DEVELOPMENTS IN MUD PROBING

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SUMMARY

The author first examines the physical conditions for mud probing measurements and then goes on to describe the instrumental possibilities. A transducer is characterized by its frequency, its mechanical Q, its directivity and its emission level. Among possible materials piezo-electric ceramics give the best results. The components of an instrument are briefly described, and then a short historical account of the method is given, showing how a decrease in working frequency and a reduction of the pulse length lead to better penetration and resolution. Several types of bottom are examined from the point of view of their interest in mud probing operations.

Finally the conditions for operating these instruments both from the surface and from the bottom are studied, and possible future developments of the method are suggested, taking into account the users' requirements as well as the most recent technical possibilities.

INTRODUCTION

I am here employing the term Mud Prober — which corresponds to the French *sondeur de vase* — for the terms pinger probe, bottom sonar, mud penetrator, bottom sounder, etc. found in English works.

Mud probing has been derived from echo sounding. A continuous seismic profiling is carried out on the uppermost layers of the bottom in order to obtain a knowledge both of its nature and its sediment structure. As in seismics, an elastic pulse is emitted, reflected from the subbottom, and rises again to the receiver to be recorded.

In most cases the record obtained during mud probes may be compared with the cores taken over the profiles. Often accurate correlations can be established and the reflectors identified (SERRUYA and LEENHARDT, 1969). The results of these studies confirm exactly what was to be expected from the theoretical principles. The reflections occur in fact at places where there are variations in acoustic impedance (LEENHARDT, 1969). This can arise from variations in density (a modification in water content or a change in the mineral composition of the particles) as well as from variations in the size of the grains. Although these last do not by their very nature give rise to a change in density, in certain circumstances they diffract the elastic waves.

Variations in elastic impedance can be very small and also very close to one another. Therefore a sensitive recorder has to be used, and a large scale recorder with a pulse duration (thus a working frequency) appropriate to the resolution sought.

In consequence the penetration versus resolution dilemma immediately becomes evident : the lower the frequency the better the penetration, but the higher the frequency the better the resolution and the identification of the reflectors shown on the record with the corresponding variations in the sediment core.

Let us firstly examine both the actual physical conditions for measuring, and then the instrumental possibilities. Reviewing the historical background to mud probing we shall see to what extent the rules laid down by physical analysis are followed. By studying the different types of bottom we will be able to define the characteristics of an ideal instrumentation. Finally we shall suggest several possible trends in instrumental progress.

I. — TECHNICAL REQUIREMENTS

The equipment, as we know, consists of an emitter (and its electronic circuitry), a receiver, an amplifier, filters, and a graphic recorder. Often the emitter serves as receiver at the same time, and it is then called a transducer. (I mean by emitter and receiver not the electronic circuits but the "aerial" of radio engineers which converts electric energy into elastic vibrations, and vice versa.) In certain cases it can be of advantage, or even necessary, to use a separate hydrophone for the reception.

A transducer is characterized by :

— *Its nominal frequency F*, which is its frequency of emission in steady state. When the pulses are very short the frequency is simply the fundamental frequency of the emitted spectrum.

— *Its mechanical Q*

As a result of technical considerations this coefficient Q of the transducer depends primarily on the material used in its construction. The ideal will be to achieve the smallest possible coefficient Q in order to obtain a band-pass that is as large as possible.

— *Its directivity*

" The directivity of a transducer is the property it possesses of distributing in space in a certain manner the energy which it exchanges with the propagation medium ". (GUIEYSSE and SABATHE).

