LOGGING BEFORE DRILLING
THE PETRO-SONDE

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About five years ago, Geophysics International introduced a tool that promised something we never before had available to our profession. That was the ability to very accurately measure true vertical depth (TVD) prior to drilling. The tool is called the Petro-Sonde. Certainly, most geophysicists recognize the inability to obtain TVD is the seismograph's single greatest failing, and the majority of R&D spending in geophysics the past decade has been focused on overcoming this handicap. The modern 3-D shooting represents a major step forward in solving this problem, but only a step forward, not a solution.

As a researcher and structural geologist addressing this problem for the past several decades, I have been keenly aware of the need to know the exact location of any depth reading. Structures mapped properly easily respond to conventional stress-analysis techniques. Unfortunately, those whose morphology has been delineated by the seismograph generally can't be analyzed, especially in a rift basin such as the Permian basin. That is because our structures here are so highly faulted. The net result is that after all these years; there is no agreement among geologists as to the origin of tth1e stress systems that created the structures.

Unfortunately, the early promise of the Petro-Sonde in assisting us in stress analysis has not been fully realized. The main reason is that the majority of the geologists and geophysicists treat the Petro-Sonde as a mysterious "black box" that could not possibly work, and they refuse to check it out in the field. Part of this is because when the Petro-Sonde first became available, its patents were pending and there could be no full disclosure of how the Petro-Sonde actually worked without jeopardizing the patents. In my article on the Petro-Sonde (Elam, 1986) I was necessarily vague about its inner workings, and that turned off many potential users.

However, Patent Number 4,686,475 was granted on August 11, 1987, and, thus, the physics of the instrument became public knowledge. Although not associated with Geophysics International, as a frequent user of the Petro-Sonde, I was sent a copy of the Patent, which went into my file unread. I had thought the place to determine if the tool worked or not was in the field, but I found that many scientists will not use a tool until they see the proof of its efficacy.

The Petro-Sonde has been instrumental in providing many structural insights in my research, which is on the plate tectonic evolution of the Permian basin. Although I thought I knew how the tool worked, I did not fully understand the physics involved, and my general description of its inner workings bothered some of my peers. I knew from repeated field observations using existing bore holes that it did accurately measure TVD, even to depths of 25,000'. In the past four years, I have spent over 100 days in the field validating its accuracy and repeatability.

For those who need more theoretical proof, I have finally taken the time to try to translate into geologist's language the complex physics explained in the united States Patent entitled Kober et al. Keep in mind that I was last exposed to electricity and magnetism at U.C.L.A. in the fall of 1942, and I am a little out of date! The developers of this tool are Carl L. Kober and H. David Proctor-Gregg of Littleton, Colorado. Unfortunately, their explanations are over most geologists and geophysicist's heads. In this paper, I will cover the physical theory only. There have been many exciting new developments in instrumentation and practice these past five years as well.

The earth is enveloped in a plasma envelope called the magnetotail that results from the interaction of the solar winds with the earth's magnetic field. Electrical currents are known to flow when a conductor passes through magnetic lines of force, and this current also flows if the magnetic field (the magnetotail) pulses. The earth has naturally occurring sheets of telluric currents that flow along the earth's surface (Dobrin, 1976, pp. 591-601). Telluric geophysical prospecting is passive and, thus, it is unlike other forms of electromagnetic prospecting, which require external or artificially induced currents.

The pulsating electromagnetic fields from the non-static time-variable telluric currents have an electrical field E(t) and a corresponding magnetic field, H(t), wherein:

$$E(t)=ZH(t) \qquad \text{Formula 1}$$

The complex impedance of the earth, Z, depends on the magnetic, dielectric and conductivity properties of the earth. The electrical field components are almost vertical, and the magnetic components are almost horizontal.

It is recognized that a low frequency window (LFW) exists when telluric currents pass through the earth's substrata. In the frequencies of the LFW, the earth acts as a conductor. (Burrell et al, 1979, pp. 981-990). In the low frequency window, it is known that the electrical field waves coming from below the surface, upon impacting the interface between earth and air, approximately double because of the voltage reflection coefficient is positive, whereas the magnetic field, having a negative reflection coefficient, cancels. Hence, antennas lying on the surface of the earth respond to such electric signals alone.

