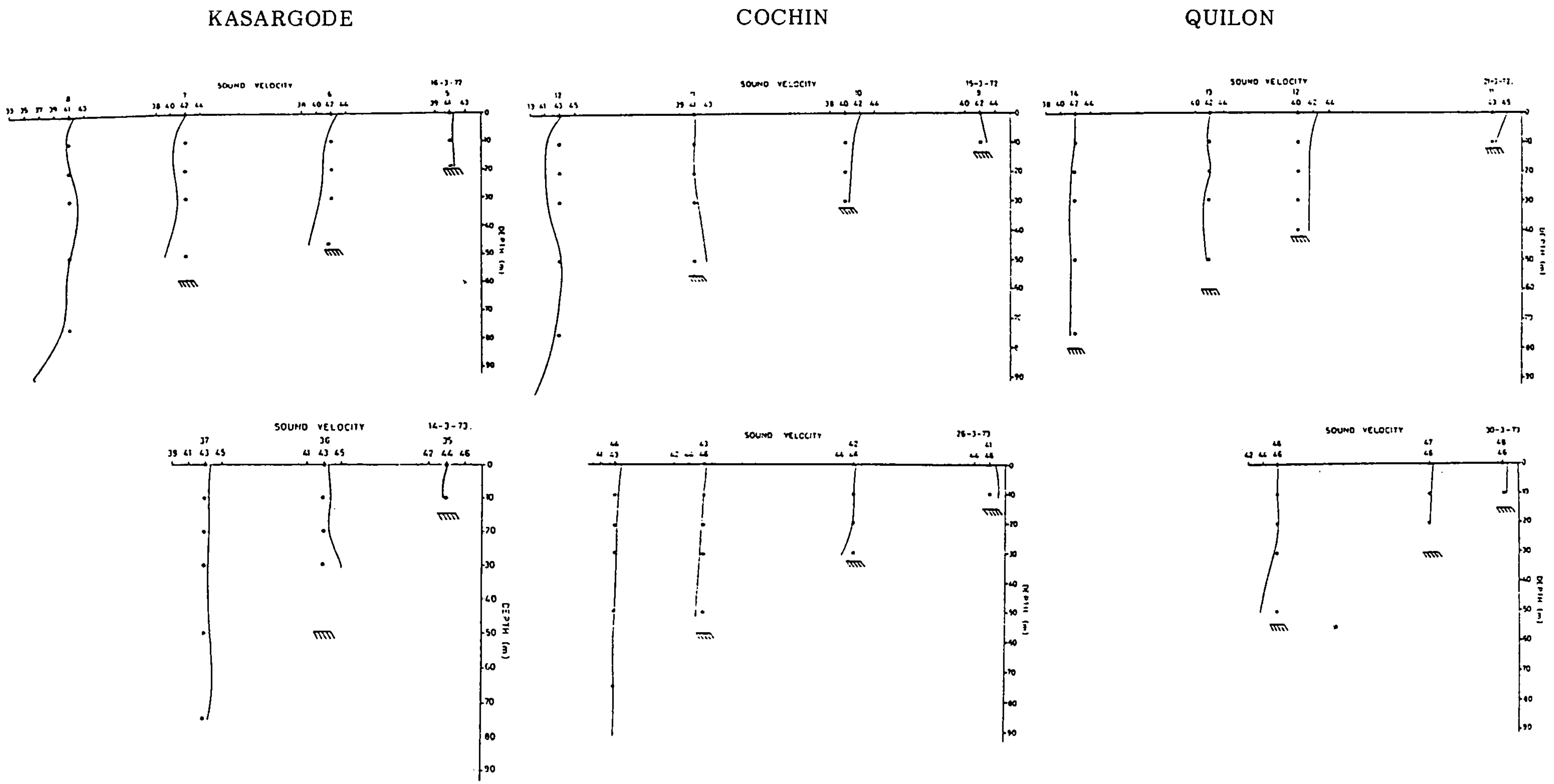

Fig. 19 Vertical distribution of sound velocity (values in M/s-1500) during March 1972 & 1973.

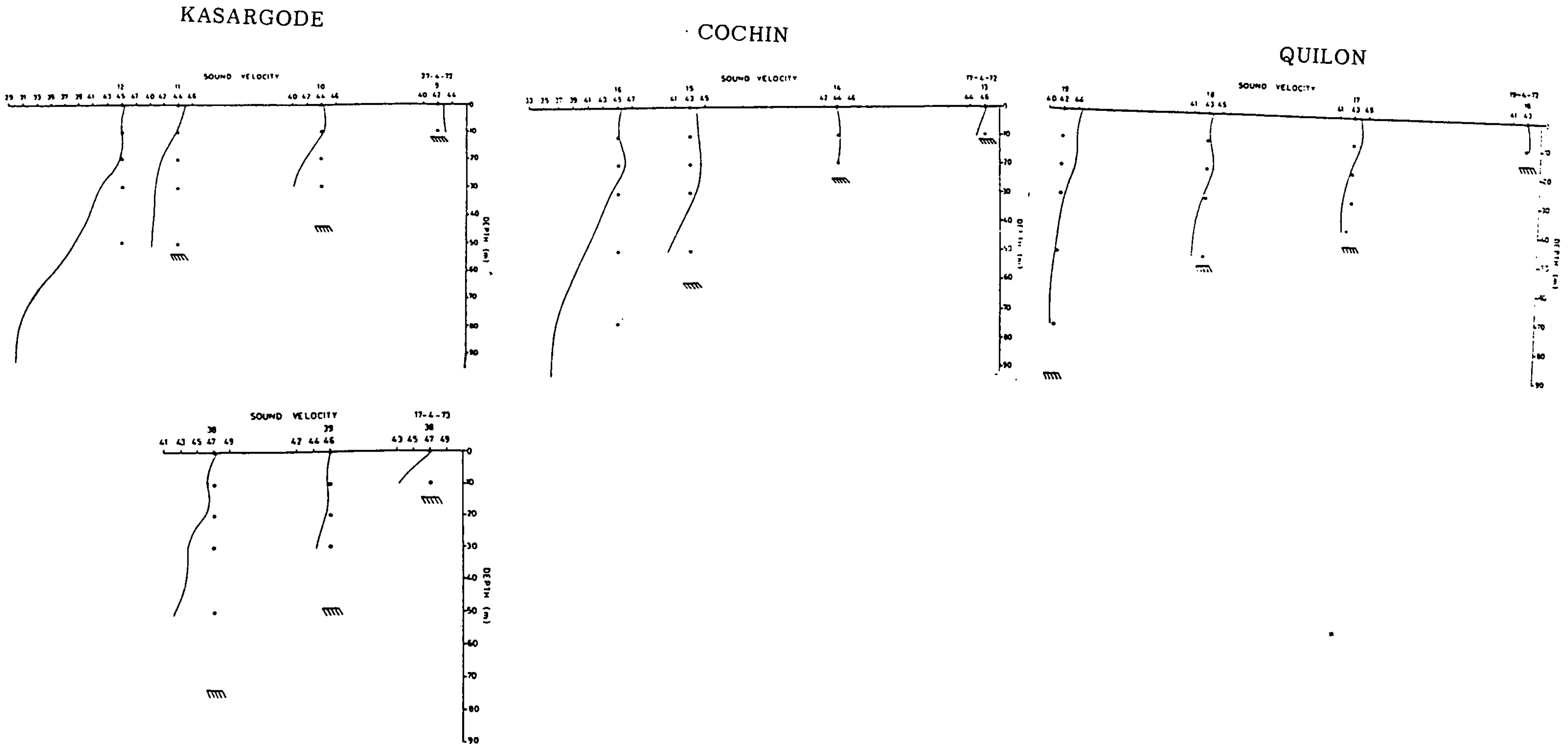

Fig. 20 Vertical distribution of sound velocity (values in M/s-1500) during April 1972 & 1973.

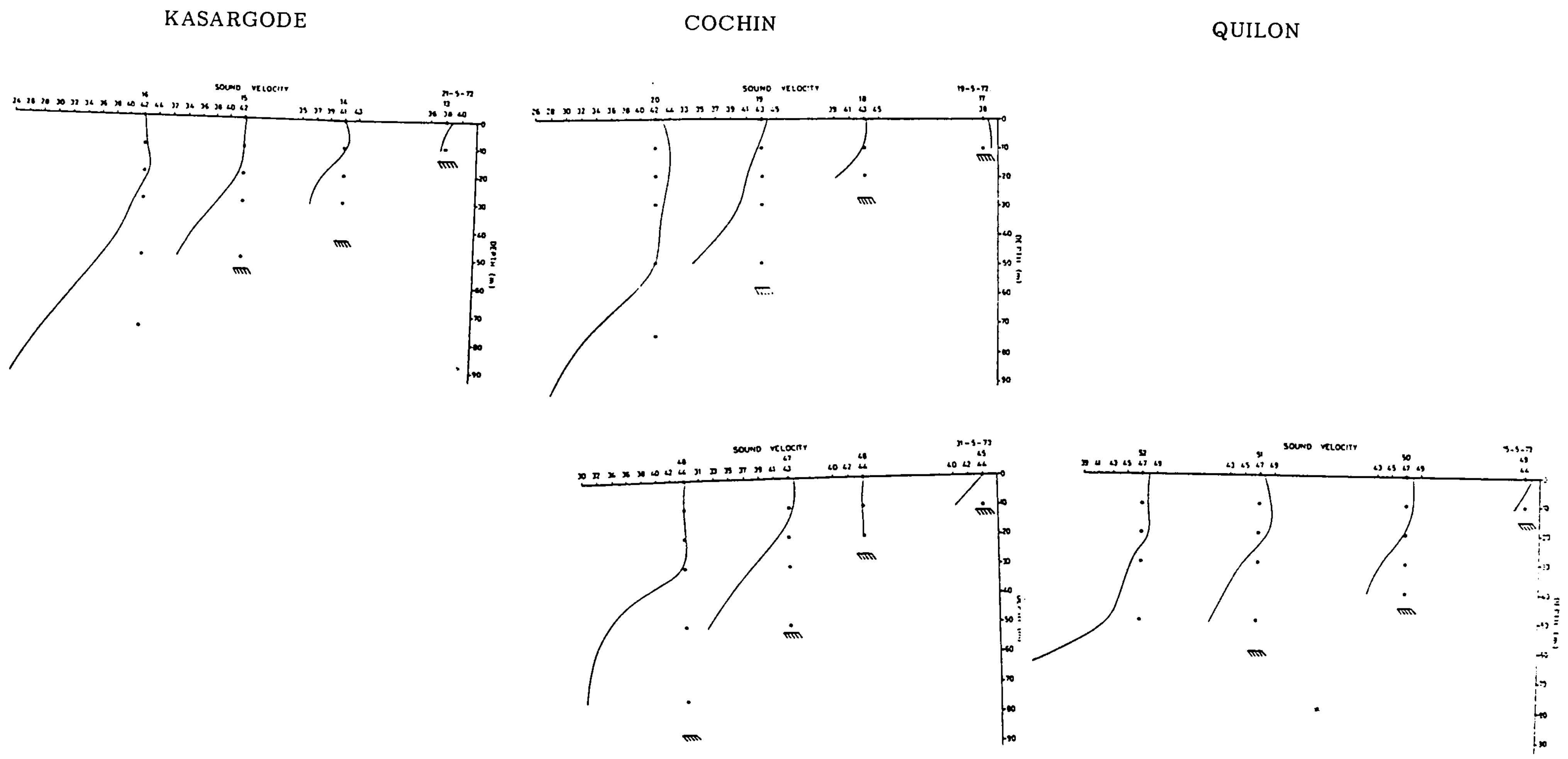

Fig. 21 Vertical distribution of sound velocity (values in m/s-1500) during May 1972 & 1973.

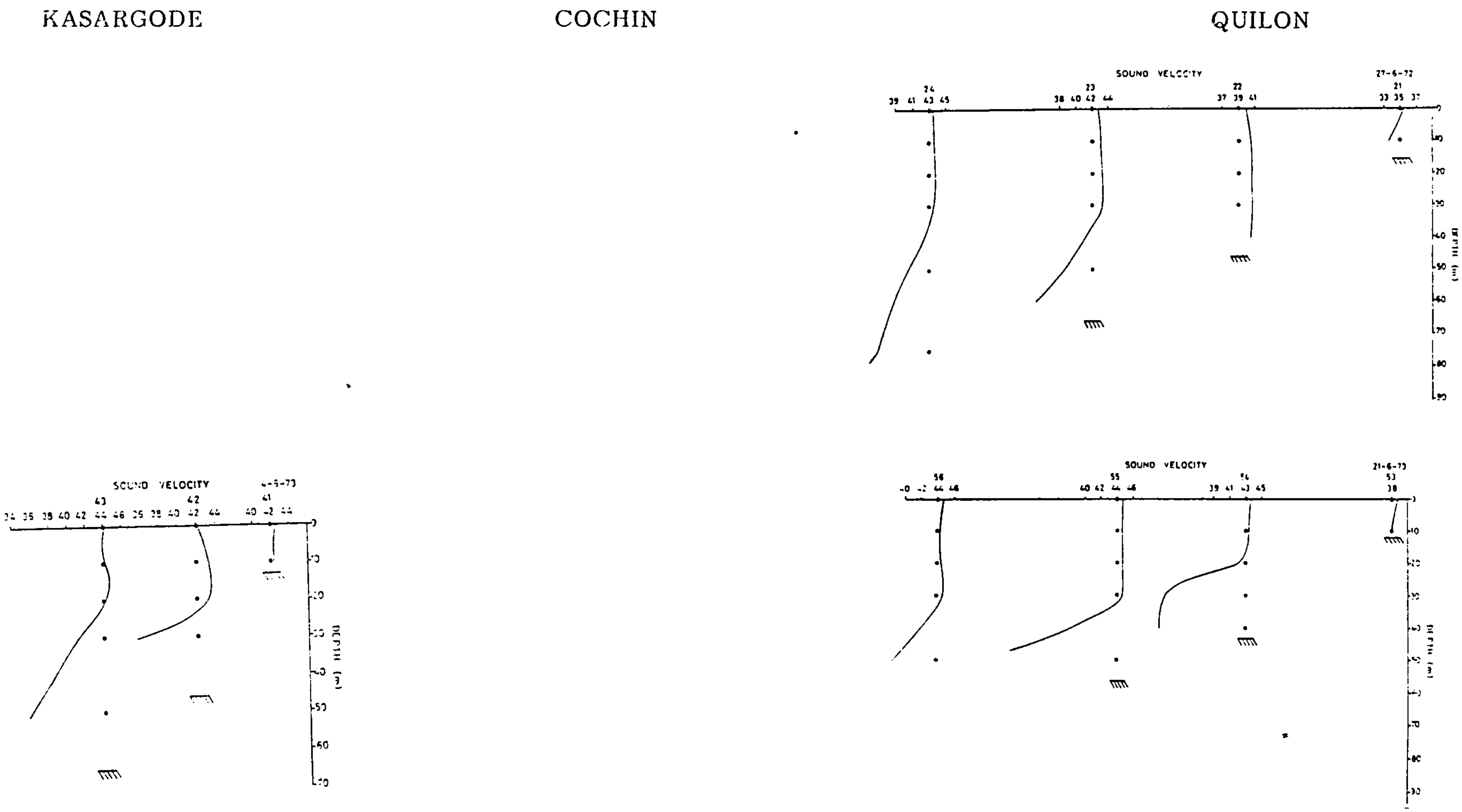

Fig. 22 Vertical distribution of sound velocity (values in m/s-1500) during June 1972 & 1973.

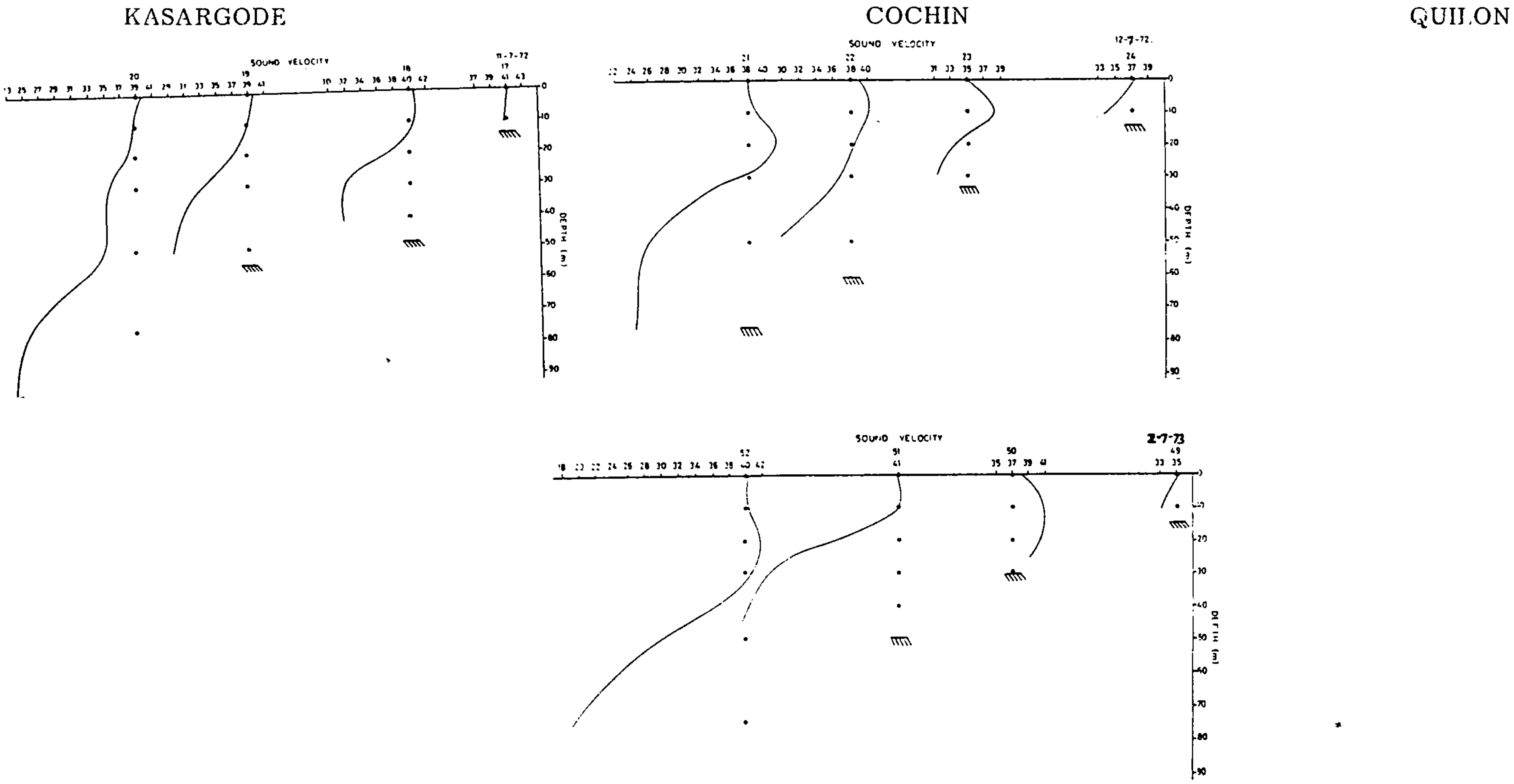

Fig. 23 Vertical distribution of sound velocity (values in m/s-1500) during July 1972 & 1973.