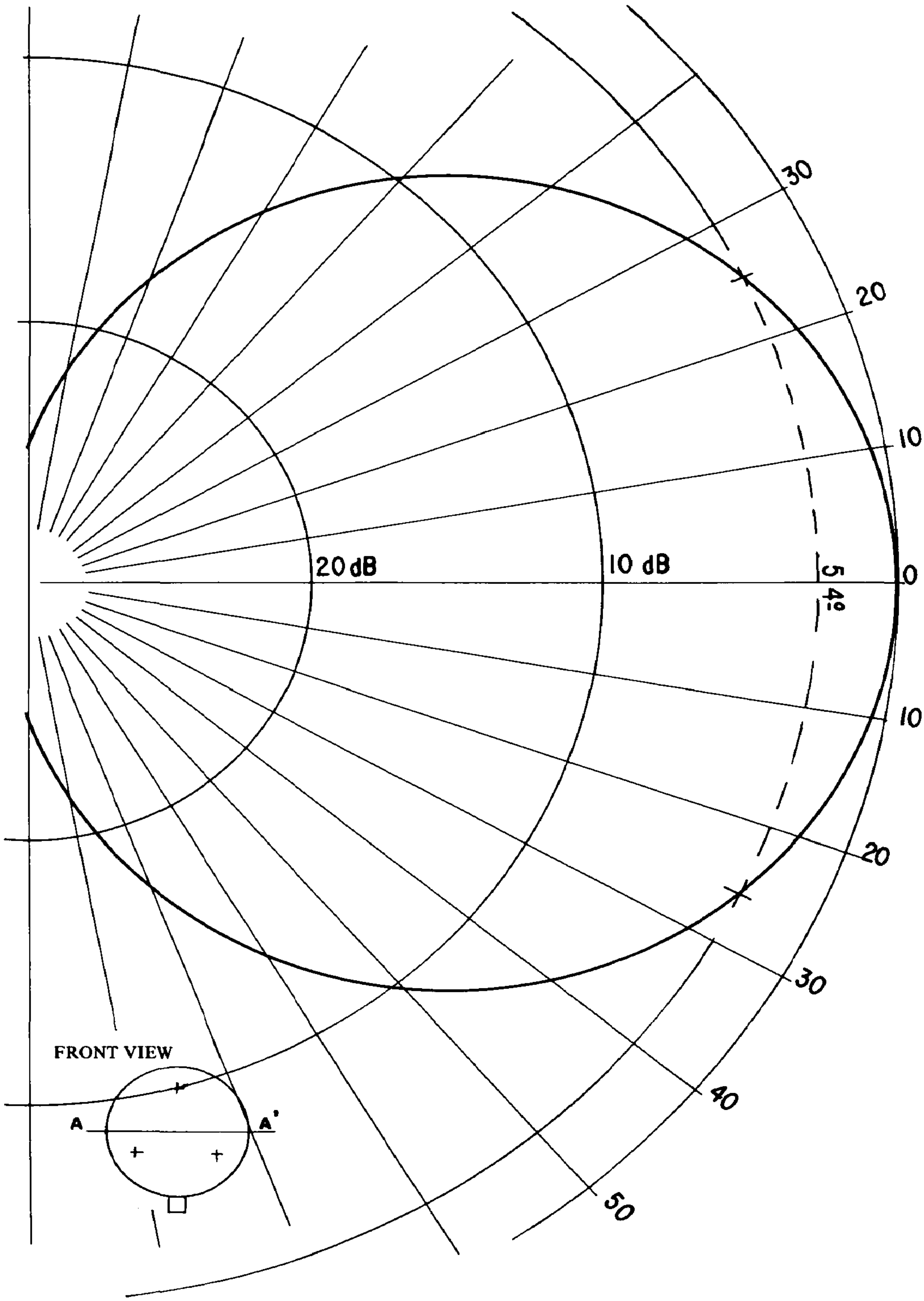

FIG. 1. — Diagram of a 5 kHz C.S.F. transducer's directivity of emission.
Each of the transducer's three projectors has a diameter of $\frac{\lambda}{2}$.
The total directivity is therefore low.

In practice the directivity depends on the ratio of the emitting surface to the emitted wavelength. In computing for transducers we employ the directivity index D expressing directivity in logarithmic form, such that if S is the active surface of the transducer and λ the emitted wavelength we obtain

$$D = 10 \log \frac{4\pi S}{\lambda^2}$$

If the active surface is a circle of diameter *d*, we have as a result :

$$D = 10 \log \frac{4\pi d}{\lambda}$$

on condition that in both cases the smallest dimension of the active surface is larger than half the wavelength. Thus directivity increases with the frequency and with the active surface of the transducer. In order to be sufficiently directional the transducers have to be bulky, especially for the low frequencies (their volume, and accordingly their weight, vary as the cube of the wavelength). Consequently we have to be satisfied with an aperture of 30°-50° (to 3 dB down) for the half beam (figure 1).

— *Its emitting level*

The emitting level Sw is the energy emitted along the axis of the transducer measured in logarithmic units.

By definition, the emitting level Sw of an omni-directional source radiating an acoustic energy of 1 Watt is 71 dB (GUIEYSSE and SABATHE). The emitting level for any source will therefore be :

$$Sw = 71 + 10 \log R + 10 \log Pe + D$$

where R is the efficiency factor for the transformation of electric to acoustic energy; Pe is the electric power (in Watts) applied to the instrument, and D its directivity index.

This definition is valid in steady state for an effective root mean square value. For measurements in the pulse mode, peak to peak values must be used. The emission level is the best energy characteristic for comparing transducers. If in fact it is solely the electric energy applied to the transducer that is given we are ignoring the factors of efficiency and directivity, and thus comparing incomplete values.

Different materials can be used for constructing transducers. According to the material chosen, better or poorer performances will be achieved, since the choice of material determines Q, R and Pe.

The Langevin piezo-electric *quartz* is no longer used in transducers.

The principal drawback to *magnetostriction* is its high mechanical coefficient, Q. Furthermore in low frequencies the equipment is necessarily very heavy and bulky. The Atlas and the Elac echo sounders are magnetostrictive, as also is the Sonoprobe.

ADP crystals (artificial diphosphate of ammonia) are used by the EDO Company. Over a hundred of these crystals are arranged in the form of an X in the transducer case. Efficiency and electric energy are both moderate.

Ceramics are a modern material; with barium titanates electric energy of 2 Watt/cm^2 can be applied. With zirconates of lead we can apply more than twice as much as this.

With ceramic material three modes of vibration are possible (figure 2).