The low frequency window (LFW) has been recognized to exist from zero up to a cutoff frequency, f_C as follows:

$$f_c = \frac{3.76 \times 10^6}{(2d)^2\sigma} \qquad \text{Formula 2}$$

where:

2d = the distance to the observance point in meters

6 = the conductivity of the medium in mhos/m

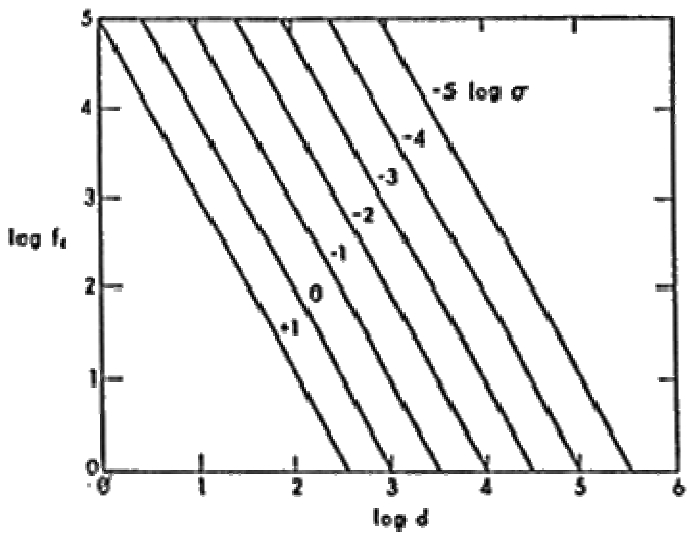
f_C = the frequency at which the electric amplitude is

3dB less than the value at zero frequency.

(Id. p. 984)

Generally the low frequency window (LFW) is in the audio range and extends from zero Hz to several kHz, depending on the earth's conductivity and depth. The Petro-Sonde provides a way to determine f_C through a single observation of the electrical field E(t) of the telluric current. By definition, d is a continuous variable, strongly influencing (by the square) the cutoff frequency, f_C; whereas the conductivity, *6*, is a piece-wise constant variable changing only the frequency with a change in lithology by less than a power of magnitude. The Petro-Sonde records these two frequency changes in the subsurface.

Fig. 1



The relationship between the log of the cutoff frequency and the log of the depth is shown for different values of conductivity (Fig. 1). For example, for a conductivity of 10^{-2} mhos/m, as the depth increases to four units, the cutoff frequency drops correspondingly. Therefore, if different strata have different values of conductivity, the cutoff frequency is affected in a piece-wise constant manner. Sea water has a resistivity of less than one ohm-meter, whereas anhydrite has a resistivity greater than 10,000 ohm-meters.

The Petro-Sonde utilizes these distinctions between the depth d (i.e., affecting the cutoff frequency by the square) and the conductivity ***6*** (i.e., affecting the cutoff frequency in a piece-wise or step function) to provide an indication of both the depth and the nature of substrata.

The Petro-Sonde also takes advantage of another characteristic of telluric currents. The field pulsations originating in the magnetotail also induce in hydrocarbon or mineral deposits a secondary telluric current, I(t), flowing at the boundaries of the volume, V, of the deposit in the form of a dipole moment I(t)L given by the following equation:

$$I(t)L = (\sigma_1 - \sigma_2)E(t)V \qquad \text{Formula 3}$$

Where E(t) is the primary electric field strength penetrating the earth from the surface through the low frequency window. (Cauterman, et al, 1979, p. 1010.)

The dipole moment I(t)L consists of a dipole distribution at the borders of the deposit, which produces a secondary pulsating electromagnetic field. These secondary field pulsations are delivered towards the surface of the earth in the form of an upgoing series of audio pulses, also band limited by the LFW at the surface. These currents join the horizontal ground wave at the surface.

Hence, the Petro-Sonde is designed to sense the primary telluric currents .in order to provide an indication of both the depth and nature of the substrata beneath the earth's surface and is further designed to sense the secondary telluric currents to provide an indication of the presence of hydrocarbons, minerals, and other inhomogeneities in the ground.

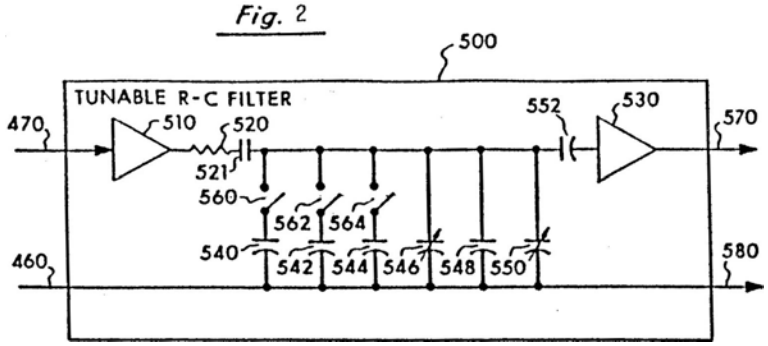
The Petro-Sonde matches the impedence of the sensor to the impedence of the ground in order to fully couple to the upcoming telluric current. The antenna in the horizontal position becomes part of the ground. The indicator of the Petro-Sonde utilizes a low ohmic resistance to discharge the charge buildup in the sensor in synchronization with the electomagnetic field. The Petro-Sonde operator is provided with a state variable filter and a deconvolution technique for indicating a solution to Formula 2. By utilizing a stereo audio output, compensated for the operator's ear sensitivity and background noise, the signal interpretation produced by the indicator is significantly enhanced.