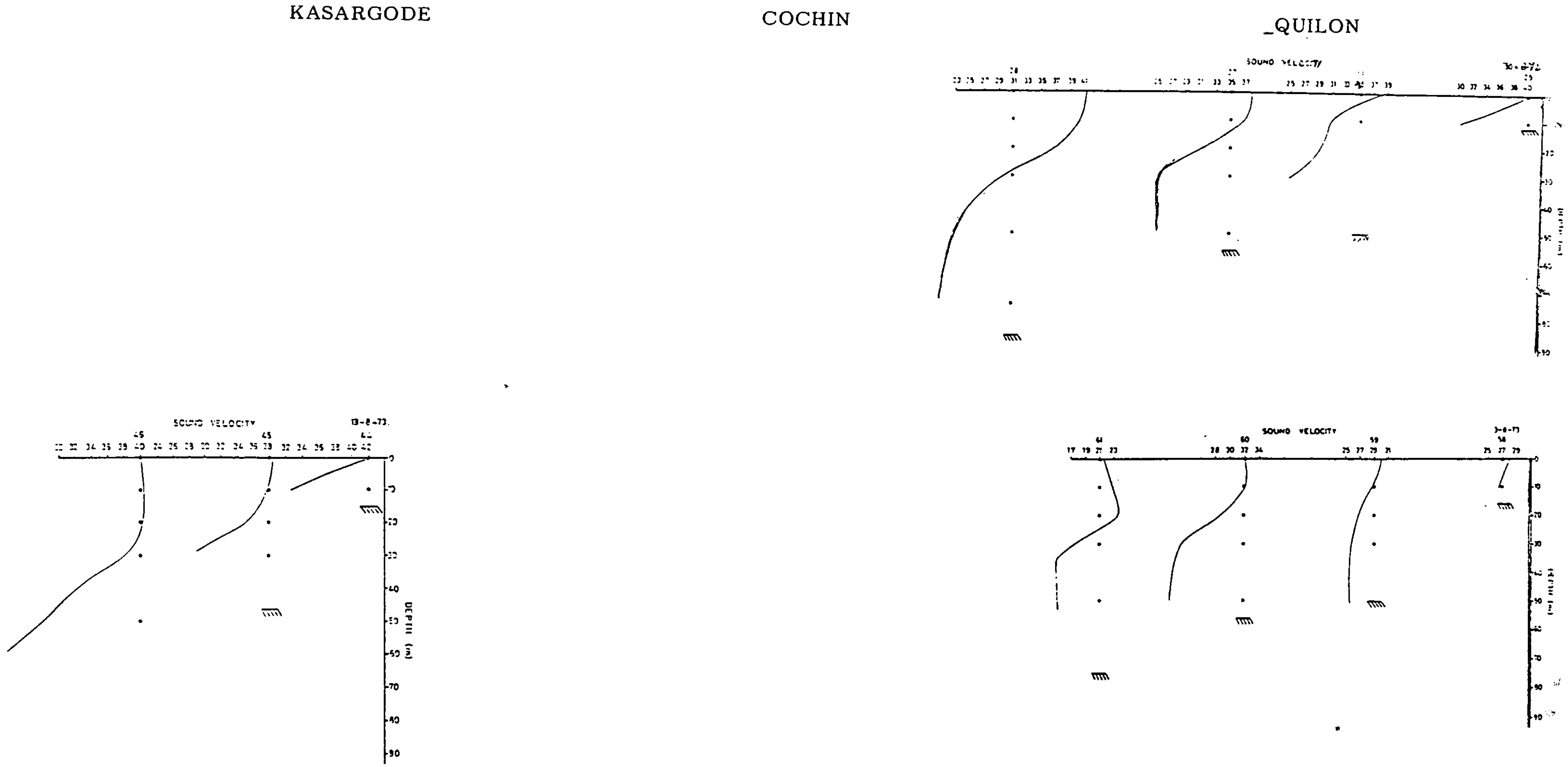

Fig. 24 Vertical distribution of sound velocity (values in m/s-1500) during August 1972 & 1973.

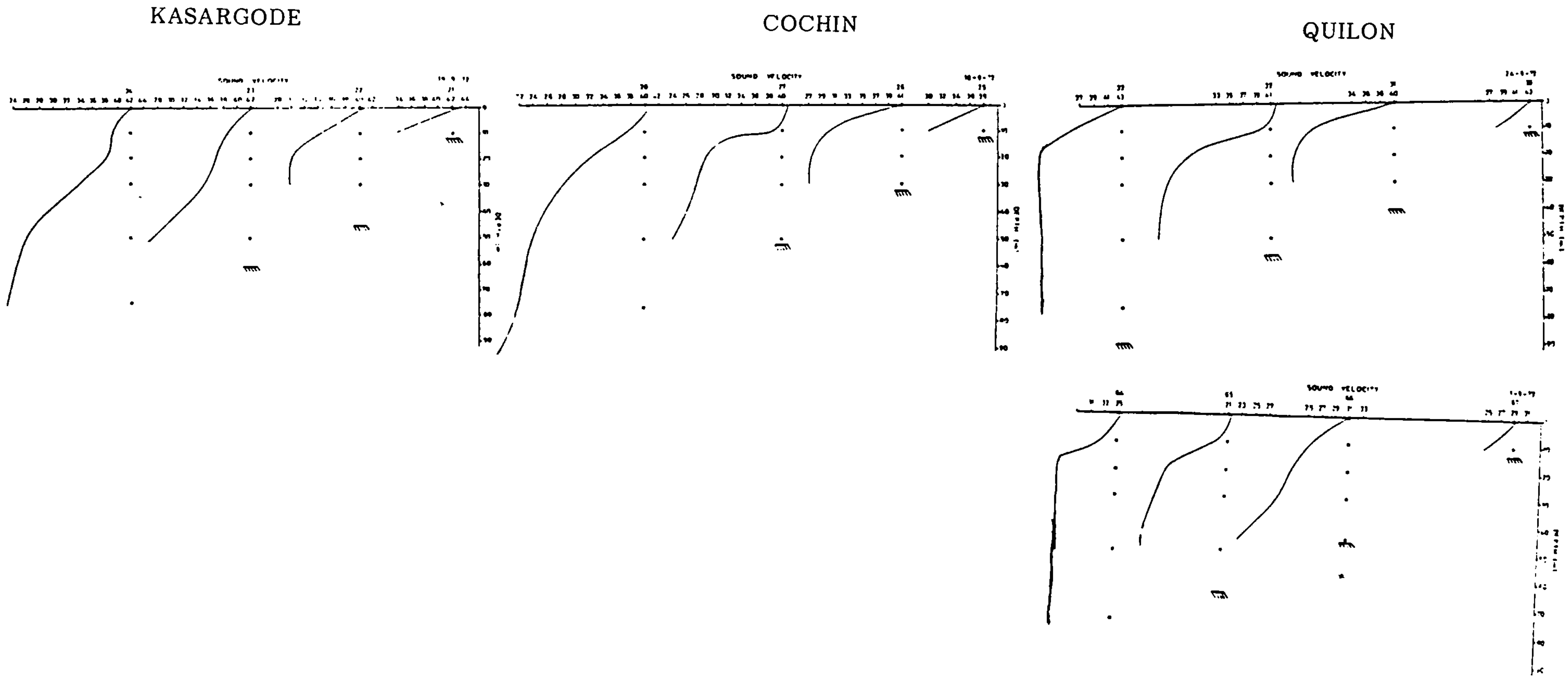

Fig. 25 Vertical distribution of sound velocity (values in M/s-1500) during September 1972 & 1973.

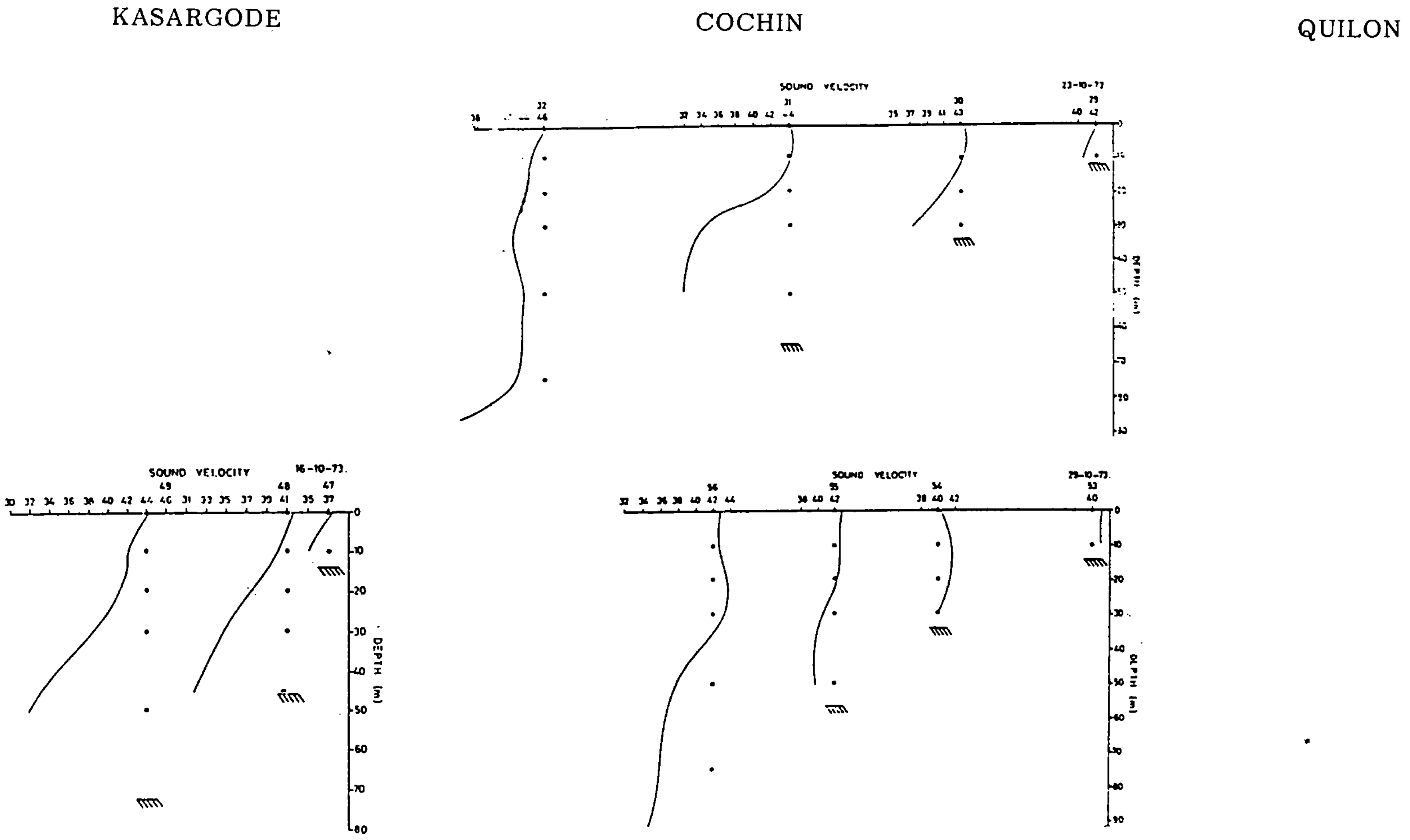

Fig. 26 Vertical distribution of sound velocity (values in m/s-1500) during October 1972 & 1973.

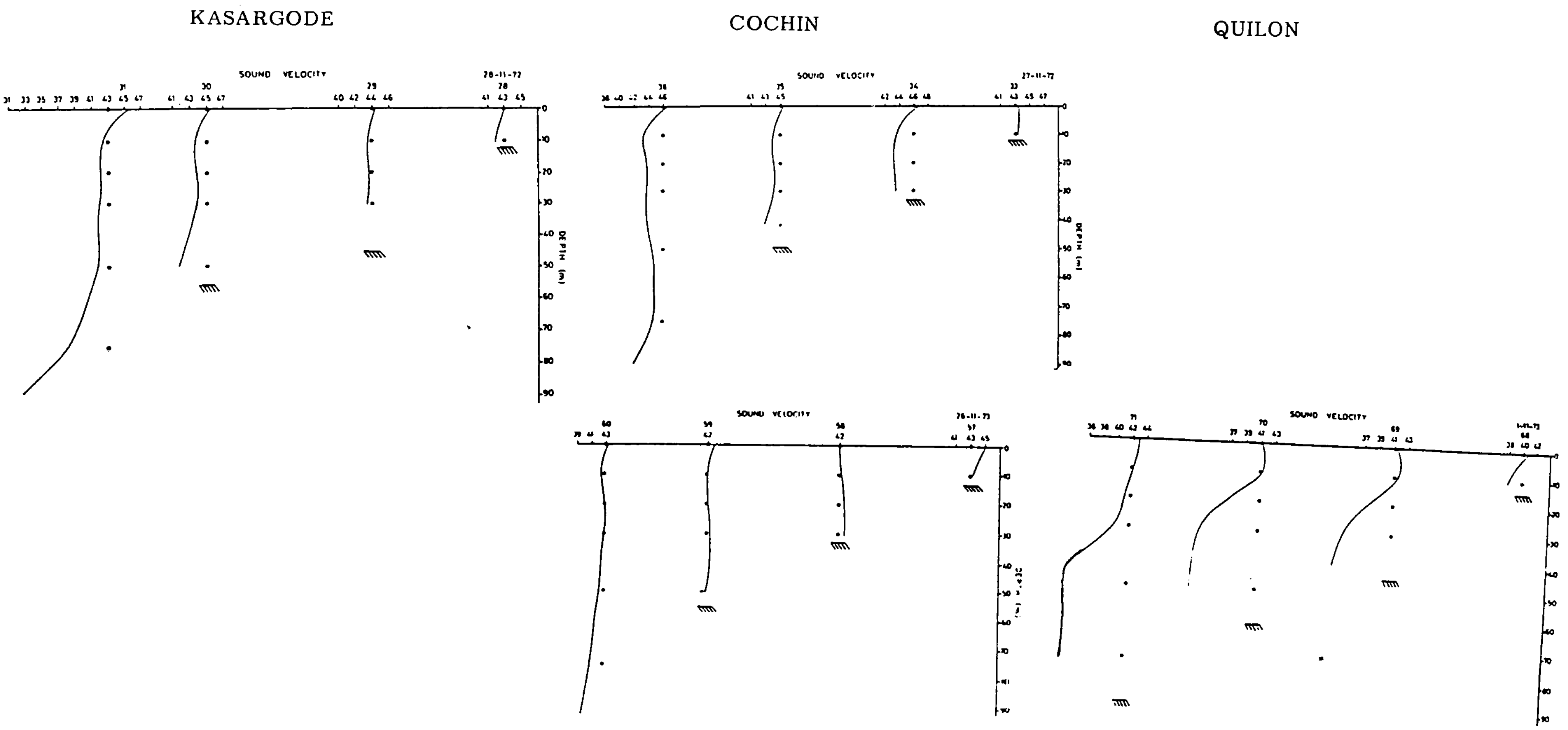

Fig. 27 Vertical distribution of sound velocity (values in m/s-1500) during November 1972 & 1973.

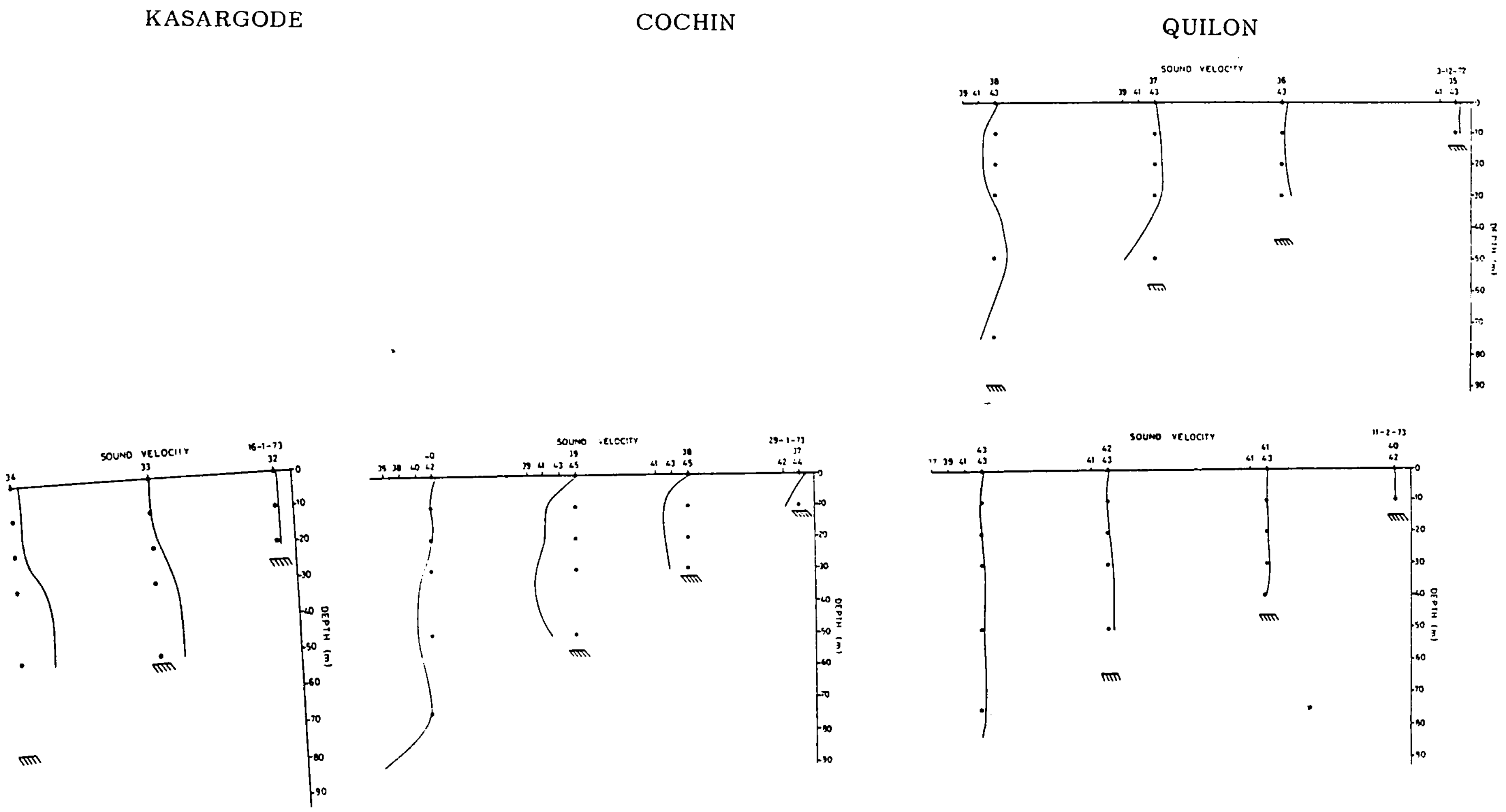

Fig. 28 Vertical distribution of sound velocity (values in M/s-1500) during December 1972, January 1973 and February 1973.