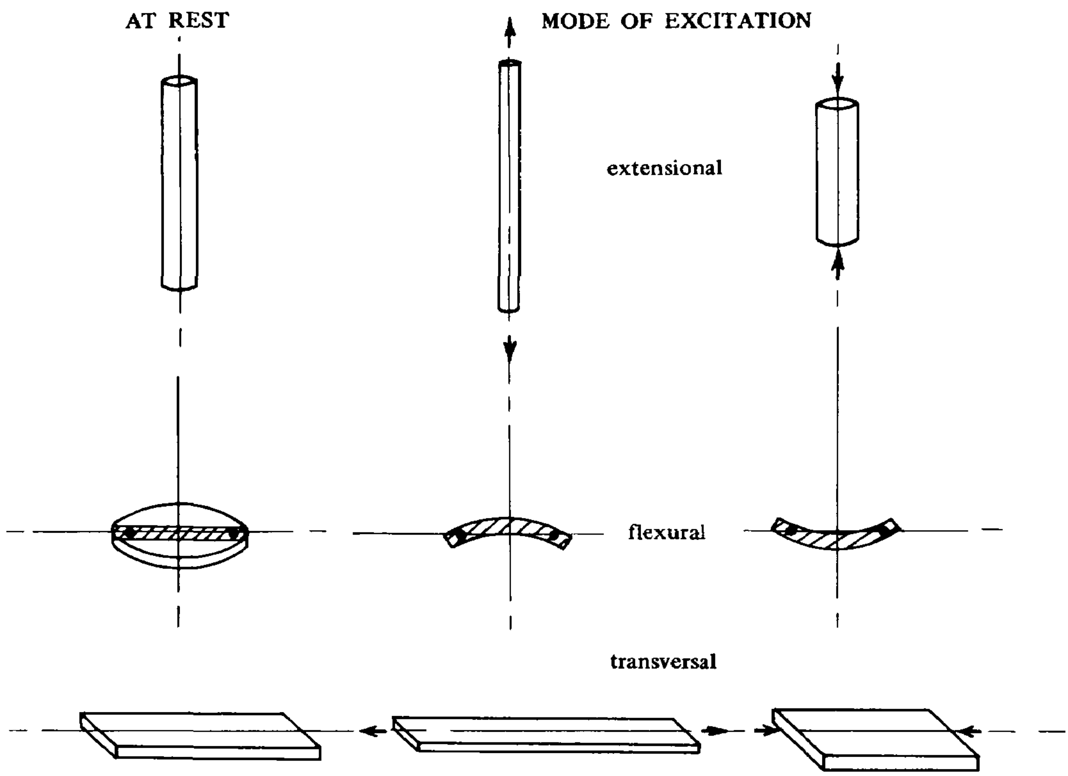

FIG. 2. — The three possible modes of vibration in ceramics. The energy is radiated downwards.

In the extensional mode the frequency of active resonance is determined by the dimension perpendicular to the active surface. This is the type adopted by BRANDT (1968) and used in the majority of transducers.

In the transversal mode the frequency of the resonance is determined by the dimension parallel to the active surface.

In the flexural mode the frequency of the resonance is determined by the dimensions both parallel and perpendicular to the active surface. The bulk of ceramic material needed to obtain a given frequency is much less than in the other types but the energy delivered is reduced.

The advantage of this last method of obtaining vibrations is that it leads to transducers of small size in the low frequencies. At the present time it is the difficulty of moulding large components in ceramic materials in order to obtain lower frequencies that constitutes the limiting factor. In ceramic materials the efficiency ratio can attain 0.6 or 0.7, and with the extensional mode Q may be as low as 3.

A mud prober could be designed as follows.

Let us first of all consider the transducer.

The fundamental frequency of this instrument is determined with due regard to the kind of sediment study we are to make. The instrument's directivity is a function of the relation between the active surface and the wavelength. If it is desired to have very good directivity then a large active surface leads to a weight, a bulkiness and a price which may all be prohibitive, especially when one takes into account the conditions under which it is operated at sea, as well as the fact that small vessels must often be used.

The electric energy is a function of the material chosen and of the instrument's active surface.

The relation of the emitted acoustic power to the active surface determines the density of power transmitted through the water. Beyond a certain density of power cavitation starts developing. The power is then absorbed by bubbles forming on the active surface of the transducer. For example, for a density of power of 2 Watt/cm^2 at 5kHz cavitation occurs at an immersion depth of 10 m and for pulses lasting longer than 10 ms. The threshold of cavitation rises if the pulses are shortened and the frequency or the immersion depth are increased.