4.3 DISCUSSION.

An attempt to summarize the above results to arrive and the overall features of the high frequency acoustic propagation characteristics in the region is made in the following paragraphs. From the beginning of the year up to the end of April, the sound velocity gradients in the three sections are found to be generally very small in magnitude. This is to be expected because during this time of the year, generally, a well mixed layer is present in the region. The gradients can be either positive or negative. In the section off Quilon, during March 1972, the gradient is first negative, then positive and again negative with increase in depth. During April, the gradient is negative in the entire water column. In 1973 it is positive from the beginning of the year to the end of March and negative in April. In the section off Cochin, in the year 1972, the sound velocity gradient is positive during March and positive in the surface layer and negative below during April. In 1973 off Cochin, it is positive during January and negative in March. In the section off Kasargode it is negative during March 72 and positive in the surface layers and negative below during April 72. In 1973, it is positive during February and negative during March.

A horizontal acoustic beam in a water layer where the sound velocity gradient is negative will get refracted and bent downwards forming a surface shadow zone. On the other hand, in a layer where the sound velocity gradient is positive, the beam will be refracted upwards forming a bottom shadow zone (Urick, 1975). In the first case, the acoustic propagation will be as in a bottom duct and the propagation losses tend to be larger because of the possible bottom losses. In the second case, the propagation will be as in a surface duct and the propagation losses tend to be smaller (Camp, 1970). The conditions existed during March 1972 off Quilon and April 1972 off Cochin and Kasargode are, however, different. During March 1972, off Quilon, the acoustic propagation will be as in a surface channel in the surface layers and as in a bottom duct in the bottom layers with a shadow zone forming just below the surface layers. At Cochin and Kasargode, during April 1972, the acoustic propagation in the surface layers will be as in a surface duct whereas below the surface it is as in a bottom duct. However, since the magnitudes of the gradients are very small during the period large horizontal ranges of propagation may be possible irrespective of the sign of the gradients.

From the period from May to October, in both the years, in the three sections sound velocity gradients are seen to be positive in the surface layers and negative below during May 1972 and June 1973 off Quilon, during July 72 and July and October 73 off Cochin and during June 72 and May and June 73 off Kasargode. During the other months, sound velocity gradients are negative in all the three sections. The magnitudes of the negative gradients in all the sections are generally large and the sharpest gradients are observed in the bottom layers until the beginning of July. After that period, in the sections off Cochin and Kasargode the magnitude of the gradients in the surface layers is larger than that in the bottom layers until the end of September. In the section off Quilon, however, larger gradients in the surface layers, during July to September, are observed only in 1972. In 1973, larger gradients are observed in the bottom layers throughout the period. During the month of October 1973, in the section off Quilon, the sound velocity gradient is seen to have reduced from its value during the monsoon season and is nearly uniform throughout the water column. In the sections off Cochin and Kasargode, during September -October, sharpest gradients are observed below 10m from the surface with smaller values of gradient both in the surface and bottom layers. This sound velocity structure is almost completely broken up by the end of October in the section off Cochin, but off Kasargode it persists until the beginning of November.

Hence irrespective, of the depth of the horizontal acoustic beam, in the three sections a surface shadow zone will generally be formed during this period in both the years under study except in the month when the sound velocity gradient is positive in the surface layers. A positive gradient in the surface layer and sharp negative gradient below causes a horizontal acoustic beam in the surface layer to be refracted upwards and form a surface duct with negligible penetration downwards. A horizontal beam in the bottom layer, however, will be refracted sharply downwards. Under this condition a shadow zone is formed below the depth of the surface layer.

In the section off Cochin during the months of August to October, and Kasargode during the months of July to October, in both the years, and in the section off Quilon during July to September in the year 1972, a horizontal acoustic beam in the surface layers, where a sharp negative sound velocity gradient is observed, is refracted and bent sharply downwards so that a surface shadow zone is formed and the useful horizontal range of propagation will be limited. But in the bottom layer the acoustic beam can have a greater range of horizontal propagation. In this case the acoustic beam is prevented from reaching the surface with the result that in the bottom layer the horizontal propagation is as in a bottom duct.

The conditions in the period from November to the end of the year show that in the section off Cochin in both the years and in the section off Kasargode during 1972 the sound velocity gradients are negative in the surface layers, positive and then negative as depth increases. At Kasargode, during 1973, however, the surface layers show positive gradients below which the gradients are negative. In the section off Quilon, however, the gradients are observed to be negative. In the first two cases the acoustic propagation in the surface layers will be as in a surface channel and surface duct respectively whereas below the surface layers the propagation will be as in a bottom duct. In these cases the shadow zone will be found below the surface layers. A horizontal beam in the third case will be refracted downwards forming a surface shadow zone. Since the magnitudes of the gradients are small, horizontal propagation ranges larger than during the monsoon season are indicated.

CHAPTER V

LONG RANGE PROPAGATION CHARACTERISTICS

5.1 Introduction

In the present context long range means distance which are many times the water depth so that sound propagates to this distance by repeated reflections from both surface and bottom. Under these conditions, the acoustic characteristics of both these boundaries will have an effect on sound transmission. Such propagation characteristics are usually observed in shallow water environment. The important theoretical approaches that exist for describing the shallow water sound field are the ray theory, normal mode theory and the parabolic approximation method. The ray theory represents the source field as a sum of ray contributions, each ray emanating from a source or its image in the surface and in the bottom. At long ranges, the number of images that will have to be considered will become very large and the computation of transmission loss will become unmanageable. The parabolic approximation method will require more sampling points in the vertical and also closer station spacing than that are available for the present study. Under these circumstances, the normal mode theory is more appropriate in the present study. In this chapter, the results of the studies, using normal mode theory, on the influence of hydrography on long range acoustic upslope propagation characteristics in the coastal waters of Kerala are presented. Attenuation of the signal is not considered in these studies because the computation of attenuation coefficient requires much detailed knowledge of the medium which is not now available.

5.2 MATERIAL AND METHODS

The methodology for the computation of long range acoustic propagation characteristics has been described in Section 2.5. The basic data required are information on sound velocity and density of water and of sediment along the three sections considered.

The values of sound velocity, C, have already been computed at standard depths as described in section 2.4. The values of sound velocity in the bottom water, C_{bw}, are obtained by extrapolation from the values obtained at standard depths. The density of water, ρ, at different standard depths are computed using the values of temperature and salinity (Bailek, 1966). The values of density of the bottom water, ρ_{bw}, are obtained by extrapolation from the values of density at standard depths.

The information on the nature of the sediment is available only for the two southern sections ie., off Quilon and Cochin. In the section off Quilon, the nature of sediment is composed of fine sand whereas off Cochin, it is clayey silt up to 20m depth and sandy silt from 20m to a depth of 50m (Hashimi et al, 1981). As the shelf sediment size in the depth ranges referred can not vary considerably from year to year, the sediment size information derived from data during 1977 have been utilized along with sound velocity and density data obtained for the period 1972 - 1973. The values of density and sound velocity of these sediment types are given in Table-2. (Hamilton and Bachman, 1982).

Table - 2. Density and Sound Velocity of Sediments

Sediment	Density ρ_b (kg/m^3)	Sound velocity C_b (m/s)
Fine sand	1962	1759
Sandy silt	1769	1699
Clayey silt	1489	1546

In the region under study, the average bottom slope is less than 1°. To study the upslope propagation characteristics, two stations each in the sections off Quilon and Cochin have been selected. One is a deep station, which is generally the third from the coast where the depth is around 50m, while the other is a shallow station. In the section off Quilon, the shallow station is the one nearest to the coast, where the depth is 15m. In the section off Cochin, however the second station from the coast, where the depth is around 30m, is chosen as the shallow station. This is to eliminate the effect of variations of sediment size on the acoustic propagation characteristics, since in the section off Cochin the sediment at the first station near the coast is composed of clayey silt. Using the values of density and sound velocity of the bottom water and sediment and using eq.7 of section 4.3, plots of angular frequency, ω, against incident angle at the bottom, θ'_m, for different modes at these selected stations have been obtained (fig. 29 to 32). For these stations, during May to September, the variations of the vertical component of the propagation constant γ_m, are found to be too large to satisfy the criterion for WKB approximation. Hence, long range propagation studies during this period has not been attempted.

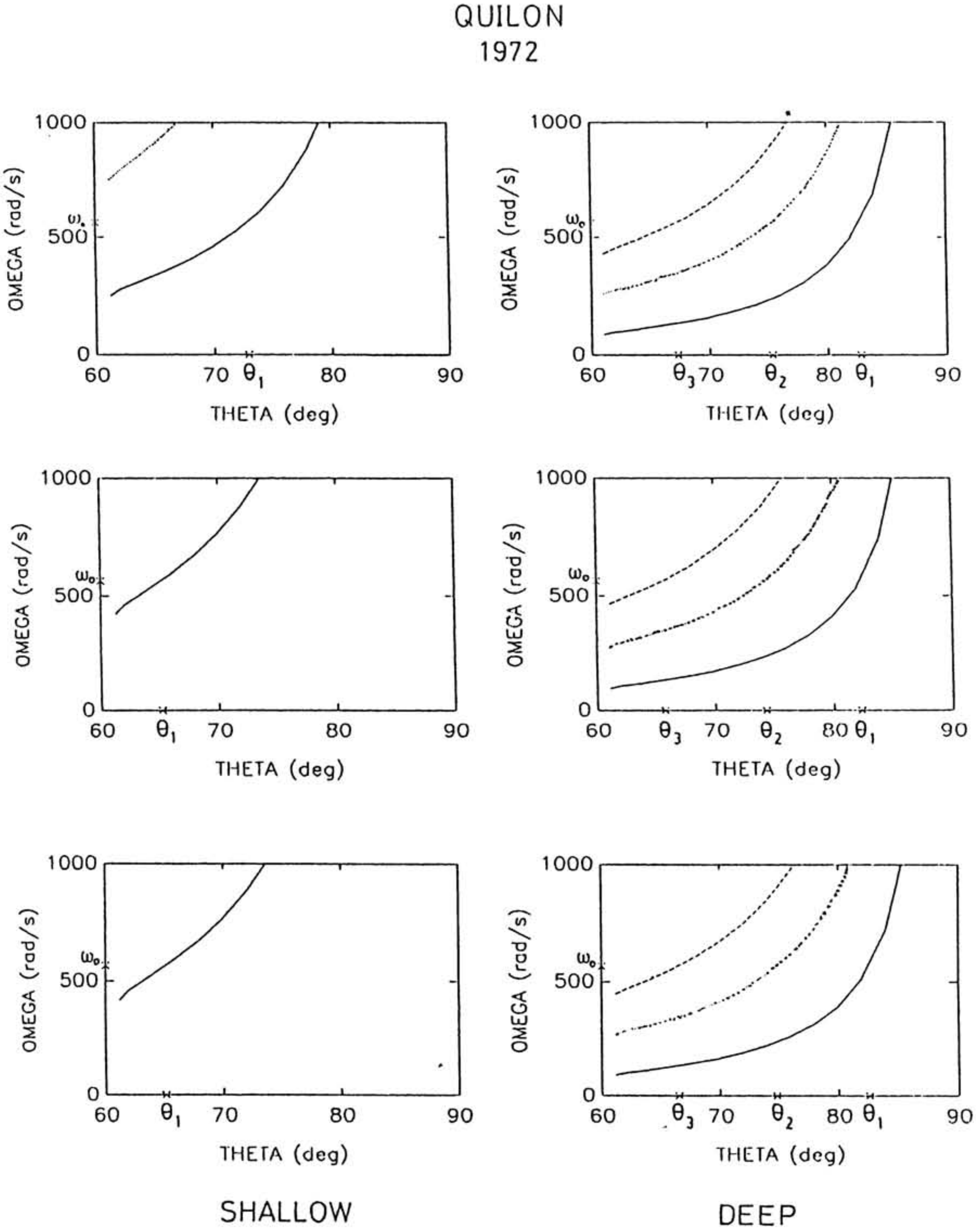

Fig.29 Angular frequency ω versus incident angle Θ'_m at the bottom for different modes. (____, Mode 1, ..., Mode 2, --------, Mode 3)

ω_o - Source frequency

Θ_m - angle of incidence of mode m.

QUILON
1973

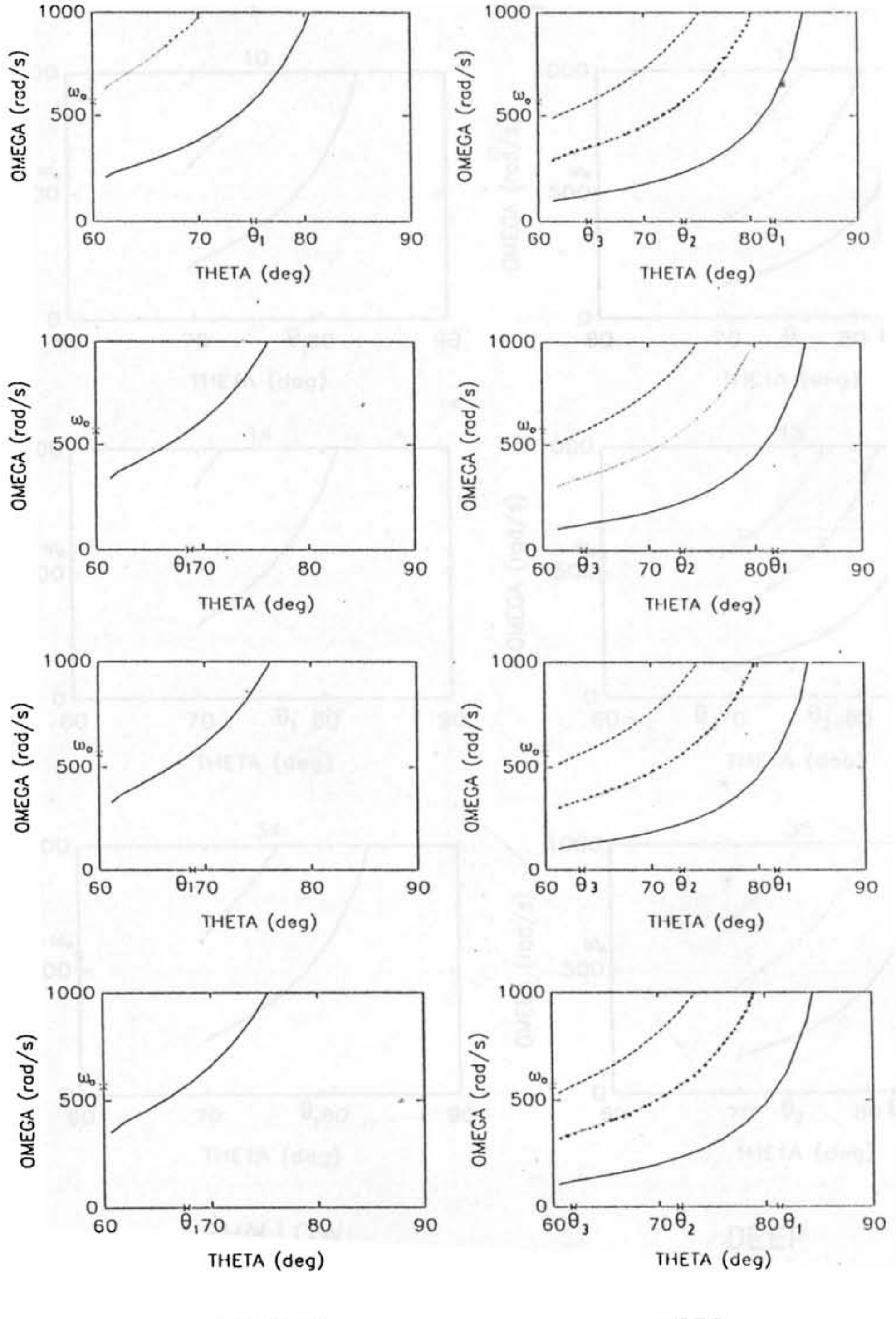

Fig.30 Angular frequency ω versus incident angle Θ'_m at the bottom for different modes. (____, Mode 1, ..., Mode 2, --------, Mode 3)

ω_o - Source frequency

Θ_m - angle of incidence of mode m.

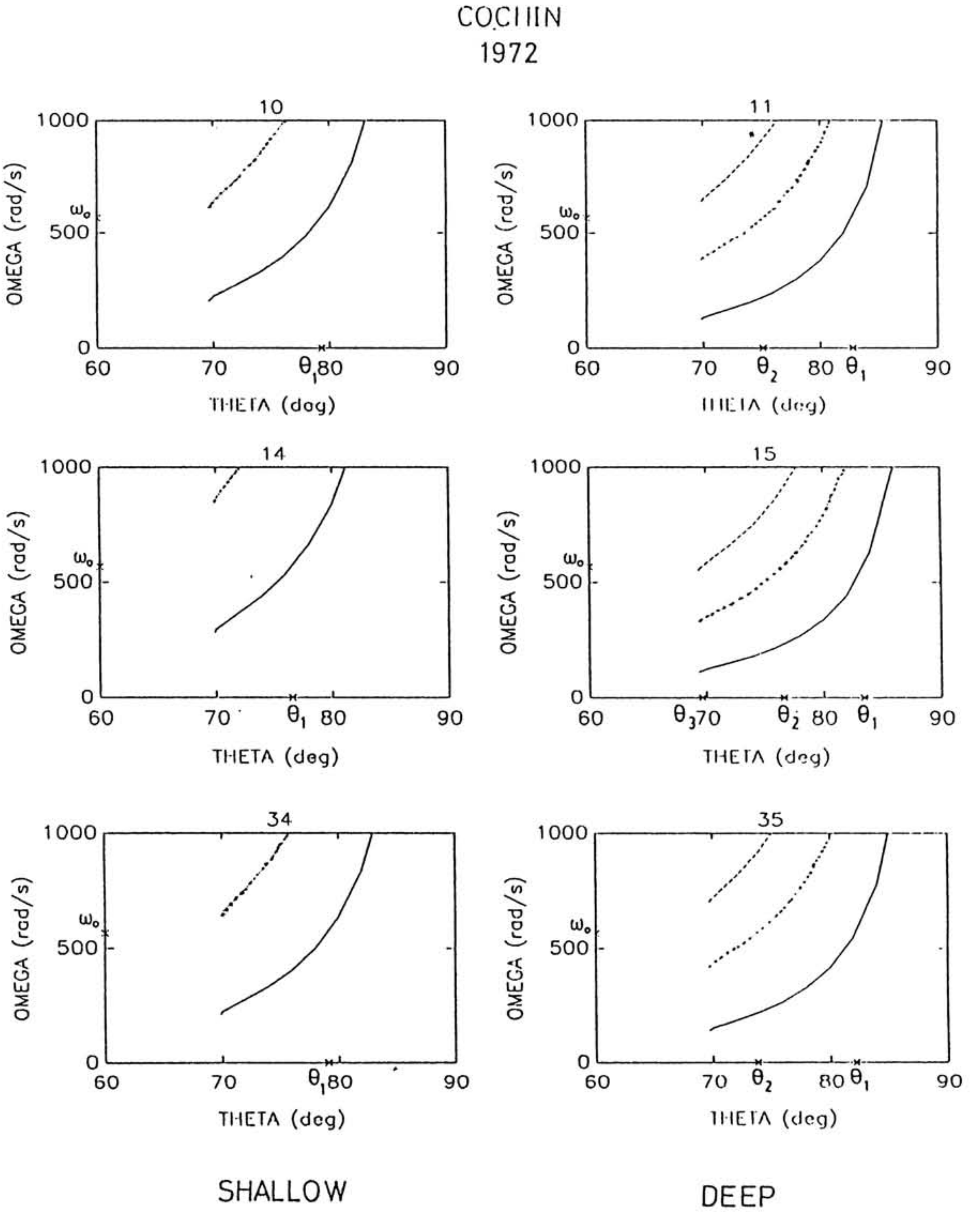

Fig. 31 Angular frequency ω versus incident angle Θ'_m at the bottom for different modes. (____, Mode 1, ..., Mode 2, --------, Mode 3)

ω_o - Source frequency

Θ_m - angle of incidence of mode m.

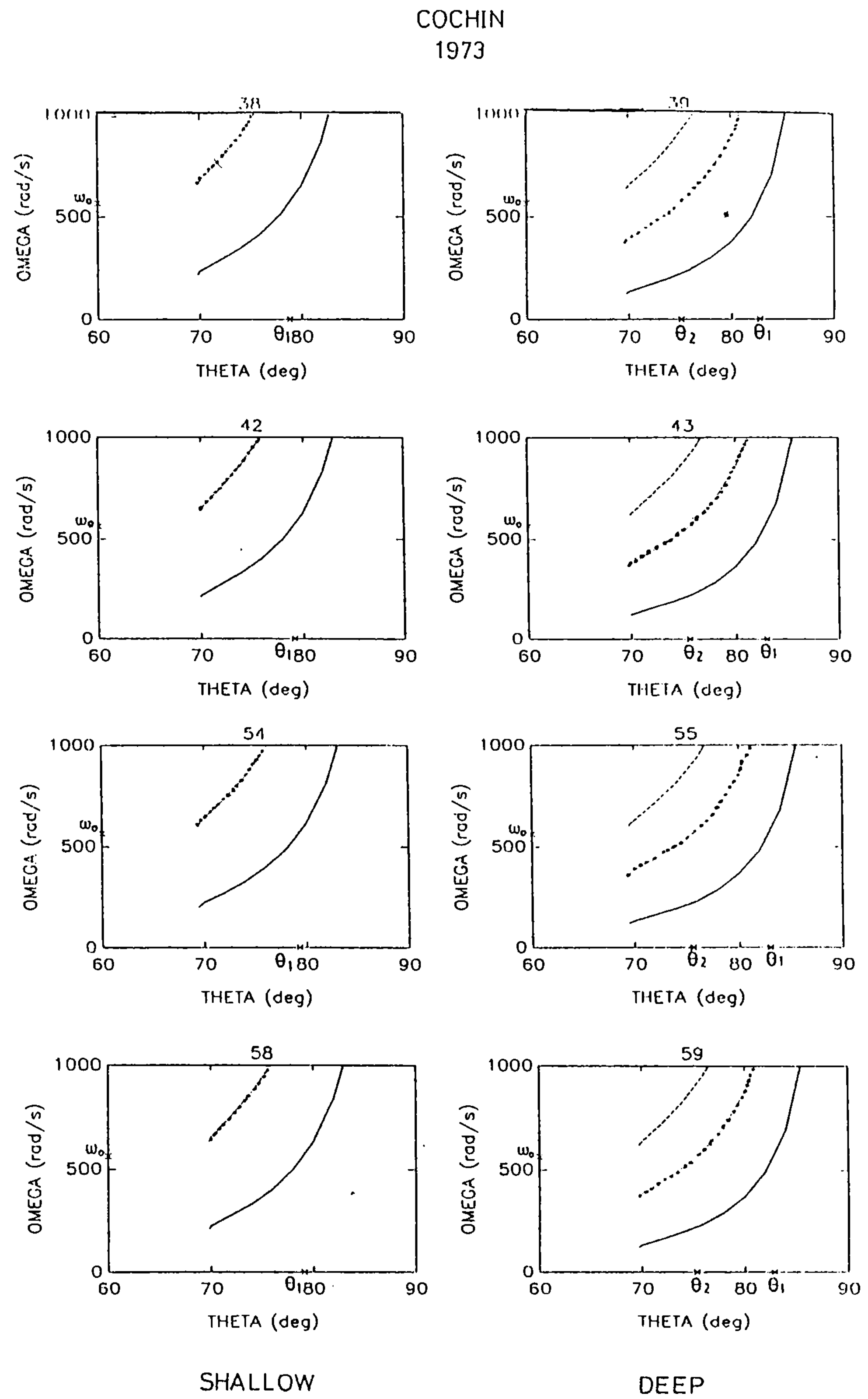

Fig.32 Angular frequency ω versus incident angle Θ'_m at the bottom for different modes. (____, Mode 1, ..., Mode 2, --------, Mode 3)

ω_o - Source frequency

Θ_m - angle of incidence of mode m.

Six frequencies ranging between 65 - 90Hz have been selected as source frequencies so that only one mode exists at the shallow stations. It is observed that in the sections of Quilon and Cochin, for the same frequency, the number of modes that exist at the deep stations are three and two respectively. The values of θm for different modes and for different frequencies are obtained from the above curves (fig. 29 to 32). Using the values of θm, the horizontal and vertical components of propagation constants at the bottom $Km(h)$ and $\gamma m(h)$ respectively, for different modes and for different frequencies are computed using eq. 8 and 9 of Section 2.4.3. $Km(h)$ is a constant for each frequency through out the water column at a station. $\gamma_m(z)$ for different depths are then computed for each station using eq.10 and modal depth functions are computed. Plots of modal depth functions against depth for 90Hz are shown in Figs. 33 - 36. Using the values of θm and $Km(h)$, the function γ_m and hence the source excitation function qm for a unit power source (1 watt) are computed for different modes. The computed values of sound velocity and density of the bottom water, the angle of incidence θm and the source excitation function qm at the selected stations for deferent modes and frequencies for Quilon and Cochin are shown in Tables 3 to 15.

To study the upslope propagation characteristics of the coastal waters, the source will have to be at the deep station and the receiver at the shallow station. For this study, the receiver is assumed to be at a depth of 10m at the shallow station. Computations are then performed by assuming that the source is at different standard depths at the deep station. Since there exists more than one mode at the deep station, the sound power

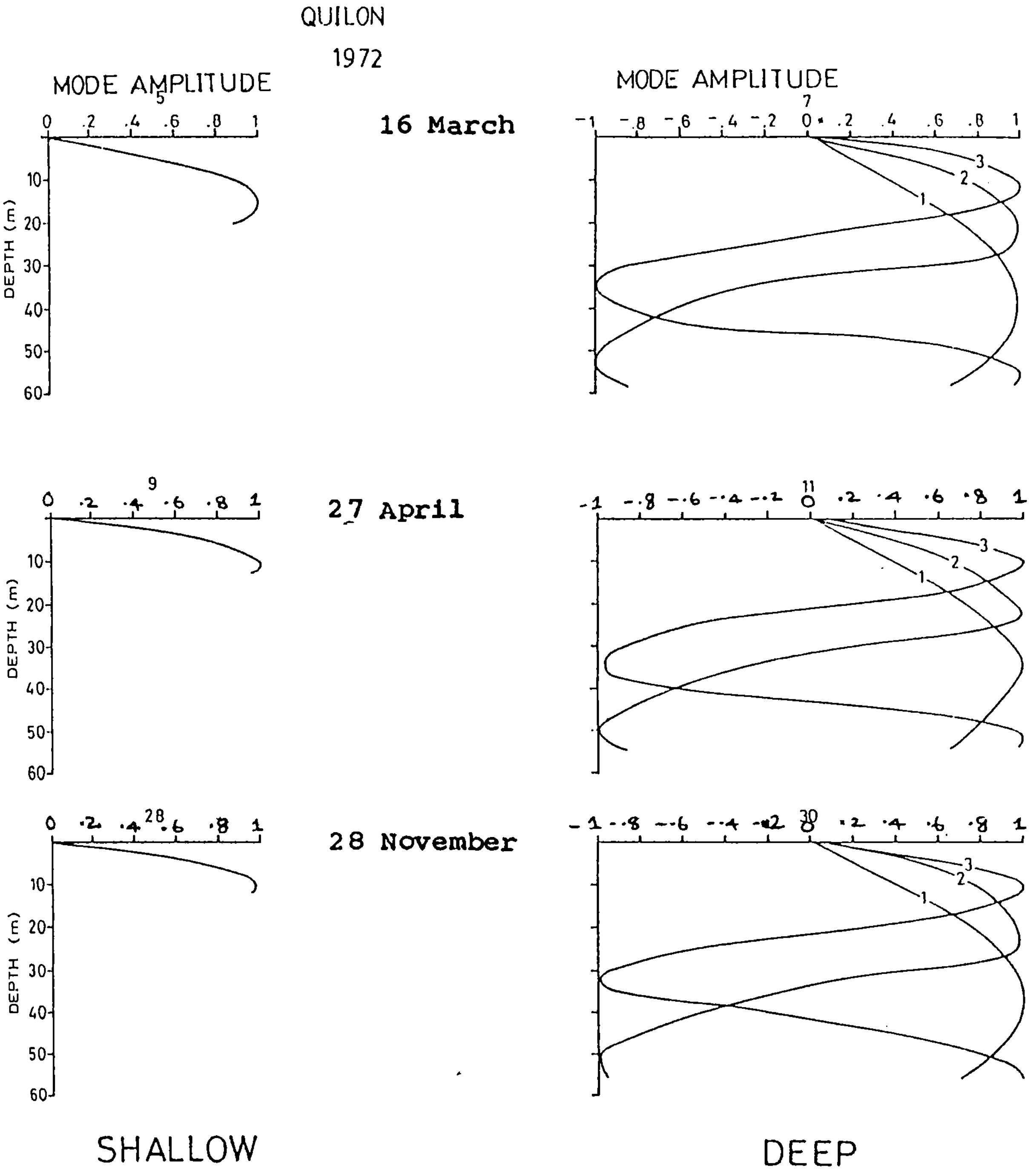

Fig. 33 Modal depth functions. Source frequency - 90Hz.

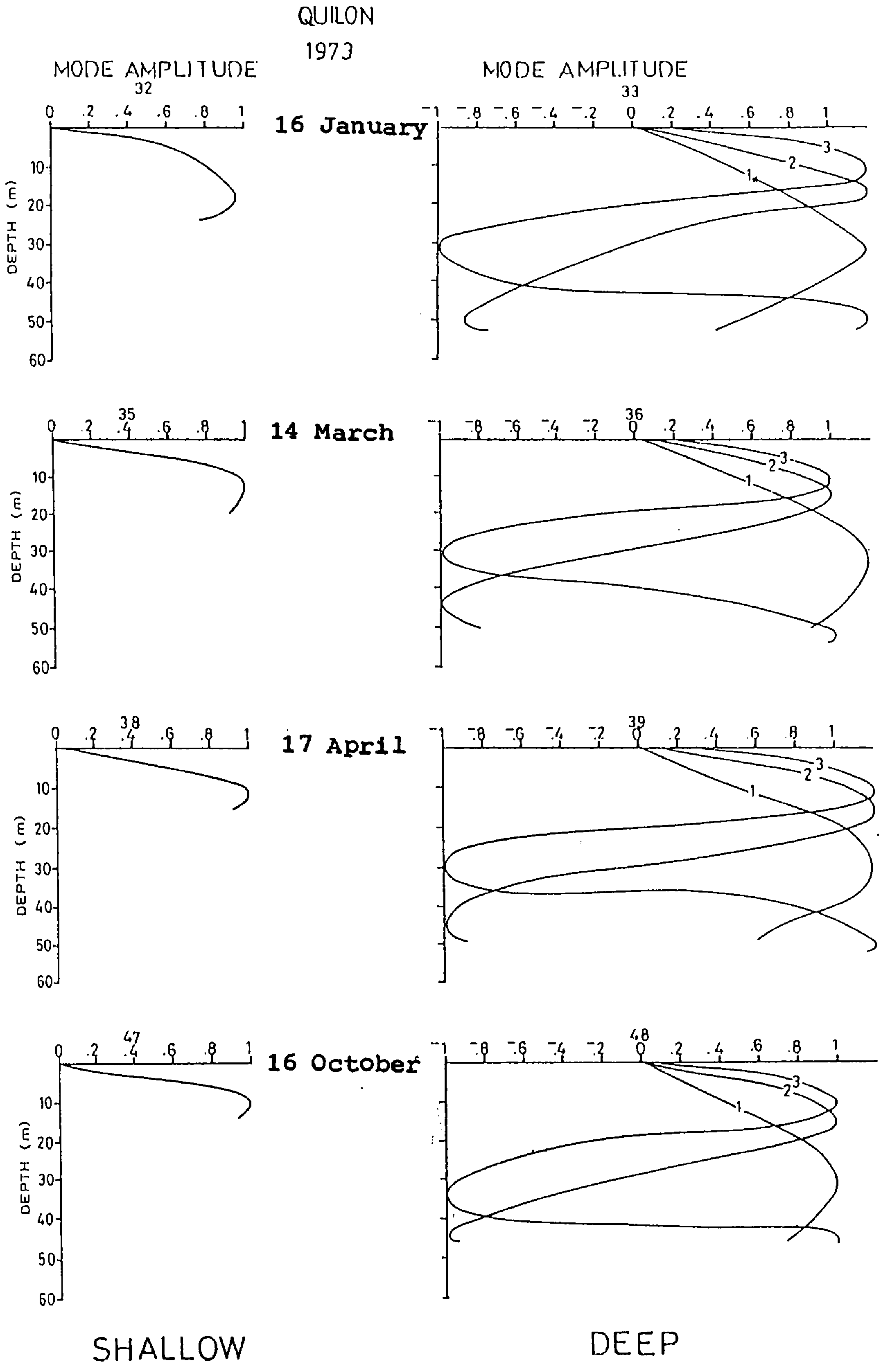

Fig. 34 Modal depth functions. Source frequency - 90Hz.

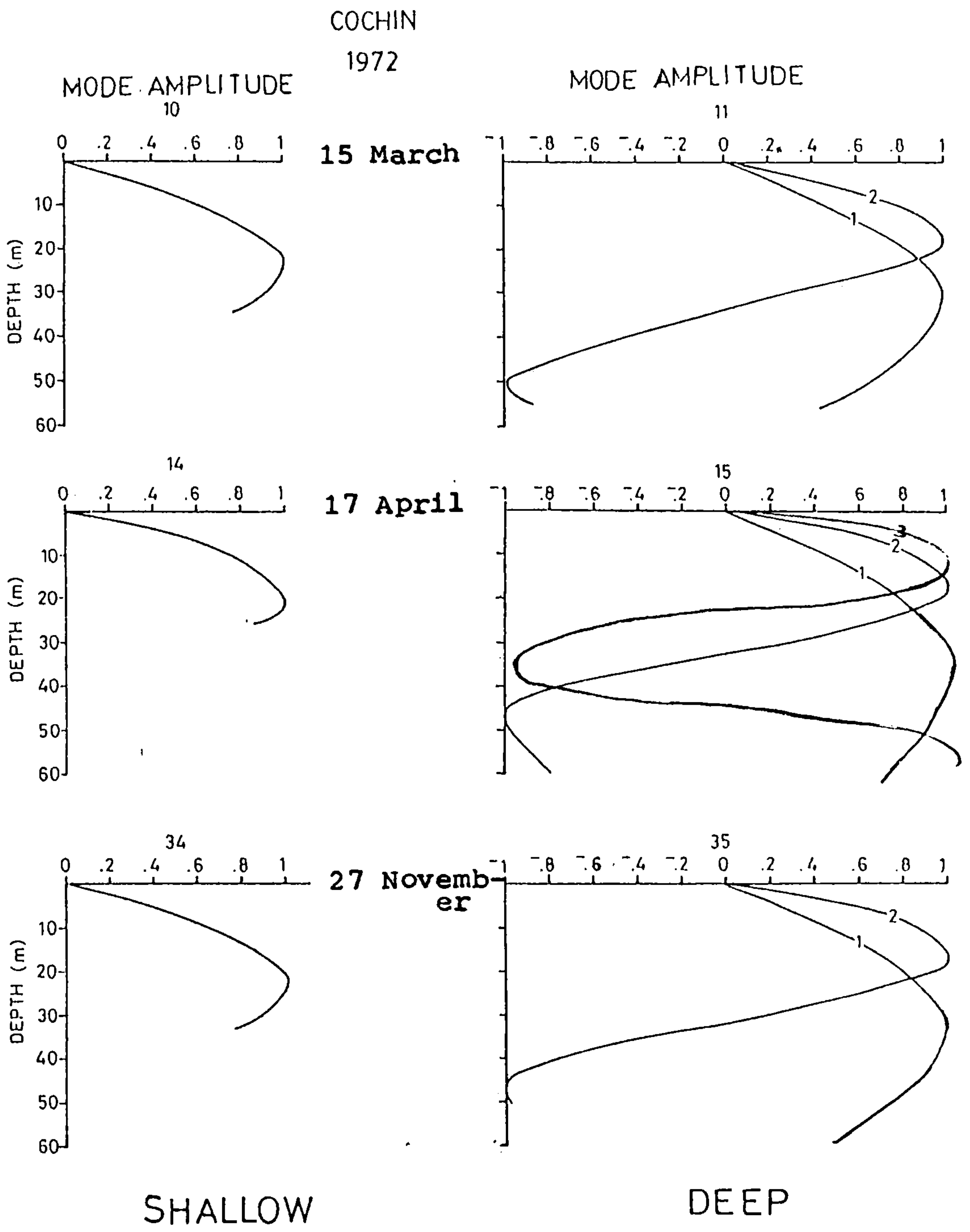

Fig. 3 5 Modal depth functions. Source frequency - 90Hz.