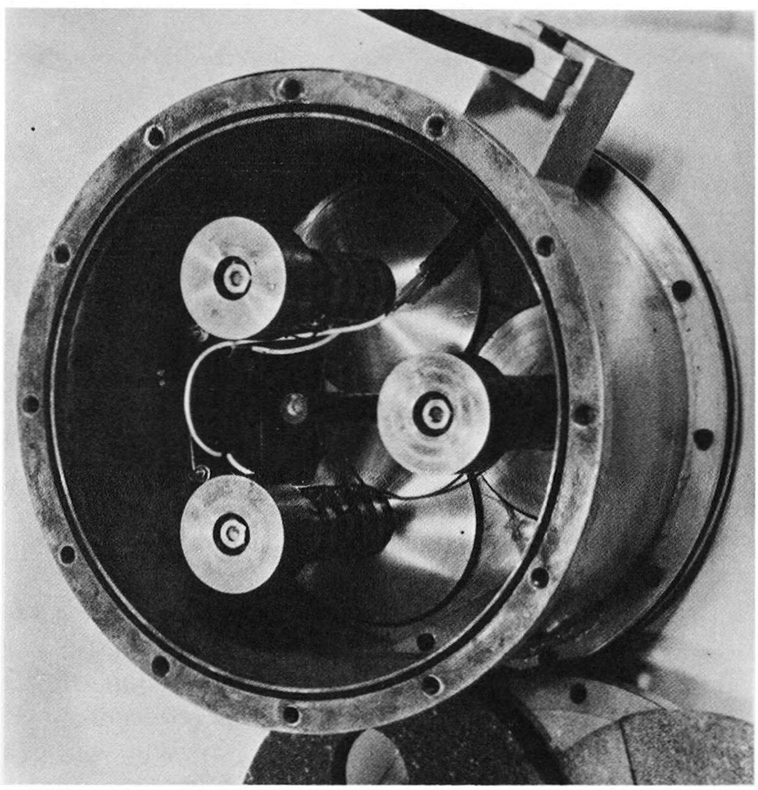

FIG. 3. — 5 kHz C.S.F. transducer.
Note that the ceramics, the aluminium discs, the cap and the counterweights are alternated. The transformer can also be seen.

A modern transducer is usually made up of several projectors. By having not one but three projectors the emission level is increased, and the directivity is improved by about 3 dB, as also is the power attainable (almost

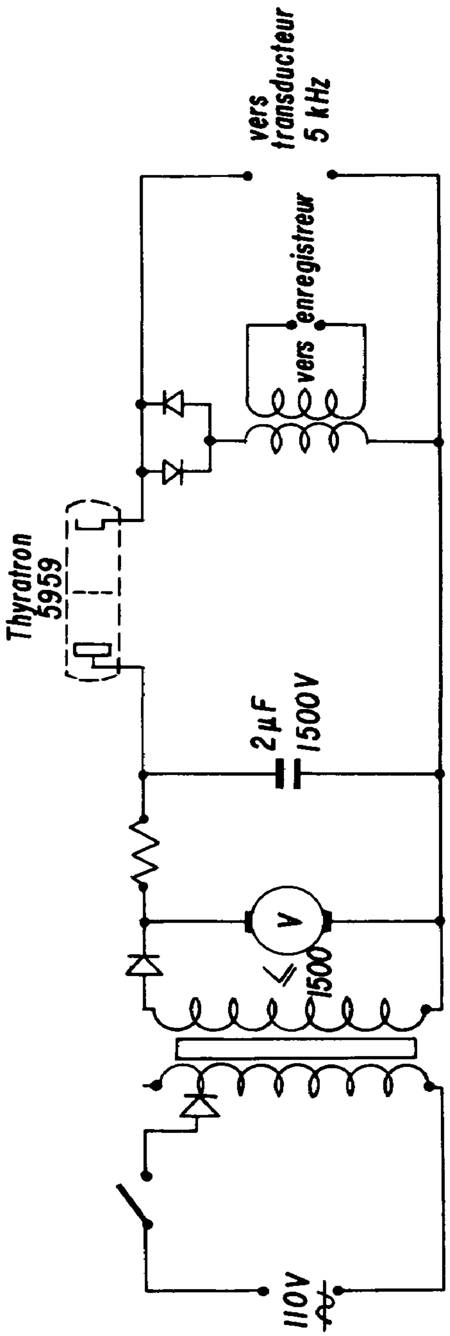

Fig. 4. — The emitter's electronics.
Simplified system with capacity discharge giving a short pulse.
The Variac at the input allows the emitted energy to be varied.
vers enregistreur = to the recorder vers transducteur = to the transducer

5 dB). The directivity diagram obtained will be less regular if we use four projectors (as do the Edgerton, Germeshausen and Grier (E. G. & G.) system at 5 kHz, as well as the Alcatel system at 5.9 kHz). The directivity will increase with a reduction of semi-angle of aperture from 27° to 13° when 12 projectors instead of three are employed (as in the Thomson-C.S.F. mud prober for the bathyscaph *Archimède*), while retaining a regular pattern (figure 3).

Much attention should be paid to the *electronic components* of the emitter.

On standard echo sounders a pulse generator feeds the transducer for a given length of time (about 5 ms for the EDO UQN/1), and the resulting resolution is distinctly poor. EDGERTON (1963-1965) has therefore preferred to use a condenser discharge which produces but a single peak, and which in water shows two or three damped oscillations (figure 4). A pulse-cutting generator can also be used, which means that the emission length can be regulated at will. The maximum emission level is not entirely achieved when the pulse acting on the transducer permits it to emit only one arc at the maximum amplitude. A longer pulse will allow us to use all the emitter's capabilities in cases when the largest possible penetration is desired and when resolution can be sacrificed. This is one of the advantages of a pulse-cutting generator.

The recorder will need to be particularly flexible, and great attention must be paid to the adjustment of the emitting power, the quality of the paper chosen for the record and to the resolution obtainable. These matters were discussed in one of my earlier articles (cf. LEENHARDT, 1966).

II. — A REVIEW OF THE BACKGROUND TO MUD PROBING

HERSEY (1963) has noted that already in pre-war days various authors had used echo-sounding equipment for observing sub-bottom reflections. The first examples of specially conceived equipment date from the 1950s, and these owed their development to SMITH and NICHOLS (1953) who used them in civil engineering projects, as well as to the efforts made in large industry to be able to give oil prospectors the possibility of studying the upper layers of the sea bottom. The first three instruments to be developed were :

— The *Telephonics Co.* (SMITH, 1958) instrument, using close set high frequencies that give rise to signals. Thus, working frequencies of 16, 11.5, 6 and 3 kHz can be obtained.