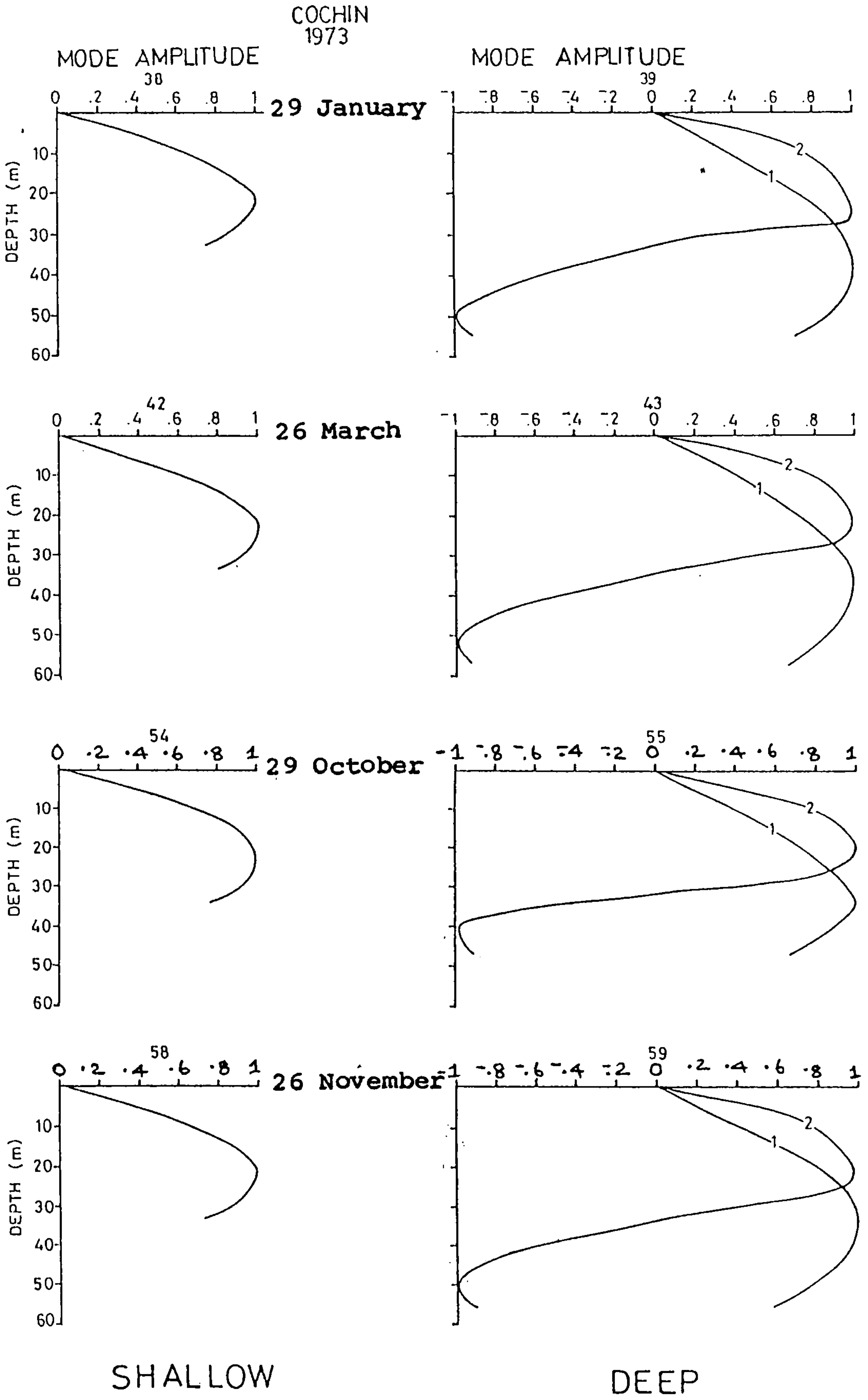

Fig.36 Modal depth functions. Source frequency - 90Hz.

radiated by the source will be transferred to the different modes depending on the amplitude of the eigen function for each of these modes at the source depth. If the stratification varies slowly with range, the power radiated into the first mode only will get propagated to the shallow stations, the other modes being cut off during their upslope propagation. The power radiated into the first mode is obtained by multiplying the output of unit power source by the ratio

$$\frac{q_1 Z_1(z)}{q_1 Z_1(z) + q_2 Z_2(z) + q_3 Z_3(z)}$$

where Zm(z) is the evaluation of eigen function of the mth mode at a depth z.

For the first mode, the mean of the source excitation function is obtained using eq. 6 and the sound pressure at the receiver is computed from eq. 12. The distance between stations are not the same when sections are occupied on different dates. To isolate the effect of stratification on transmission loss, a constant average station distance of 20Km is used for the computation of sound pressure at the receiver. The transmission loss is then computed from eq.13. A computer program developed to compute the transmission loss for the purpose of this study is given in Appendix-2.

5.3 RESULTS

Figs. 37 to 44 show plots of transmission loss for six frequencies ranging from 65 - 90 Hz in the sections off Quilon and Cochin during different months of 1972 and 1973, for a receiver depth of 10m at the shallow station, against the source depth at different standard depths at the deep station.

5.3.1 QUILON

Studies on the transmission loss in the section off Quilon have shown that during 1972 the signal frequency of 65Hz is less than the cutoff frequency at the shallow station. This indicates that the signal produced at this frequency at the deep station off Quilon will not reach the shallow station. During 1973, however, 65Hz is greater than the cutoff frequency at the shallow station indicating possibility of transmission of energy between the deep and shallow station at this frequency.

Another feature that is observed in the section relates to the number of modes present at the deep station. During 1972, it is observed that only two modes are present at the deep station for all the frequencies under study. During 1973, however, the number of modes at the deep station are two for lower frequencies and three for higher frequencies. During January 1973, only two modes are present up to a frequency of 75Hz and three modes for the higher frequencies. During the subsequent months of the year, two modes are observed up to a frequency of 80Hz and three for the higher frequencies.

The variation of transmission loss with depth is seen to have similar characteristics during both the years and for all the frequencies under study. It is seen that the transmission loss has comparatively larger value when the source is near the sea surface. The transmission loss decreases as the depth increases and at a depth of 30m, the minimum value is observed. The transmission loss again increases when the source depth increases further. It is also observed that the transmission loss is larger, when the source is near the surface than when it is near the bottom.

It is observed that the section off Quilon shows variations in transmission loss with space, time and source frequency. During March 1972, the transmission loss slightly increases as the source frequency increases except at 20m where it decreases slightly. The increase of transmission loss for the range of frequencies under study is less than 1dB. During March 1973, however, the transmission loss decreases as frequency increases up to 80Hz. Subsequent increase in transmission loss at 85Hz may be attributed to the increase in the number of modes at the deep station. The transmission losses with the source at different depths are observed to be less by 2 to 5 dB during 1973 compared to 1972.

During April 1972, the transmission loss decreases by 3dB as the frequency increases from 65-90Hz. The transmission loss for the source frequency of 70Hz is greater by 2 to 4dB than during March 72. For the other frequencies, the transmission loss is less by around 2dB except at the bottom where it is greater by 2dB compared to March. During April 1973, the transmission loss characteristics are observed to be similar to those during March 1973 except at the bottom where it is greater than during March 1973 (2 to 4dB). The transmission loss during April 1973 is less by 2 to 5dB than during April 1972.

During the month of November 1972, the transmission loss decreases by about 3dB as the frequency increases through the range

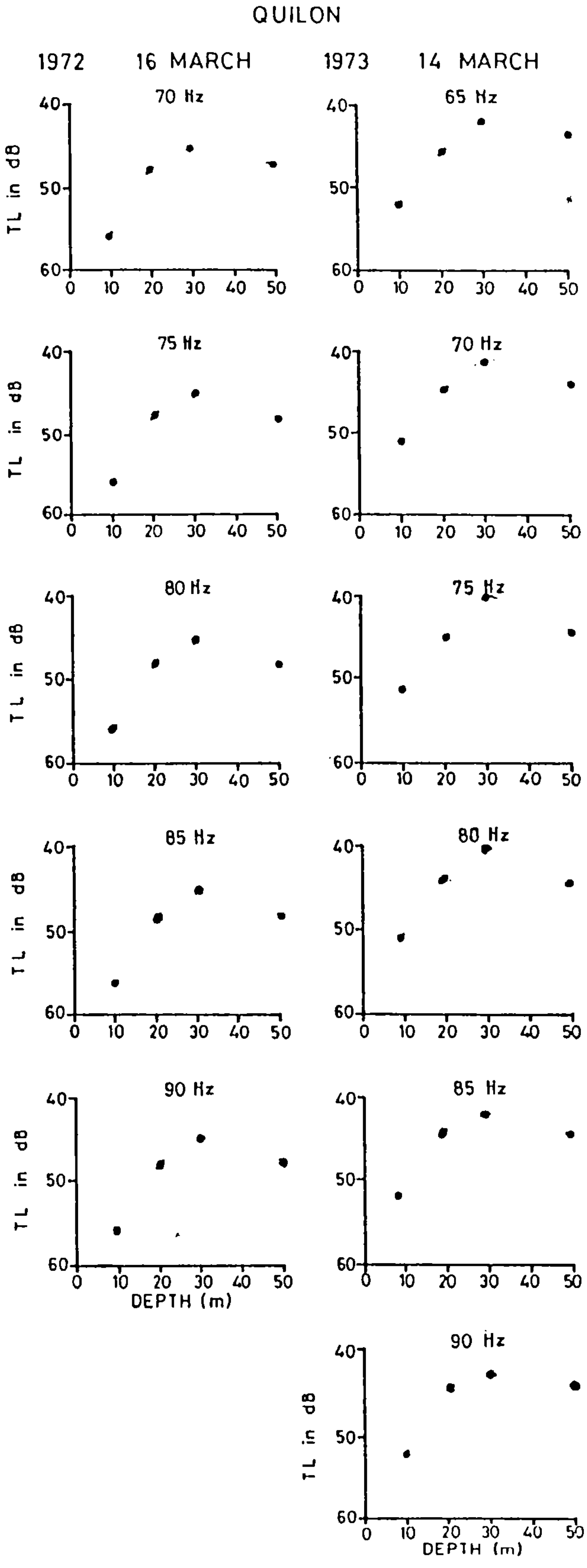

fig. 37 Transmission loss versus source depth for different frequencies at a range of 20 Km. Receiver depth - 10m.

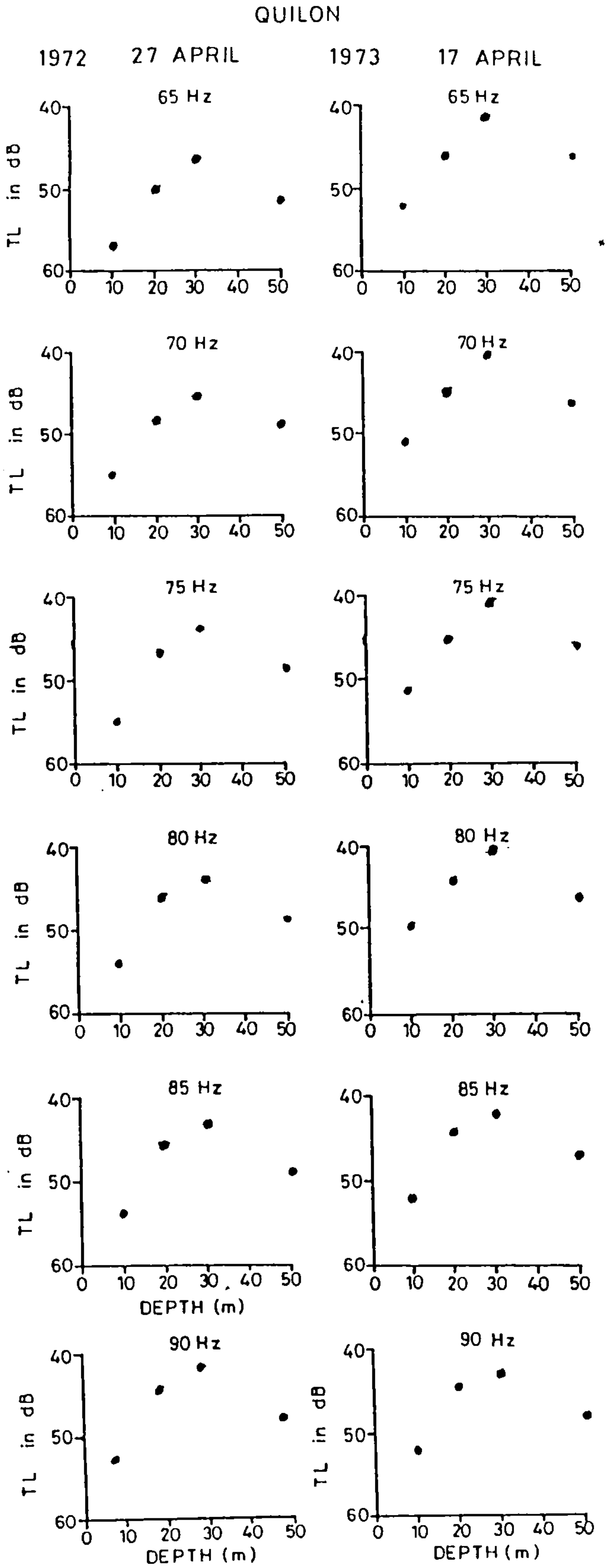

Fig. 38 Transmission loss versus source depth for different frequencies at a range of 20 Km. Receiver depth - 10m.

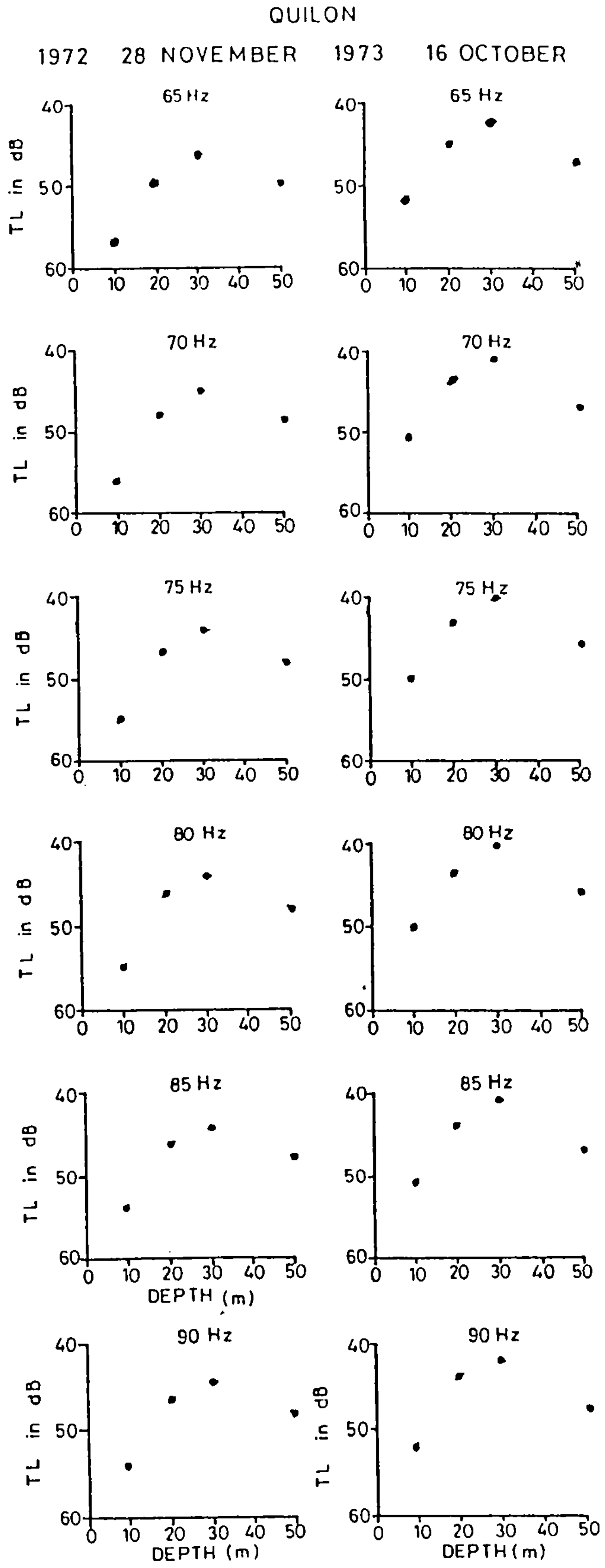

Fig.39 Transmission loss versus source depth for different frequencies at a range of 20 Km. Receiver depth - 10m.

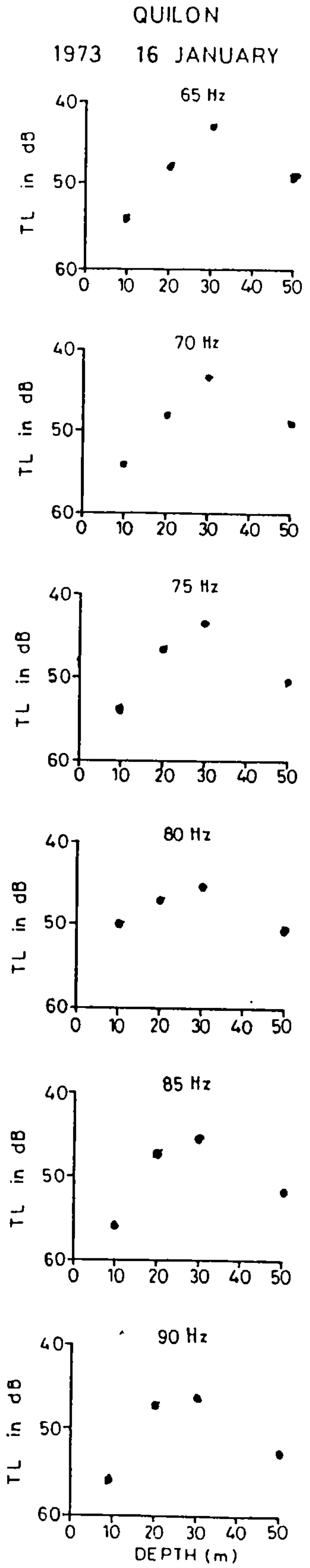

Fig. 40 Transmission loss versus source depth for different frequencies at a range of 20 Km. Receiver depth - 10m.

TABLE - 3: COMPUTED VALUES OF ANGLE OF INCIDENCE AND SOURCE EXCITATION AT DIFFERENT MODES FOR STATION QUILON.

SOURCE FREQUENCY 65Hz (S denotes shallow station, D denotes deep station).

Month & Year	Station	Density of bottom water ρ_{bw} (Kg/m^3)	Sound Velocity in bottom water C_{bw} (m/s)	Mode 1		Mode 2		Mode 3	
				θ_1 (^{o})	q_1 ($m^{5/2}/s^2$)	θ_2 (^{o})	q_2 ($m^{5/2}/s^2$)	θ_3 (^{o})	q_3 ($m^{5/2}/s^2$)
1972 March	S	1021.56	1541.40	80.52	0.35	70.25	0.37		
	D	1021.10	1538.30	-	-	-	-		
1972 April	S	1021.36	1543.20	79.94	0.37	68.92	0.39		
	D	1021.98	1540.00	-	-	-	-		
1972 November	S	1021.46	1541.80	80.22	0.36	99.58	0.38		
	D	1023.26	1541.20	-	-	-	-		
1973 January	S	1021.63	1541.40	70.88	0.62	-	-		
	D	1021.40	1543.90	79.61	0.39	68.17	0.39		
1973 March	S	1021.30	1543.40	63.48	0.55	-	-		
	D	1022.01	1544.80	79.27	0.40	67.40	0.40		
1973 April	S	1021.36	1541.20	63.44	0.56	-	-		
	D	1022.41	1542.00	79.10	0.40	66.98	0.40		
1973 October	S	1023.33	1534.20	62.23	0.50	-	-		
	D	1023.80	1531.60	78.53	0.42	65.72	0.41		

TABLE- 4: COMPUTED VALUES OF ANGLE OF INCIDENCE AND SOURCE EXCITATION AT DIFFERENT MODES FOR STATION QUILON.
SOURCE FREQUENCY 70Hz, (S denotes shallow station, D denotes deep station).

Month & Year	Station	Density of bottom water ρ_{bw} (Kg/m^3)	Sound Velocity in bottom water C_{bw} (m/s)	Mode 1		Mode 2		Mode 3	
				0_1( )	q_1(m$^{5/2}$/s^2)	0_2( )	q_2(m$^{5/2}$/s^2)	0_3( )	q_3(m$^{5/2}$/s^2)
1972 March	S	1021.56	1541.40	69.28	0.67	-	-	-	-
	D	1021.10	1538.30	81.10	0.35	71.52	0.37	61.80	0.21
1972 April	S	1021.36	1543.20	61.52	0.23	-	-	-	-
	D	1021.98	1540.00	80.53	0.37	70.28	0.38	-	-
1972 November	S	1021.46	1541.80	61.46	0.24	-	-	-	-
	D	1023.26	1541.20	80.81	0.36	70.90	0.38	-	-
1973 January	S	1021.63	1541.40	71.92	0.63	-	-	-	-
	D	1021.40	1543.90	80.23	0.38	69.58	0.39	-	-
1973 March	S	1021.30	1543.40	64.66	0.63	-	-	-	-
	D	1022.01	1544.80	79.91	0.39	68.84	0.40	-	-
1973 April	S	1021.36	1541.20	64.64	0.64	-	-	-	-
	D	1022.41	1542.00	79.74	0.39	68.47	0.41	-	-
1973 October	S	1023.33	1534.20	63.40	0.61	-	-	-	-
	D	1023.80	1531.60	79.21	0.41	67.23	0.42	-	-

TABLE - 5: COMPUTED VALUES OF ANGLE OF INCIDENCE AND SOURCE EXCITATION AT DIFFERENT MODES FOR STATION QUILON. SOURCE FREQUENCY 75Hz. (S denotes shallow station, D denotes deep station).

Month & Year	Station	Density of bottom water ρ_{bw} (Kg/m^3)	Sound Velocity in bottom water C_{bw} (m/s)	Mode 1		Mode 2		Mode 3	
				θ_1 (°)	q_1 ($m^{5/2}/s^2$)	θ_2 (°)	q_2 ($m^{5/2}/s^2$)	θ_3 (°)	q_3 ($m^{5/2}/s^2$)
1972 March	S	1021.56	1541.40	70.31	0.68	-	-	-	-
	D	1021.10	1538.30	81.60	0.34	72.64	0.36	63.05	0.31
1972 April	S	1021.36	1543.20	62.30	0.45	-	-	-	-
	D	1021.98	1540.00	81.07	0.36	71.47	0.38	61.35	0.19
1973 November	S	1021.46	1541.80	62.26	0.46	-	-	-	-
	D	1023.26	1541.20	81.33	0.35	72.06	0.37	62.19	0.27
1973 January	S	1021.63	1541.40	72.85	0.63	-	-	-	-
	D	1021.40	1543.90	80.77	0.37	70.81	0.39	-	-
1973 March	S	1021.30	1543.40	65.80	0.69	-	-	-	-
	D	1022.01	1544.80	80.47	0.39	70.11	0.40	-	-
1973 April	S	1021.36	1541.20	65.78	0.70	-	-	-	-
	D	1022.41	1542.00	80.31	0.39	69.76	0.40	-	-
1973 October	S	1023.33	1534.20	64.55	0.69	-	-	-	-
	D	1023.80	1531.60	79.80	0.40	68.64	0.42	-	-

TABLE - 6: COMPUTED VALUES OF ANGLE OF INCIDENCE AND SOURCE EXCITATION AT DIFFERENT MODES FOR STATION QUILON. SOURCE FREQUENCY 80Hz. (S denotes shallow station, D denotes deep station).

Month & Year	Station	Density of bottom water ρ_{bw} (Kg/m^3)	Sound Velocity in bottom water C_{bw} (m/s)	Mode 1		Mode 2		Mode 3	
				θ_1 (°)	q_1 ($m^{5/2}/s^2$)	θ_2 (°)	q_2 ($m^{5/2}/s^2$)	θ_3 (°)	q_3 ($m^{5/2}/s^2$)
1972 March	S	1021.56	1541.40	71.24	0.69	-	-	-	-
	D	1021.10	1538.30	82.04	0.33	73.62	0.35	64.62	0.33
1972 April	S	1021.36	1543.20	63.23	0.59	-	-	-	-
	D	1021.98	1540.00	81.79	0.34	73.08	0.36	63.75	0.32
1972 November	S	1021.46	1541.80	63.20	0.59	-	-	-	-
	D	1023.26	1541.20	81.79	0.34	73.08	0.36	63.75	0.32
1973 January	S	1021.63	1541.40	73.68	0.62	-	-	-	-
	D	1021.40	1543.90	81.26	0.36	71.89	0.38	61.96	0.25
1973 March	S	1021.30	1543.40	66.85	0.72	-	-	-	-
	D	1022.01	1544.80	81.00	0.38	71.23	0.39	-	-
1973 April	S	1021.36	1541.20	66.83	0.73	-	-	-	-
	D	1022.41	1542.00	80.82	0.38	70.90	0.39	-	-
1973 October	S	1023.33	1534.20	65.64	0.73	-	-	-	-
	D	1023.80	1531.60	3 80.83 //	0.39	69.85	0.42	-	-

TABLE - 7: COMPUTED VALUES OF ANGLE OF INCIDENCE AND SOURCE EXCITATION AT DIFFERENT MODES FOR STATION QUILON. SOURCE FREQUENCY 85Hz. (S denotes shallow station, D denotes deep station).

Month & Year	Station	Density of bottom water ρ_{bw} (Kg/m^3)	Sound Velocity in botton water C_{bw} (m/s)	Mode 1		Mode 2		Mode 3	
				θ_1 (^{o})	q_1 ($m^{5/2}/s^2$)	θ_2 (^{o})	q_2 ($m^{5/2}/s^2$)	θ_3 (^{o})	q_3 ($m^{5/2}/s^2$)
1972 March	S	1021.56	1541.40	72.08	0.69	-	-	-	-
	D	1021.10	1538.30	82.44	0.33	74.50	0.35	66.03	0.34
1972 April	S	1021.36	1543.20	64.20	0.68	-	-	-	-
	D	1021.98	1540.00	81.96	0.35	73.50	0.37	64.35	0.34
1972 November	S	1021.46	1541.80	64.17	0.68	-	-	-	-
	D	1023.26	1541.20	82.21	0.34	73.98	0.36	65.19	0.34
1973 January	S	1021.63	1541.40	74.43	0.62	-	-	-	-
	D	1021.40	1543.90	81.69	0.36	72.86	0.38	63.41	0.32
1973 March	S	1021.30	1543.40	67.83	0.75	-	-	-	-
	D	1022.01	1544.80	81.41	0.37	72.23	0.39	62.46	0.29
1973 April	S	1021.36	1541.20	67.82	0.76	-	-	-	-
	D	1022.41	1542.00	81.27	0.37	71.92	0.40	61.99	0.27
1973 October	S	1023.33	1534.20	66.65	0.77	-	-	-	-
	D	1023.80	1531.60	80.82	0.39	70.92	0.42	60.57	0.09.

TABLE - 8: COMPUTED VALUES OF ANGLE OF INCIDENCE AND SOURCE EXCITATION AT DIFFERENT MODES FOR STATION QUILON. SOURCE FREQUENCY 90Hz. (S denotes shallow station, D denotes deep station).

Month & year	Station	Density of bottom water ρ_{bw} (Kg/m^3)	Sound velocity in bottom water C_{bw} (m/s)	Mode 1		Mode 2		Mode 3	
				θ_1 (^{o})	q_1 ($m^{5/2}/s^2$)	θ_2 (^{o})	q_2 ($m^{5/2}/s^2$)	θ_3 (^{o})	q_3 ($m^{5/2}/s^2$)
1972 March	S	1021.56	1541.40	72.85	0.69	-	-	-	-
	D	1021.10	1538.30	82.81	0.32	75.29	0.34	67.29	0.34
1972 April	S	1021.36	1543.20	65.13	0.74	-	-	-	-
	D	1021.98	1540.00	82.35	0.34	74.29	0.36	65.68	0.35
1972 November	S	1021.46	1541.80	65.11	0.74	-	-	-	-
	D	1023.26	1541.20	82.58	0.33	74.79	0.35	66.49	0.34
1973 January	S	1021.63	1541.40	75.11	0.62	-	-	-	-
	D	1021.40	1543.90	82.09	0.35	73.72	0.37	64.77	0.35
1973 March	S	1021.30	1543.40	68.73	0.77	-	-	-	-
	D	1022.01	1544.80	81.82	0.37	73.12	0.38	63.84	0.34
1973 April	S	1021.36	1541.20	68.72	0.77	-	-	-	-
	D	1022.41	1542.00	81.68	0.37	72.83	0.39	63.36	0.34
1973 October	S	1023.33	1534.20	67.583	0.79	-	-	-	-
	D	1023.80	1531.60	81.25	0.38	71.88	0.41	61.86	0.32

of frequency under study. With the source at different depths, transmission losses have more or less the same values as in April except at the bottom where it is less. During October 1973 also, the transmission loss characteristic is observed to be similar to that during April 1973. The values during 1973 are less by 2 to 5dB compared to 1972.

Decrease in the transmission loss with increasing frequency is indicated up to 75Hz during January 1973 also. The subsequent sudden increase in transmission loss at 80Hz may be attributed to the increase in the number of modes at the deep station at this frequency. The transmission loss at the bottom is higher and those at the other depths are lower compared to November 1972.

In the period under study, the values of the transmission loss in this section various between 50 and 56dB when the source in near the surface and between 40 and 46dB when the source is at 30m. The transmission loss shows much larger variation between 44 and 53dB when the source in near the bottom.

5.3.2 COCHIN

In the section off Cochin the source frequency of 65Hz is less than the cutoff frequency at the shallow station only during November 1972. It is observed that only two modes are present for all the frequencies in both the years except during April 1972 when three modes are observed for the source frequency of 90Hz. The variations of transmission loss with depth is similar in nature to those observed in the section off Quilon. However, during April 1972, transmission loss does not show increasing trend below 30m and indicates more or less constant value.

Detailed studies in the section off Cochin show that the transmission loss characteristics vary with space, time and source frequency. During March 1972, transmission loss slightly decreases (by less than 1dB) as the source frequency increases, at all depths except at the bottom where it increases (approximately by 2dB). During March 1973 also, the variation of transmission loss with source frequency is similar to that during March 1972, but of lesser magnitudes. With the source at different depths, the transmission losses are found to be the same as those during March 1972 except at the bottom where it is lesser by about 1dB.

During April 1973, the transmission loss decreases as the source frequency increases up to 85Hz. The increase in transmission loss caused by increase in the number of modes is observed at 90Hz. The transmission loss compared to March 1973 is less by about 1dB, except when the source is near the bottom, where the magnitude is less by about 4dB, During November 1973, however, the transmission loss decrease by less than 1dB except near the bottom where it increases by about 2dB. It varies by about 1 to 2dB compared to 1972.

The nature of variations in transmission loss during January 1973 are similar to those during November 1972, but with larger magnitudes.

During the period of study, the magnitude of transmission loss is found to vary between 56 and 59dB at the surface, 46 and 49dB at 30m and 48 and 52dB at the bottom.

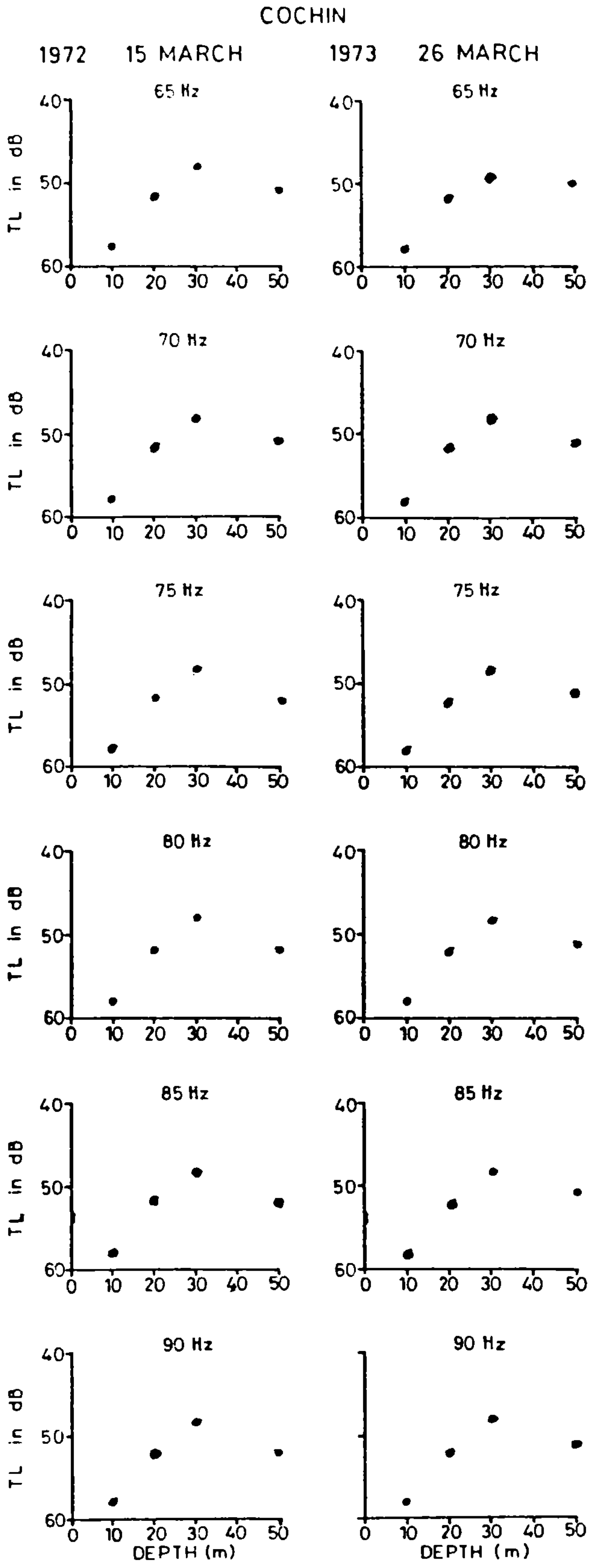

Fig. 41 Transmission loss versus source depth for different frequences at a range of 20 Km. Receiver depth 10m.

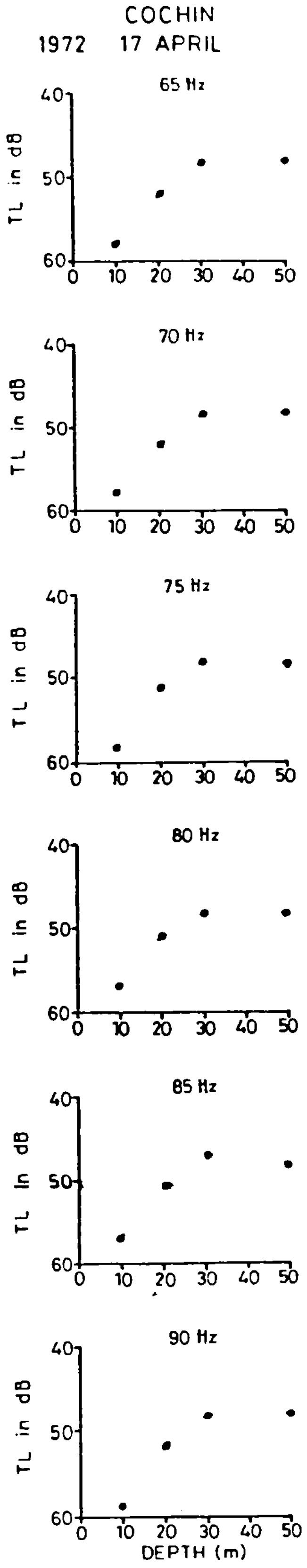

Fig. 42 Transmission loss versus source depth for different frequencies at a range of 20 Km. Receiver depth - 10m.