— The *Sonoprobe,* which functions at 3.6 kHz (MacCLURE *et al.,* 1958).

— The *Subsurex* (PADBERG, 1958), which is probably similar to the Sonoprobe, but whose characteristics are not published. There is no mention in the literature of the use of this instrument.

These three instruments employ magnetostriction for their transducers and dry paper for the recorders. All are lacking in resolution, are weighty and costly, but their penetration is good. Scientists at Scripps Institution of

Oceanography have widely used the Sonoprobe with good results, and a Telephonics Co. report mentions that a penetration of 200 m into the chalk was obtained at the time of the study for the English Channel tunnel.

The second generation of mud probers came into being as a result of observations by HERSEY (1965) from 1957 onwards. In the course of his oceanographic surveys HERSEY made many bathymetric records with an Alden P.G.R. He linked an EDO transducer of the standard echo-sounding equipment to a recorder in order to be free of the different filters of the EDO UQN/1, and he reduced the pulselength by an appropriate modification of the transmitting components. In this manner he was able to record some good penetration in soft sediments on abyssal plains.

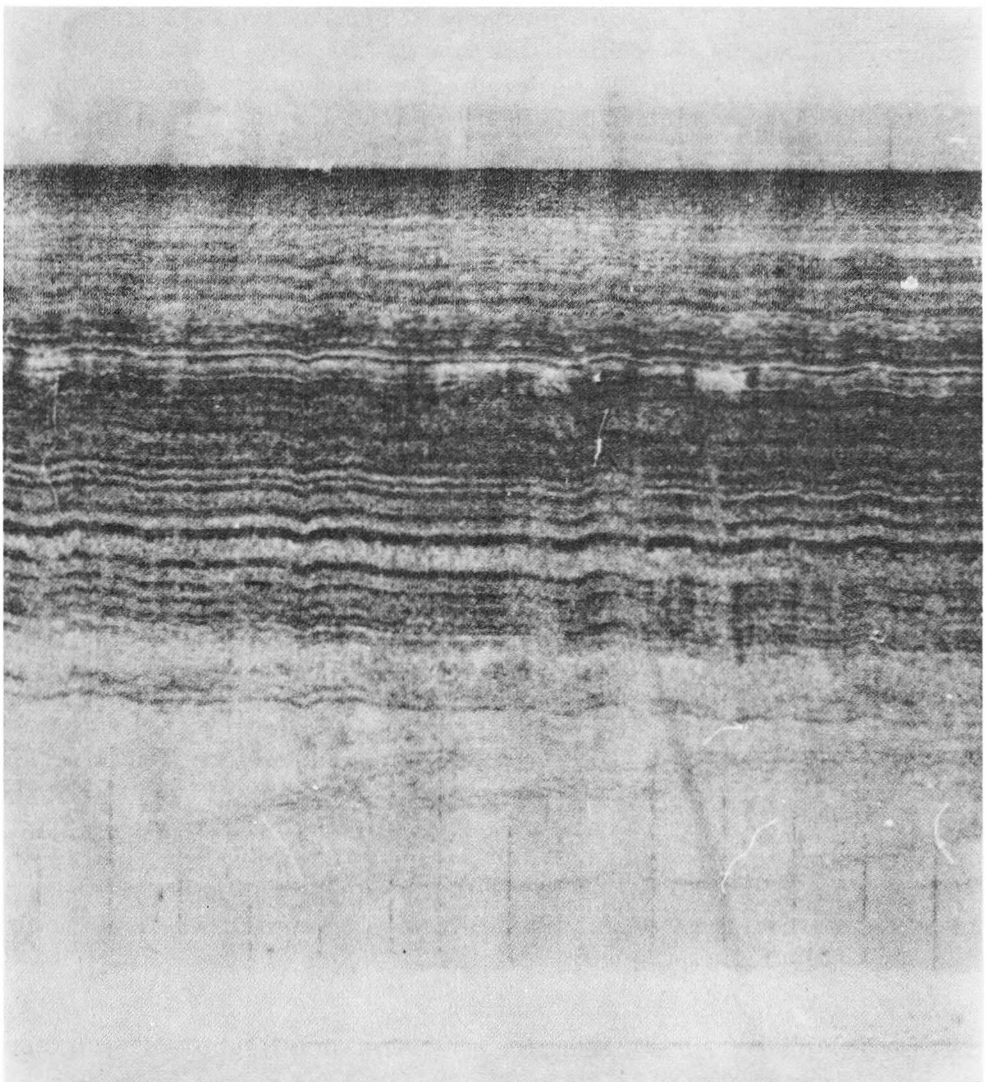

FIG. 5. — Record taken with the Mud Penetrator in the western part of the Lake of Geneva. As the recorder does not have a programme the black line corresponding to the emission shown at the top of the record masks the line of the bottom which is inscribed at the recorder's second sweep. The water depth is about 60 m and the sweep scale represents the same depth. The penetration in the post glacial silt is over 30 m.

EDGERTON (1963) took advantage of these observations to construct the Mud Penetrator (LEENHARDT, 1964). This is a very simple piece of equipment making it possible to work on even the smallest of launches. The results obtained with the Mud Penetrator depend essentially on the kind of sediment. In the Petit Lac (Lake of Geneva) I have recorded (SERRUYA, LEENHARDT & LOMBARD) a penetration of more than 40 m in depths of 60 m in post-glacial sediments (figure 5).