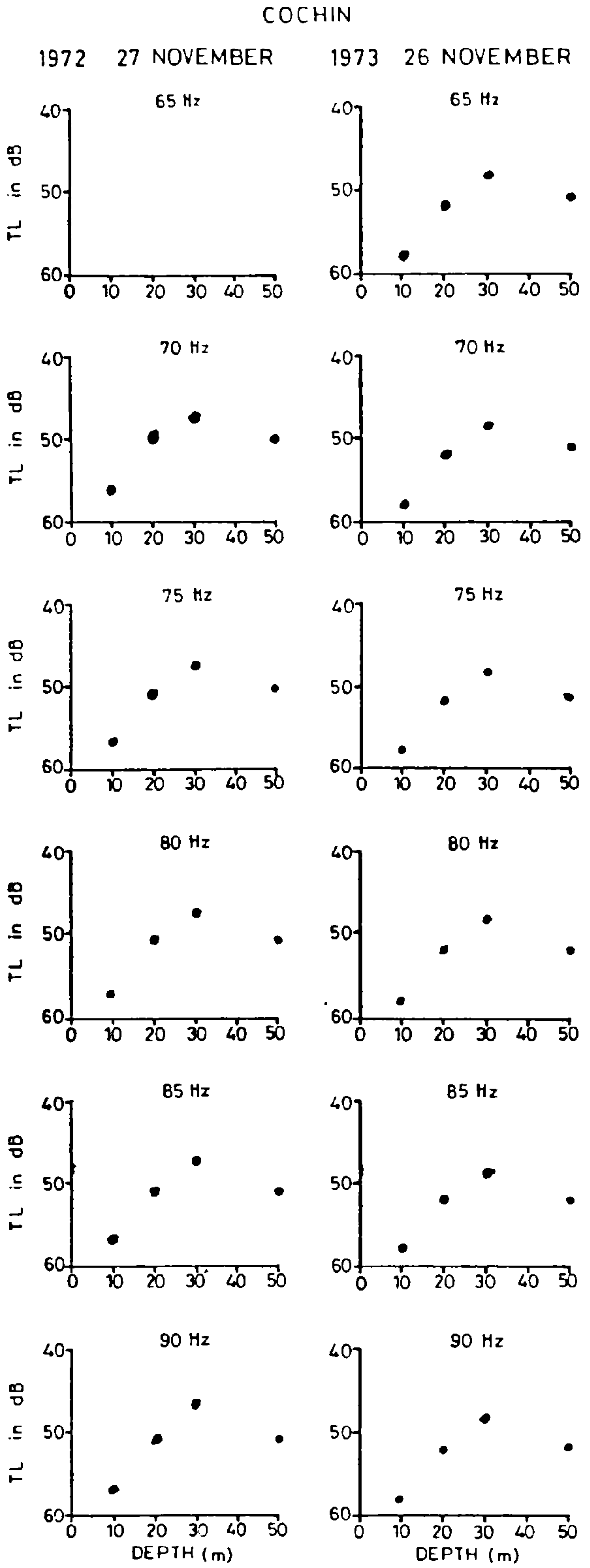

Fig. 43 Transmission loss versus source depth for different frequencies at a range of 20 Km. Receiver depth - 10m.

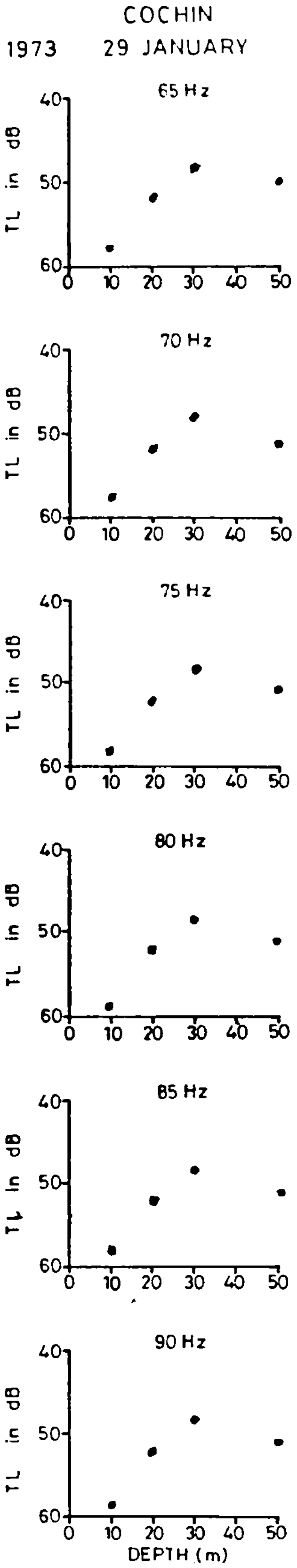
COCHIN
1973 29 JANUARY

Fig. 44 Transmission loss versus source depth for different frequencies at a range of 20 Km. Receiver depth - 10m.

TABLE - 9: COMPUTED VALUES OF ANGLE OF INCIDENCE AND SOURCE EXCITATION FUNCTION AT DIFFERENT MODES FOR STATION COCHIN

SOURCE FREQUENCY 65Hz.

Month & year	Station	Density of Bottom water ρ_{bw} (Kg/m^3)	Sound velocity in bottom water C_{bw} (m/s)	Mode 1		Mode 2		Mode 3	
				θ_1 (°)	q_1 ($m^{5/2}/s^2$)	θ_2 (°)	q_2 ($m^{5/2}/s^2$)	θ_3 (°)	q_3 ($m^{5/2}/s^2$)
1972 March	S	1020.60	1540.60	76.32	0.46	-	-	-	-
	D	1021.34	1543.00	80.55	0.34	70.48	0.23	-	-
1972 April	S	1021.33	1544.00	73.12	0.47	-	-	-	-
	D	1022.01	1538.00	81.40	0.32	72.19	0.30	-	-
1972 November	S	1022.18	1543.50	76.06	0.46	-	-	-	-
	D	1022.45	1541.80	79.80	0.37	-	-	-	-
1973 January	S	1021.53	1542.60	75.73	0.47	-	-	-	-
	D	1021.66	1542.30	80.55	0.34	70.47	0.24	-	-
1973 March	S	1021.98	1541.40	76.07	0.46	-	-	-	-
	D	1022.01	1544.50	80.82	0.33	70.98	0.27	-	-
1973 April	S	1022.74	1539.40	76.30	0.46	-	-	-	-
	D	1022.11	1539.40	80.80	0.34	70.94	0.28	-	-
1973 October	S	1021.43	1542.90	76.05	0.46	-	-	-	-
	D	1022.48	1541.80	80.68	0.34	70.72	0.26	-	-

TABLE - 10: COMPUTED VALUES OF ANGLE OF INCIDENCE AND SOURCE EXCITATION FUNCTION AT DIFFERENT MODES FOR STATION COCHIN. SOURCE FREQUENCY 70Hz.

Month & year		Station	Density of bottom water ρ_{bw} (Kg/m^3)	Sound velocity in bottom water c_{bw} (m/s)	Mode 1		Mode 2		Mode 3	
					0_1 ( )	q_1 (m$^{5/2}$/s^2)	0_2 ( )	q_2 (m$^{5/2}$/s^2)	0_3 ( )	q_3 (m$^{5/2}$/s^2)
1972	March	S	1020.60	1540.60	77.05	0.46	-	-	-	-
		D	1021.34	1543.00	81.09	0.34	71.55	0.29	-	-
1972	April	S	1021.33	1544.00	73.92	0.50	-	-	-	-
		D	1022.01	1538.00	81.90	0.31	73.27	0.31	-	-
1972	November	S	1022.18	1543.50	76.79	0.46	-	-	-	-
		D	1022.45	1541.80	80.38	0.36	70.17	0.22	-	-
1973	January	S	1021.53	1542.60	76.48	0.47	-	-	-	-
		D	1021.66	1542.30	81.09	0.34	71.55	0.30	-	-
1973	March	S	1021.98	1544.40	76.80	0.46	-	-	-	-
		D	1022.01	1544.50	81.35	0.33	72.08	0.30	-	-
1973	April	S	1022.74	1539.40	77.04	0.46	-	-	-	-
		D	1022.11	1539.40	81.33	0.33	72.05	0.31	-	-
1973	October	S	1021.43	1542.90	76.79	0.46	-	-	-	-
		D	1022.48	1541.80	81.22	0.33	71.81	0.30	-	-

TABLE - 11: COMPUTED VALUES OF ANGLE OF INCIDENCE AND SOURCE EXCITATION FUNCTION AT DIFFERENT MODES FOR STATION COCHIN. SOURCE FREQUENCY 75Hz.

Month & year		Station	Density of bottom water ρ_{bw} (Kg/m^3)	Sound velocity in bottom water C_{bw} (m/s)	Mode 1		Mode 2		Mode 3	
					θ_1 (°)	q_1 ($m^{5/2}/s^2$)	θ_2 (°)	q_2 ($m^{5/2}/s^2$)	θ_3 (°)	q_3 ($m^{5/2}/s^2$)
1972	March	S	1020.60	1540.60	77.70	0.46	-	-	-	-
		D	1021.34	1543.00	81.58	0.33	72.56	0.31	-	-
1972	April	S	1021.33	1544.00	74.66	0.51	-	-	-	-
		D	1022.01	1538.00	82.35	0.30	74.24	0.31	-	-
1972	November	S	1022.18	1543.50	77.45	0.46	-	-	-	-
		D	1022.45	1541.80	80.89	0.36	71.15	0.30	-	-
1973	January	S	1021.53	1542.60	77.15	0.47	-	-	-	-
		D	1021.66	1542.30	81.57	0.33	72.56	0.32	-	-
1973	March	S	1021.98	1544.40	7746	0.46	-	-	-	-
		D	1022.01	1544.50	81.82	0.32	73.08	0.31	-	-
1973	April	S	1022.74	1539.40	77.69	0.46	-	-	-	-
		D	1022.11	1539.40	81.80	0.33	73.06	0.32	-	-
1973	October	S	1021.43	1542.90	77.44	0.46	-	-	-	-
		D	1022.48	1541.80	81.69	0.33	72.82	0.32	-	-

TABLE - 12: COMPUTED VALUES OF ANGLE OF INCIDENCE AND SOURCE EXCITATION FUNCTION AT DIFFERENT MODES FOR STATION COCHIN SOURCE FREQUENCY 80Hz.

Month & Year		Station	Density of bottom water ρ_{bw} (Kg/m^3)	Sound velocity in bottom water C_{bw} (m/s)	Mode 1		Mode 2		Mode 3	
					θ_1 (o)	q_1 (m$^{5/2}$/s^2)	θ_2 (o)	q_2 (m$^{5/2}$/s^2)	θ_3 (o)	q_3 (m$^{5/2}$/s^2)
1972	March	S	1020.60	1540.60	78.29	0.46	-	-	-	-
		D	1021.34	1543.00	82.01	0.33	73.49	0.32	-	-
1972	April	S	1021.33	1544.00	75.34	0.52	-	-	-	-
		D	1022.01	1538.00	82.75	0.30	75.09	0.31	-	-
1972	November	S	1022.18	1543.50	78.05	0.46	~~72.11~~ -	~~0.32~~ -	-	-
		D	1022.45	1541.80	81.36	0.35	72.11	0.32	-	-
1973	January	S	1021.53	1542.60	77.76	0.47	-	-	-	-
		D	1021.66	1542.30	82.01	0.33	73.48	0.32	-	-
1973	March	S	1021.98	1544.40	78.06	0.46	-	-	-	-
		D	1022.01	1544.50	82.24	0.32	73,98	0.32	-	-
1973	April	S	1022.74	1539.40	78.28	0.46	-	-	-	-
		D	1022.11	1539.40	82,23	0.32	73.97	0.32	-	-
1973	October	S	1021.43	1542.90	78.04	0.46	-	-	-	-
		D	1022.48	1541.80	82.12	0.33	73.73	0.32	-	-

TABLE - 13: COMPUTED VALUES OF ANGLE OF INCIDENCE AND SOURCE EXCITATION FUNCTION AT DIFFERENT MODES FOR STATION COCHIN

SOURCE FREQUENCY 85Hz.

Month & Year	Station	Density of Bottom Water ρ bw(Kg/m^3)	Sound velociry in bottom water C_{bw} (m/s)	Mode 1		Mode 2		Mode 3	
				θ_1(^{o})	q_1($m^{5/2}/s^2$)	θ_2(^{o})	q_2($m^{5/2}/s^2$)	θ_3(^{o})	q_3($m^{5/2}/s^2$)
1972 March	S	1020.60	1540.60	78.83	0.45	-	-	-	-
	D	1021.34	1543.00	82.39	0.32	74.32	0.33	-	-
1972 April	S	1021.33	1544.00	75.97	0.53	-	-	-	-
	D	1022.01	1538.00	83.10	0.29	75.87	0.31	-	-
1972 November	S	1022.18	1543.50	78.59	0.46	-	-	-	-
	D	1022.45	1541.80	81.77	0.35	72.99	0.34	-	-
1973 January	S	1021.53	1542.60	78.30	0.47	-	-	-	-
	D	1021.66	1542.30	82.39	0.32	74.32	0.33	-	-
1973 March	S	1021.98	1544.40	78.59	0.46	-	-	-	-
	D	1022.01	1544.50	82.61	0.31	74.80	0.32	-	-
1973 April	S	1022.74	1539.40	78.81	0.45	-	-	-	-
	D	1022.11	1539.40	82.61	0.32	74.79	0.32	-	-
1973 October	S	1021.43	1542.90	78.58	0.46	-	-	-	-
	D	1022.48	1541.80	82.50	0.32	74.56	0.32	-	-

TABLE - 14: COMPUTED VALUES OF ANGLE OF INCIDENCE AND SOURCE EXCITATION FUNCTION AT DIFFERENT MODES FOR STATION COCHIN

SOURCE FREQUENCY 90Hz.

Month & Year	Station	Density of Bottom Water ρ_{bw}(Kg/m^3)	Sound velociry in bottom water C_{bw} (m/s)	Mode 1		Mode 2		Mode 3	
				θ_1(°)	q_1($m^{5/2}/s^2$)	θ_2(°)	q_2($m^{5/2}/s^2$)	θ_3(°)	q_3($m^{5/2}/s^2$)
1972 March	S	1020.60	1540.60	79.31	0.45	-	-	-	-
	D	1021.34	1543.00	82.74	0.32	75.08	0.33	-	-
1972 April	S	1021.33	1544.00	76.54	0.53	-	-	-	-
	D	1022.01	1538.00	83.43	0.29	76.56	0.30	69.59	0.18
1972 November	S	1022.18	1543.50	79.07	0.46	-	-	-	-
	D	1022.45	1541.80	82.14	0.34	73.79	0.34	-	-
1973 January	S	1021.53	1542.60	78.81	0.46	-	-	-	-
	D	1021.66	1542.30	82.74	0.32	75.08	0.33	-	-
1973 March	S	1021.98	1544.40	79.08	0.45	-	-	-	-
	D	1022.01	1544.50	82.96	0.31	75.53	0.32	-	-
1973 April	S	1022.74	1539.40	79.30	0.45	-	-	-	-
	D	1022.11	1539.40	82.95	0.31	75.53	0.32	-	-
1973 October	S	1021.43	1542.90	79.08	0.46	-	-	-	-
	D	1022.48	1541.80	82.85	0.32	75.31	0.32	-	-

Eventhough, direct comparison will not be possible between the sections off Quilon and Cochin, since the depths of the shallow station are different, it may be generally observed that the transmission loss is larger off Cochin compared to Quilon. This can also be seen from values of source excitation function q, given in Table-3-14. It is observed that the values of q at deep station is generally lower in the section off Cochin compared to Quilon. The magnitude of q varies between 0.32 and 0.42 in the section off Quilon and between 0.22 and 0.37 in the section off Cochin. Investigation on alongshore propagation characteristics have not been carried out due to non-availability of data from station of close spacing required for the WKB approach.

5.4 DISCUSSION

In a wedge shaped Ocean, the different modes that exist in a deep station will propagate upslope and the higher modes will be cut off at appropriate depths determined by the expression

$$h_c = \frac{\bar{C}\,(m - 1/2)}{2f_0 \, \mathrm{Cos}\,\theta_c}$$

Since only one mode exists in the shallow station, only the first mode from the deep station and the power contained in it will reach the shallow station. This is so because there will not be any transfer of energy from one mode to the other when the stratification is only slightly irregular. Jensen and Kuperman (1980) have given evidence to the effect that there is little conversion of energy from one mode to another, when sound propagates in a wedge-shaped ocean.

The vertical variation of transmission loss with minimum loss at mid depth and maximum loss near the surface, observed in the sections off Quilon and Cochin appears to be a typical distribution observed in shallow water environment. Jensen and Kuperman (1980) have reported a similar variation in transmission loss in an isovelocity wedge-shaped ocean with a penetrable isovelocity bottom. Since the energy contained in the first mode only is transmitted to the shallow station, it is possible to work out an optimum source depth such that energy transmission in the higher modes is minimum. It is however not possible to workout an optimum source strength to get maximum range.

Generally, the larger transmission loss observed off Cochin compared to Quilon can be attributed to the presence of a finer sediment, sandy silt, in the former section. As the grain size decreases, the transmission loss increases. In the section off Cochin, near the coast up to 20m depth, the sediment is reported to be clayey silt. For this type of sediment, the cut off frequency will be well above 500Hz, so that the source frequency less than 90Hz will be attenuated almost completely in this region.

CHAPTER VI

SUMMARY AND CONCLUSIONS

6.1 Summary

The value of temperature, salinity and sound velocity in the coastal waters of Kerala are subjected to both temporal and spatial variations. The variations in the above parameters influence the acoustic propagation characteristics in the region. An attempt has been made to examine the nature and magnitude of variations of the above oceanic parameters and their influence on the acoustic propogation characteristics in the region.

The material used for the study and the general methodology adopted for different computations have been discussed in Chapter 2. Vertical distributions of temperature and salinity at each station have been presented and compared with the vertical distributions of other adjacent station. The formula used for the computation of sound velocity and the methodology for the computation of long range acoustic propagation characteristics have also been discussed. Methods of computation of horizontal and vertical components of propagation constants, the eigen functions, source excitation function, transmission loss, etc are presented in the Chapter.

The results of the studies on temporal and spatial variations of acoustic characteristics in relation to temperature, and salinity in the coastal water of Kerala are presented and discussed in Chapter 3. Vertical sections of these parameters have been presented and discussed in this chapter. Sound velocity at the surfaces increase from March to April. Generally the maximum values are observed during April. The values in 1973 are higher compared 1972. The vertical gradient of sound velocity increases during the period. Occasionally, positive gradients are also observed. Surface values of sound velocity are lower during May than during April. Values are higher in 1973 compared to 1972. The vertical gradients of sound velocity are also larger during this month. The surface values of sound velocity are lower during June-September compared to the earlier months. They decrease during this period and the minimum is reached during August. The sound velocity gradients are sharper in the bottom layers till the beginning of July. Sharper gradients are observed close to the surface during August and September. Generally, lower values of sound velocity and larger values of gradients are observed in 1973 compared to 1972. In both the years, the section off Kasargode shows differences from the other two southern section till the beginning of July. Surface values of sound velocity are larger during October-November than the earlier months. The values reach a secondary maximum during November. These maximum values are less in 1973 compared to 1972. The gradients become less sharp during October than during the monsoon period and the sharper gradients are observed at mid-depths. In November, this structure is completely broken up and the magnitude of gradients become very small. The surface values of sound velocity decrease from November and reach a secondary maximum in February. The magnitudes of sound velocity gradients are small. Positive values of gradients are also observed.