The instrument is easy to use, but lacks power in depths of more than 200 m. The use of an EDO transducer working on a frequency lower than its resonance frequency (12 kHz) led to considerable loss of efficiency (EDGERTON & LEENHARDT, 1966).

To make good use of the observations of SMITH (1958) and the laws governing absorption in porous substances scientists required transducers with lower frequencies. To achieve this they had to abandon the diphosphate of ammonia (ADP) of the EDO echosounding transducers and use instead piezo-electric ceramic materials. EDGERTON (1965) and LEENHARDT (1964) confirm that the penetration obtained at 6 kHz is considerably higher than with the Mud Penetrator. For the last two years the manufacturers E.G. & G. and C.S.F. have used a frequency of 5 kHz for their instruments (LEENHARDT, 1969). The Compagnie Générale de Géophysique (CARMAGNOL, personal communication) has obtained very good profiles in the Gironde (figure 6) with the C.S.F. 5 kHz instrument. The only systematic comparisons between 12 kHz and 6 kHz equipment were made in the Charles River (EDGERTON, 1963-1965) and at Villefranche (LEENHARDT, 1964).

During the past few years other instruments have been manufactured but it seems to me that they will not be worth developing either because their nominal frequency is too high (SOMERS & STUBBS, 1962; JOHANSEN, 1966) or because the transducer is constructed of magnetostrictive material (SIMRAD), or else because the recorder is of insufficiently good quality.

LE PICHON (personal communication) notes that the Lamont Geological Observatory employs a 3 kHz sounder at the same time as they lift cores.

The different types of sounders used by the Monaco Oceanographic Museum are shown in table I. Mention should be made of the *Mud Soucoupe* described by EDGERTON & LEENHARDT (1966) as follows : " The special recorder and its capacity discharge transmitting components giving a very short elastic pulse were conceived by E. CURLEY and constructed with the help of the Research Committee of the National Geographic Society. Trials took place at the Massachusetts Institute of Technology where the pulse length was still further reduced.

" Two types of pulses can be emitted :

" (1) Frequency 7.7 kHz, length 0.5 ms, emission level 92 dB (reference 1 barye at 1 m);

" (2) Frequency 10 kHz, length 0.1 ms, emission level 95 dB.

" The transducer uses ADP crystals. It was mounted under one of the diving saucer's jets. A lead battery of 12 Volts, 50 ampere hours in an oil bath isolating it from the sea water was mounted outside the hull.

" Scales on the record can be 30, 100 or 300 m for a 5-inch paper width. A scale line at each 26 m (35 ms) appears on all the records ".

III. — TYPES OF SEA-BOTTOM

We can distinguish several different regions in which mud and unstable bottom can be sounded.

In *abyssal plains* the bottom is often fine mud, regularly stratified at the interfaces separating the different levels, here the coefficients of reflection are low, often arising from granulometric variations in the sediment. The regularity of the sedimentation facilitates sounding. Present day penetrations attain 20 m with ease (HERSEY, 1965) provided instruments of sufficient emission level are used (e.g. with a 12 kHz EDO transducer and its circuitry) and that they are carefully and correctly operated. (Rolling can mean that the echo is lost on account of the fact that the travel time is considerable.)

Glacial sediments are encountered on continental shelves and in certain lakes. The materials of which they are formed are fine, and it is the differences in their water content that give rise to variations in the coefficient of reflection (SERRUYA & LEENHARDT, 1969). In both cases it is easy to obtain the results even with magnetostrictive material, although without good resolution.

On the *continental shelf* the types of bottom can be classified as follows:

— Muddy bottom where penetration is usually good.

— Sandy or pebbly bottom where the penetration is a function of the ratio of the diameter of an average grain to the wavelength used. If this ratio is higher than 0.03 penetration is no longer possible, for the energy is diffracted.

— Rocky or weed-covered bottom. Over rocks no results can be obtained, and over weeds they are lacking in precision.

Finally it should be noted that :

— In certain tropical estuaries where the frontier between bottom and water is very ill-defined (LEENHARDT, 1966) a low frequency bathymetric sounder (15 kHz for example) would mean that the ship might pass through a fluid mixture of sediment and water liable to damage the machinery if pumped in. A high frequency sounder (80 kHz), however, would indicate the surface of this mixture instead of the bottom.

— River mouths where the sounder can serve to show up (EDGERTON, 1966; LEENHARDT, 1968) the interface between salt and fresh water, provided that the fresh water flow is not too turbulent.

— Biologically active lakes where a certain amount of gas is enveloped in the sediments by the action of sedimentation. The bottom is then very absorbent and a good reflector (LEENHARDT, 1964). Nantua Lake (France) is a good example of this, and it has also been known for a long while in the Lake of Maracaibo (Venezuela) (LEVIN).

IV. — WORKING CONDITIONS

From the surface

With existing " fish " (usually either a wooden frame or a counterweight) it is difficult to achieve a speed of over 4 knots. Transducers of 5 or 6 kHz can weigh up to 100 kg in air (and in general more than 50 kg) but it is always possible to use them from small launches. Constructing profiled "fish" will mean that it will be possible to attain much greater speeds, but this leads to equipment requiring relatively sizeable ships to tow it. The "fish" will then be larger than the transducer's active surface and much longer, and its weight several times that of the transducer. Progress in this sector would be simple, but costly.

From the bottom

In certain cases, for instance over mud silting over a landslide of large blocks, or on the steep slopes of the pre-continent, no results can be obtained from the surface. It will then be possible to place a transducer on a diving saucer or a bathyscaph. (An 8 kHz instrument has been constructed for the *Archimède* by the C.S.F.).

In shallow water it is possible to immerse the transducer by slinging it, but this complicates considerably the problems of operating the equipment that have been mentioned above.

With a separate hydrophone

A transformer can be used in order to raise the starting voltage of the transducer, but this entails a loss of sensitivity. It can therefore be of advantage to use a receiver that is separate from the emitter. This is indispensable when sounding in very shallow water when the transducer (or the excitation circuit) has a high mechanical Q. The excitation trail is then so strong that it masks both the bottom and the sub-bottom reflections. A receiver similar to the emitter is therefore used (the Sonoprobe, or the Telephonics Co. instrument, EDGERTON) or else a hydrophone with a suitable pass-band (CARMAGNOL uses an MP 510 — personal communication) (See figure 6).

It should be noted that with the Mud penetrator the noise of flowing water is nil at 12 kHz. Negligible noise was encountered with the 5 kHz C.S.F. instrument mounted on an only moderately profiled "fish" running at 4 knots (2-8 kHz pass-band). However this noise becomes more perceptible, although not unduly inconvenient, in the Alcatel transducer of 3.3 kHz (same pass-band).

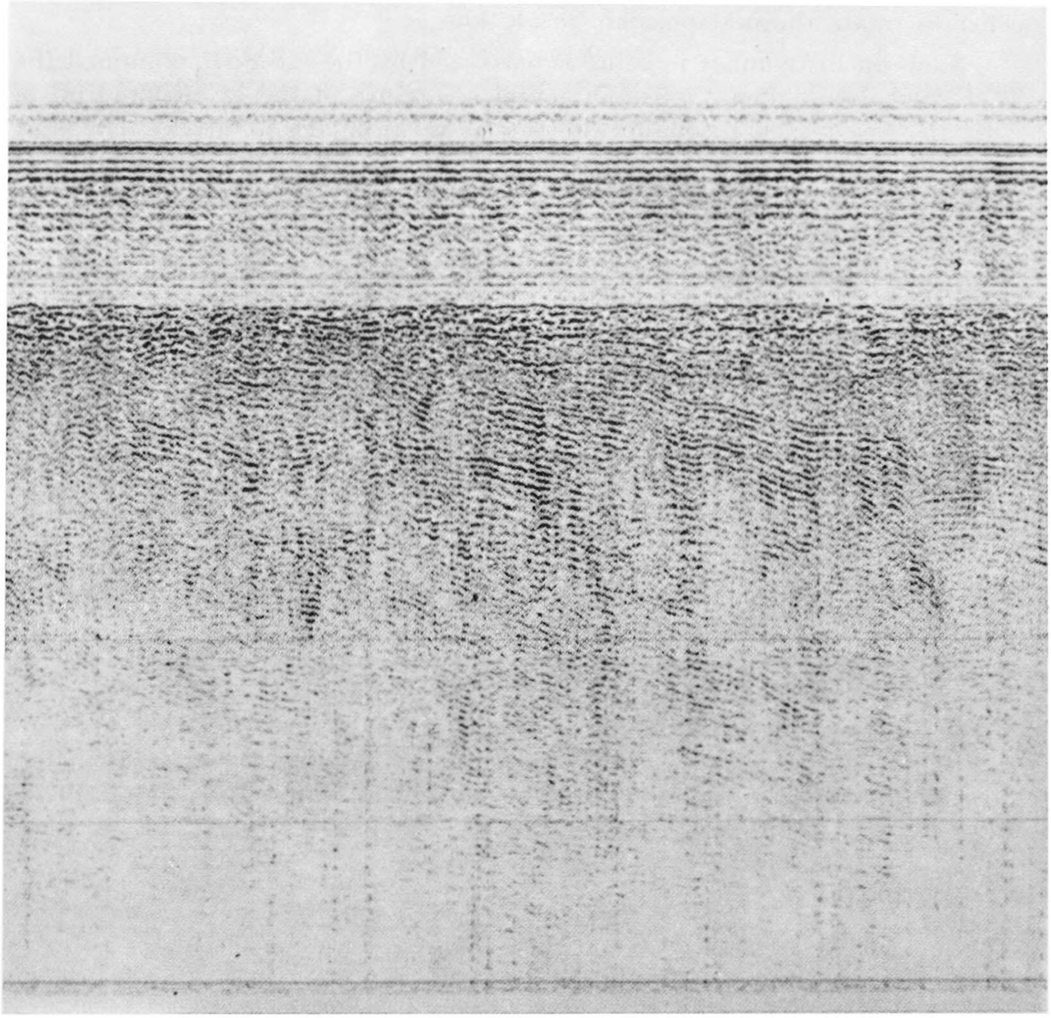

Fig. 6. — 5 kHz C.S.F. record.
A record made by M. Carmagnol. The vertical scale is 50 ms.

In mud probing at the present speeds of operation questions of noise are still only of minor importance.

V. — SUGGESTIONS FOR IMPROVING THE EQUIPMENT

The following paragraphs express my personal opinions, and they moreover concern technical developments in France only.