The seasonal variations of high frequency acoustic propagation characteristics caused by the seasonal variation of sound velocity gradient have been discussed with the help of vertical profits in Chapter 4. The sound velocity gradients are generally smaller from November to the end of April and larger during the rest of the year. During January and February and occasionally during March, positive velocity gradients are observed in the region indicating that the acoustic propagation will be as in a surface duct or surface channel with a bottom shadow zone. In this case the range of propagation will be very large. During the period from March to June and from October to December, generally, a sound velocity distribution with positive gradients in the upper layers and negative gradients below is observed. At Cochin the same pattern of distribution is observed in July also. Occasionally negative gradients throughout the water column are also observed during the period. In the former case the propagation in the surface layers will be as in a surface duct or surface channel with a shadow zone just below the surface layer. The propagation in the bottom layer in this case will be as in a bottom duct with a shadow zone just below the surface layer. In the latter case, however, the propagation will be as in a bottom duct with a surface shadow zone. In the period from July to October, the sound velocity gradient in negative and the overall value is large. The largest gradients are observed in the bottom layers during the former half of the period and it rises to the surface during the latter half. In this situation the acoustic propagation is as in a bottom duct and the useful range of propagation is very much limited.

The long range upslope acoustic propagation characteristics in the coastal waters have been discussed in chapter 5. The data used and the computational procedures adopted for the computation of transmission loss for the upslope propagation in a wedge-shaped ocean have been presented. The transmission loss is minimum when the source is at mid-depths and increases towards both surface and bottom. When the source is near the surface, the transmission loss is more than when it is near the bottom. The transmission loss generally decreases as the frequency increases. However the transmission loss is found to increase with frequency during March 1972 at Quilon and November 1972 and January 1972 at Cochin. The magnitude of transmission loss depends on the nature of sediment, the finer the sediment, the larger the transmission loss.

6.2 CONCLUSIONS

The results of the present investigation carried out for 1972 and 1973, which were a drought year and normal monsoon year respectively, provide almost the minimum and maximum ranges of variability of monsoon dependent parameters. The studies thus help us to establish limits of inter-annual changes of acoustic propagation characteristics in the area of study.

The studies have shown that the seasonal variations of sound velocity in the coastal waters of Kerala are very large and that the magnitudes of the variations depend on the strength of the monsoon.

For high frequency acoustic propagation, large ranges are possible during the months from November to the end of April during which time a mixed layer is present in the region. During the period from May to the end of October, the possible horizontal ranges are limited.

The long range upslope propagation characteristics are such that the transmission loss is less when the source is at mid-depths and it is maximum when the source is near the surface.

During the period from May to the end of October, the vertical sound velocity gradient is such that the criterion for WKB approximation is not satisfied. During this period, particularly when there is intensive upwelling, the horizontal variation of sound velocity also is comparatively large. In such situations, the eigen function should be computed directly by dividing the water column into a large number of layers and the computing the phase shift in each such layer. Also the station spacing must be closer. This means that such a study would require continuous measurement of vertical sound velocity distribution and closer spacing of stations. More exact information about the depth profile and the sediment are also required. Nagl et al (1978) have given the criteria for the maximum frequency and the minimum number of segments that can be considered in an environment where the sound velocity varies with range. Even though normal mode acoustic propagation models have been developed for range dependent environment (Jensen and Kuperman, 1979; Jensen and Ferla, 1979) none of them envisages situation that is encountered along Kerala coast during monsoon time. Further research should be directed towards the modification of the existing range dependent models to suit the situation observed in this region.

APPENDIX-1

SPEED OF SOUND IN SEA WATER

Speed of sound in seawater U

$$U(S,t,p) = C_w(t,p) + A(t,p)S + B(t,p)\,S^{3/2} + D(t,p)S^2$$

$$C_w(t,p) = C_{00} + C_{01}t + C_{02}t^2 + C_{03}t^3 + C_{04}t^4 + C_{05}t^5$$

$$+ (C_{10} + C_{11}t + C_{12}t^2 + C_{13}t^3 + C_{14}t^4)\ p$$

$$+ (C_{20} + C_{21}t + C_{22}t^2 + C_{23}t^3 + C_{24}t^4)\ p^2$$

$$+ (C_{30} + C_{31}t + C_{32}t^2)\ p^3$$

$C_{00} = + 1402.388$

$C_{01} = + 5.03711$

$C_{02} = - 5.80852\ \text{E-2}$

$C_{03} = + 3.3420\ \text{E-4}$

$C_{04} = - 1.47800\ \text{E-6}$

$C_{05} = + 3.1464\ \text{E-9}$

$C_{10} = + 0.153563$

$C_{11} = + 6.8982\ \text{E-4}$

$C_{12} = - 8.1788\ \text{E-6}$

$C_{13} = + 1.3621\ \text{E-7}$

$C_{14} = - 6.1185\ \text{E-10}$

$C_{20} = + 3.1260\ \text{E-5}$

$C_{21} = - 1.7107\ \text{E-6}$

$C_{22} = + 2.5974\ \text{E-8}$

$C_{23} = - 2.5335\ \text{E-10}$

$C_{24} = + 1.0405\ \text{E-12}$

$C_{30} = - 9.7729\ \text{E-9}$

$C_{31} = + 3.8504\ \text{E-10}$

$C_{32} = - 2.3643\ \text{E-12}$

$$\begin{aligned} A(t,p) = {} & A_{00} + A_{01}t + A_{02}t^2 + A_{03}t^3 + A_{04}t^4 \\ & + (A_{10} + A_{11}t + A_{12}t^2 + A_{13}t^3 + A_{14}t^4)\ p \\ & + (A_{20} + A_{21}t + A_{22}t^2 + A_{23}t^3)\ p^2 \\ & + (A_{30} + A_{31}t + A_{32}t^2)\ p^3 \end{aligned}$$

$A_{00} = +\ 1.389$

$A_{01} = -\ 1.262$ E-2

$A_{02} = +\ 7.164$ E-5

$A_{03} = +\ 2.006$ E-6

$A_{04} = -\ 3.21$ E-8

$A_{10} = +\ 9.4742$ E-5

$A_{11} = -\ 1.2580$ E-5

$A_{12} = -\ 6.4885$ E-8

$A_{13} = +\ 1.0507$ E-8

$A_{14} = -\ 2.0122$ E-10

$A_{20} = -\ 3.9064$ E-7

$A_{21} = +\ 9.1041$ E-9

$A_{22} = -\ 1.6002$ E-10

$A_{23} = +\ 7.988$ E-12

$A_{30} = +\ 1.100$ E-10

$A_{31} = +\ 6.649$ E-12

$A_{32} = -\ 3.389$ E-13

$$B(t,p) = B_{00} + B_{01}t + (B_{10} + B_{11}t)\ p$$

$B_{00} = -\ 1.922$ E-2

$B_{01} = -\ 4.42$ E-5

$B_{10} = +\ 7.3637$ E-5

$B_{11} = +\ 1.7945$ E-7

$$D(t,p) = D_{00} + D_{10}\ p$$

$D_{00} = +\ 1.727$ E-3

$D_{10} = -\ 7.9836$ E-6

FUNCTION SUB-PROGRAM TO COMPUTE SOUND VELOCITY

```
      REAL FUNCTION SVEL(S,T,PO)
C ******************************
C SOUND SPEED SEAWATER
C UNITS:
C        PRESSURE         PO        DECIBARS
C        TEMPERATURE      T         DEG CELSIUS
C        SALINITY         S
C        SOUND SPEED      SVEL      METERS/SECOND
C
C ******************************
      EQUIVALENCE (A0,B0,C0),(A1,B1,C1),(A2,C2),(A3,C3)
C
C   SCALE PRESSURE TO BARS
      P=PO/10.
      SR = SQRT(ABS(S))
C S**2 TERM
      D = 1.727E-3 - 7.9836E-6*P
C S**3/2 TERM
      B1 = 7.3637E-5 +1.7945E-7*T
      B0 = -1.922E-2 -4.42E-5*T
      B = B0 + B1*P
C S**1 TERM
      A3 = (-3.389E-13*T+6.649E-12)*T+1.100E-10
      A2 = ((7.988E-12*T-1.6002E-10)*T+9.1041E-9)*T-3.9064E-7
      A1 = (((-2.0122E-10*T+1.0507E-8)*T-6.4885E-8)*T-1.2580E-5)*T
     X     +9.4742E-5
      A0 = (((-3.21E-8*T+2.006E-6)*T+7.164E-5)*T-1.262E-2)*T
     X     +1.389
      A = ((A3*P+A2)*P+A1)*P+A0
C S**0 TERM
      C3 = (-2.3643E-12*T+3.8504E-10)*T-9.7729E-9
      C2 = (((1.0405E-12*T-2.5335E-10)*T+2.5974E-8)*T-1.7107E-6)*T
     X     +3.1260E-5
      C1 = (((-6.1185E-10*T+1.3621E-7)*T-8.1788E-6)*T+6.8982E-4)*T
     X     +0.153563
      C0 = ((((3.1464E-9*T-1.47800E-6)*T+3.3420E-4)*T-5.80852E-2)*T
     X     +5.03711)*T+1402.388
      C = ((C3*P+C2)*P+C1)*P+C0
C SOUND SPEED RETURN
      SVEL = C + (A+B*SR+D*S)*S
      RETURN
      END
```

```
C                           APPENDIX 2
C
C           COMPUTER PROGRAM TO COMPUTE TRANSMISSION LOSS
C
C     I          - DEPTH INDEX (I=NB AT BOTTOM)
C     J          - STATION INDEX (J=1 FOR SHALLOW AND 2 FOR DEEP)
C     K          - MODE INDEX
C     THEC       - CRITICAL ANGLE
C     THETA      - INCIDENT ANGLE
C     CCO        - SOUND VELOCITY IN WATER
C     ROO        - DENSITY OF WATER
C     CCI        - SOUND VELOCITY IN SEDIMENT
C     ROI        - DENSITY OF SEDIMENT
C     AKM        - HORIZONTAL COMPONENT OF WAVE NUMBER
C     GAM1       - EIGEN FUNCTION AT SOURCE DEPTH
C     QM         - SOURCE EXCITATION FUNCTION
C     TL         - TRANSMISSION LOSS

$DEBUG
      DIMENSION ISNO(2),NDEP(2),CCO(2,10),ROO(2,10),DEP(2,10)
      DIMENSION PM(2,3),QM(2,3)
      DIMENSION THEC(2,3),OMEC(2,3),THETA(2,3),OMEGA1(2,3),ID(2,3)
      DIMENSION AKM(2,3),AKMS(2,3),GAM(2,3),AAA(2,3)
      DIMENSION GAM1(2,3,10),SGAMZ(2,3,10),GMH(2,3),GM(2,3)
      DIMENSION P1(5),R1(5),PRO(5),PDB(5),PODB(5),TL(5)
      CHARACTER*16 FNAME

C     GET INPUT FILENAME

      WRITE(*,*)'GIVE INPUT FILENAME WITHIN SINGLE QUOTES'
      READ(*,*)FNAME
      WRITE(3,2)
      WRITE(3,*)FNAME
      OPEN(5,FILE=FNAME)

C     DEFINE CONSTANTS

      PI=3.14159
      RD=PI/180.
C     OMEGO=565.49
      EPS=0.0001
      ITER=0
      NOS=2

C     DO COMPUTATION FOR NOS STATIONS

      DO 4000 J=1,NOS
C     READ INPUT VALUES

50    READ(5,*)ISNO(J),NDEP(J),CCI,ROI,AK1
      DO 30 I=1,NDEP(J)
30    READ(5,*) DEP(J,I),CCO(J,I),ROO(J,I)
4000  CONTINUE

C     DO COMPUTATION FOR VARIOUS VALUES OF OMEGO

C     WRITE(*,*)'INITIAL VALUE OF IME'
C     READ(*,*)IMB

      DO 1000 IME=70,90,10
```

```
      OMEGO=2.0*PI*IME

C     DO COMPUTATIONS FOR 3 MODES

      DO 400 J=1,NOS
      DO 400 K=1,3
      ID(J,K)=0
      AMI=K

C     COMPUTE CRITICAL ANGLE AND WC

      NB=NDEP(J)
      THEC(J,K)=ASIN(CCO(J,NB)/CCI)
      OMEC(J,K)=CCO(J,NB)*((AMI-0.5)*PI)/(DEP(J,NB)*COS(THEC(J,K)))

C     SKIP INTERPOLATION IF WC >WO

      IF(OMEC(J,K).GT.OMEGO) THEN
      ID(J,K)=1
      GO TO 400
      ENDIF

C     INTERPOLATE VALUE OF THEM CORRESPONDING TO OMEGO
C     USING BISECTION METHOD

320   ANG=THEC(J,K)
      NPATH=1
      H=2.0*RD
31    ITER=ITER+1
      CALL FUN(ANG,OMEGA,ROO(J,NB),CCO(J,NB),ROI,CCI,DEP(J,NB),AMI)
      FX=OMEGO-OMEGA
      CALL FUN(ANG+H,OMEGA,ROO(J,NB),CCO(J,NB),ROI,CCI,DEP(J,NB),AMI)
      FXH=OMEGO-OMEGA
      IF (FXH*FX) 51,51,41
41    ANG=ANG+H
      FX=FXH
      GOTO (31,51),NPATH
51    H=H/2.0
      NPATH=2
      IF(H-EPS) 900,900,31
900   THETA(J,K)=ANG
      OMEGA1(J,K)=OMEGA

C     COMPUTE GAMO AT BOTTOM

      GAM1(J,K,NB)=(OMEGO/CCO(J,NB))*COS(ANG)
C     COMPUTE GAM1 AT EACH DEPTH FROM BOTTOM TO SURFACE

      DO 40 I=1,NB-1
      II=NB-I
      Q1=(2.0*ABS(CCO(J,II+1)-CCO(J,II)))/(CCO(J,NB)**3
     1*(DEP(J,II+1)-DEP(J,II)))
      GAM1(J,K,II)=GAM1(J,K,NB)**2-Q1*OMEGO*OMEGO
     1*(DEP(J,II+1)-DEP(J,II))
      GAM1(J,K,II)=SQRT(GAM1(J,K,II))
40    CONTINUE

C     COMPUTE SIN(GAMZ) AT EACH DEPTH FORM SURFACE TO BOTTOM AND GAMH

55    SUM=0.0
      SGAMZ(J,K,II)=0.0
```

```
      DO 60 I=II+1,NB
      SUM=SUM+(GAM1(J,K,I)+GAM1(J,K,I-1))*(DEP(J,I)-DEP(J,I-1))/2.0
      SGAMZ(J,K,I)=SIN(SUM)
60    CONTINUE
      GMH(J,K)=SUM
      GM(J,K)=GMH(J,K)/DEP(J,NB)

C     COMPUTE QM

305   AKM(J,K)=OMEGO*SIN(THETA(J,K))/CCO(J,NB)
      GAM(J,K)=OMEGO*COS(THETA(J,K))/CCO(J,NB)
      TERM1=AKM(J,K)**2
      TERM2=AK1**2
      IF (TERM1.LT.TERM2) THEN
      WRITE(3,13)ISNO(J),K,IME,TERM1,TERM2
      GO TO 1000
      ENDIF
      BM=SQRT(TERM1-TERM2)
      AAA(J,K)=ROI/(2*BM)
      AKMS(J,K)=SQRT(AKM(J,K))
      PP=SIN(2.0*GMH(J,K))/(4.0*GM(J,K))
      P2=ROO(J,NB)*(DEP(J,NB)/2.0-PP)
      PM(J,K)=1000.*(P2+AAA(J,K))
      QM(J,K)=(2.0*PI*SQRT(1000.*ROO(J,NB)*CCO(J,NB)))
     1/(PM(J,K)*AKMS(J,K))
400   CONTINUE

C     PRINT INPUT DATA AND RESULTS

      DO 500 J=1,NOS
      WRITE(3,3)
      WRITE(3,4)ISNO(J),NDEP(J),CCI,ROI,AK1
      WRITE(3,5)
      DO 501 I=1,NDEP(J)
501   WRITE(3,6) DEP(J,I),CCO(J,I),ROO(J,I)
      DO 502 K=1,3
      IF(ID(J,K).NE.1) THEN
      WRITE(3,7)
      DO 503 I=1,NDEP(J)
503   WRITE(3,8)DEP(J,I),GAM1(J,K,I),SGAMZ(J,K,I)
      WRITE(3,9)
      WRITE(3,10)ISNO(J),K,THETA(J,K)/RD,QM(J,K)
      ENDIF
502   CONTINUE
500   CONTINUE

C     COMPUTE TRANSMISSION LOSS FOR DEPTHS FROM 10 TO 50

      GMEAN=SQRT(QM(1,1)*QM(2,1))
      I=2
      P1(I)=GMEAN*SGAMZ(1,1,2)*SGAMZ(2,1,I)
      SUM=0.0
      DO 410 K=1,3
410   SUM=SUM+QM(2,K)*ABS(SGAMZ(2,K,I))
      R1(I)=SQRT(QM(2,1)*SGAMZ(2,1,I)/SUM)
      PRO(I)=P1(I)*R1(I)*ROO(1,2)*1000.
      PDB(I)=20.0*ALOG10(PRO(I)/SQRT(20000.))
      PODB(I)=20.0*ALOG10(SQRT(1000.*ROO(2,I)*CCO(2,I)/(4.0*PI)))
      TL(I)=PODB(I)-PDB(I)
450   CONTINUE
```

```
      WRITE(3,11)
      I=2
600   WRITE(3,12)DEP(2,I),IME,P1(I),R1(I),PRO(I),PDB(I),PODB(I),TL(I)

1000  CONTINUE

2     FORMAT(1X,'COMPUTATIONS FOR FILE ')
3     FORMAT(/,1X,'ST.NO NDEP     CCI    ROI     AK1')
4     FORMAT(1X,2I5,F8.2,F6.3,F7.4)
5     FORMAT(/,1X,'DEPTH  S.VEL   DENS')
6     FORMAT(1X,F5.1,F7.1,F7.4)
7     FORMAT(/,1X,' DEPTH   GAM1  SGAMZ')
8     FORMAT(3(1X,F6.3))
9     FORMAT(/1X,'ISNO MODE   THETA     QM')
10    FORMAT(1X,I4,I5,F8.3,F7.4)
11    FORMAT(/1X,'DEPTH ANG      P1      R1     PRO     PDB   PODB      TL
     1)
12    FORMAT(1X,F5.1,1X,I3,2F7.4,4F7.2)
13    FORMAT(3(1X,I5),2(1X,F10.6))
      END
      SUBROUTINE FUN(ANG,OMEGA,RO,CO,RI,CI,HI,AI)
      PI=3.14159
      AA=SIN(ANG)**2
      BBB=(((CI/CO)**2)*AA)
      IF(BBB.LE.1.0) THEN
      OMEGA=0.0
      RETURN
      ENDIF
      BBB=SQRT(BBB-1.0)
      FYLR=ATAN((RO*CO*BBB)/(RI*CI*COS(ANG)))
      OMEGA=CO*((AI-0.5)*PI+FYLR)/(HI*COS(ANG))
      RETURN
      END
```

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