In comparison with the problems of high capacity seismic sources the technical problems of sounding in mud can be considered as minor. Thus we find little mention of them in the literature. For engineering and sedimentological uses it would be preferable to have an instrument of variable frequency, and to use the highest frequency to give a satisfactory result, in order to retain the best possible resolution.

Such an instrument is being constructed by the C.S.F. It is named the TE-F, and it combines the fundamental resonance of the extensional mode with the secondary resonance of the flexural mode to give a constant emission level between 4 and 16 kHz (to within 2.5 dB). This instrument has to be used with a separate hydrophone for, except for its fundamental frequency, the TE-F has irregular sensitivity.

A cutting generator of 1 kW effective power will be incorporated for operating this transducer.

Yet another conception could be developed : the use of compressed pulses. Instead of applying the relation BT — 1 linking the pass-band B to the emission length T if we are using the pulse mode, pulse compression — a technique first used in methods of treating information — makes it possible to write $B \times T = \mu$.

The compressed length of excitation fixing the resolution is $\tau = \frac{1}{B} = \frac{T}{\mu}$.

The emission level of a transducer receiving a long excitation will increase by 10 log μ in relation to the emission level of a short pulse. Since μ can easily attain 100, we can ask ourselves whether, with a 10 or 12 kHz instrument (hence one that is still small, light and directional) the gain in energy (the resulting emission level would be nearly 130 dB) would compensate the loss of penetration due to the absorption of the higher frequencies, although it would retain the excellent resolution which is the Mud Penetrator's great advantage.

CONCLUSION

Mud probing is used in both pure and applied sedimentology. The results are considerably improved when the resolution is increased by the use of short pulses recorded on electrochemical paper of good definition.

All the existing instruments taking these improvements into account are still of fixed frequency. It is seldom that comparisons can be made *in situ* of the various different kinds of equipment.

The most recent improvements make it possible to envisage :

1. Instruments that are larger and heavier than formerly, but of variable frequency;

2. Light instruments using relatively high frequencies, but with high energy on account of the pulse compression.

Generally the " fish " used in mud probing is not profiled, and thus the ship is obliged to reduce speed to 4 knots at the most, and this constitutes a drawback. But the use of hydrodynamic "fish" enabling work to be carried out at 10-12 knots would on the other hand entail the use of larger

Table I

Transducers Principal resonance frequency "F" (in kHz)	3.3	4.5	5	5.9	6	7.7	8	10	12
	← Values indicated by the manufacturers →								
Secondary resonance frequency "F" (in kHz)	9.5	up to 14		15			16		34
Manufacturer	Alcatel	C.S.F.	C.S.F.	Alcatel	E.G. & G	E.D.O.	C.S.F.	E.D.O.	E.D.O.
Type	P G 3	TEF	26482FB	BF58	Prototype	324	Bathyscaph	324	324
Emission level (dB ref. 1 barye at 1 metre)	108	≃ 107	108	113	108	92	115	95	105
Acoustic energy (Watts)	1700	700	1000	1300	750?	500?	1000	600	700
Minimum pulse length (ms)	0.5	0.5	0.4	0.5	0.3	0.5	0.5	0.1	0.1
Total active surface (cm^2)	255	340	910	380		470	830	470	470
Semi-angle of main lobe	50°	90°	27°	25°			13°	16°	17° at low power
Directivity index (dB ref. 1 barye at 1 metre)	5	5	8	11		12	14.8	14	16
Reception sensitivity (at the transducer output the dB ref. 1 barye at 1 metre)	– 60 dB	– 80 dB	– 80 dB *	– 67 dB		– 83 dB **		– 86 dB **	– 80 dB *
Parallel resistance (ohms)	2600	50		8500					
Parallel capacitance (pF)	27000	tuned on 4.5 kHz	22 000 per vibrator	20200					7000
Kind of transducer	Zirconate of lead	Zirconate of lead	Zirconate of lead	Barium titanate	Barium titanate	A.D.P.	Barium titanate	A.D.P.	A.D.P.
Number of vibrators	1	1	3	4	1	Many crystals	12	Many crystals	Many crystals
Mode of vibration (ceramics)	Extensional	Extensional and flexural	Extensional	Extensional	Transversal		Extensional		
Transducer dimensions in mm	Ø = 242 l = 445	Ø = 210 l = 260	Ø = 336 l = 245	520 x 410 x 340		Ø = 342	Ø = 430 h = 240	Ø = 342	Ø = 342
Transducer weight in air (kg)	52	10	38	# 60		21	117	21	21
Transducer weight in water (kg)	40	7	20	# 20		12	75	12	12
Maximum working depth (m)	300	50	300	300		10000	10000	10000	10000
Mechanical Q $\left(= \frac{F}{\Delta F}\right)$	# 4	3	3.5	# 8		#.11	4	# 11	11
Electric power (Watt)	3000	1000	1500	2200			> 1000		2150
Efficiency (%)	55	70	65	60			65		35
For use on	Surface	Surface	Surface	Surface	Surface	Saucer	Bathyscaph	Saucer	Surface

* verified values   ** sensitivity of transducer and its electronic circuitry

vessels, and it is not by any means certain that this solution would be economic. On larger ships it would probably be more advantageous to have a bulky transducer fixed to the hull.

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