The purpose of the Petro-Sonde is to provide a technique for measuring the depth and the characteristics of the underlying strata, including the presence of oil. In order to determine the depth of different lithological formations or the presence or absence of hydrocarbons, coal, water, or minerals, a deconvolution of the data is necessary. This is accomplished by using the spectrum or Fourier transform of Q(t) or I(t):

$$I(t) = d/dt\, Q(t) \quad \text{Formula 4}$$

The depth of the substrata is determined by solving Formula 2 for 2d. By decreasing the cut-off frequency, f_C, greater depth can be obtained for c signal analysis. Recent changes in instrumentation increased the search depth from 20,000' to 40,000'.

Fig. 2



According to the above formulation on Fig. 2, the output occurring on the lines to the earphones 570 and 580 is essentially white noise corresponding to the transform of Q(t) or I(t) ranging from zero Hz to the cutoff frequency, f_C. Since Formula 2 is non-linear, a direct reading of the depth scale is c required, and bias capacitor 548 is bigger than capacitors 540, 542, and 544. Thus, depth 2d relates linearly to the change f_{CO}:

$$2d = \left(\frac{3.67 \times 10^6}{f_{co} \sigma} \right)^{\frac{1}{2}} \left(\frac{1\frac{1}{2}\, \Delta f_c}{f_{co}} \right)$$ Formula 5

The bias capacitor provides a direct reading of the depth scale for the Petro-Sonde. To analyze depths down to thousands of feet, the decade capacitance 540, 542, and 544 are selectively switched in.

At this point, it is important to return to the mathematical problem of Formula 2. Two unknowns exist, so the formula cannot be solved mathematically with one reading of the electrical field of the telluric currents. However, the Petro-Sonde provides an indication of the solution as follows. By setting the tunable filter (Fig. 2) to a depth of 2d and determining the cutoff frequency, f_C, then only a small error is present in the reading due to the steepness of the straight conductivity constant lines set forth in Fig. 1.

Fig. 3

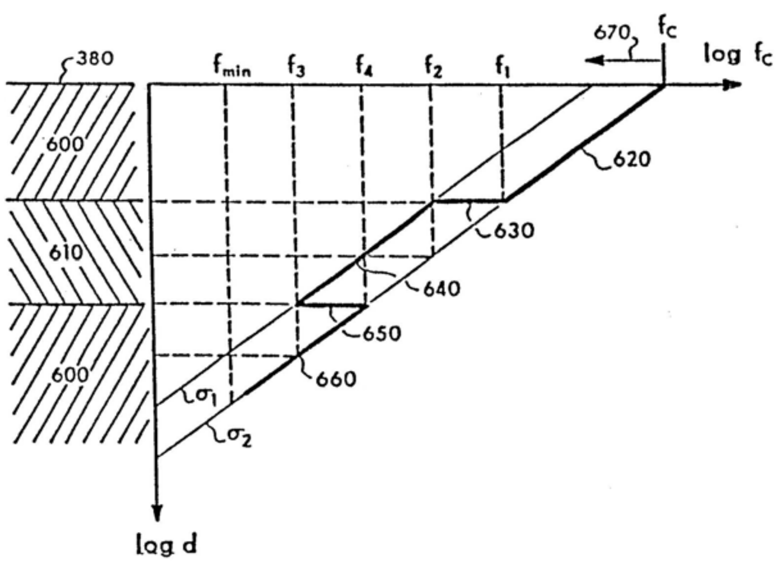


Fig. 3 sets forth a plot of the log of depth versus the log of the cutoff frequency in this example where the lithologies are limestone (600) and shale (610). Plotted on the graph of log d versus log f_C are two different conductivities, which are constant for a given substrata. The conductivity for the two lithologies are 6_2 and 6_1. Note how the cutoff frequency lowers as the depth increases linearly along line 620. However, when the cutoff frequency reaches the limestone-shale interface, it makes a step change along line 630, and that step change *is* recorded by the Petro-Sonde. As the depth *is* increased, the cutoff frequency is linearly decreased along line 640 corresponding to the conductivity line 61 for shale. At the shale-limestone interface, the cutoff frequency again makes a step jump, increasing the value of the cutoff frequency to the conductivity curve for limestone, and that change is also noted by the Petro-Sonde. It can be seen that depth *is* a continuous variable, strongly influencing by its square the cutoff frequency, <u>whereas conductivity influences the cutoff frequency only in step functions.</u>

Each lithologic formation has its own characteristic white noise, and, therefore, not only can the depth of each formation be determined by the Petro-Sonde, but it will assist in identifying the various formations after calibration to nearby wells.

In sum, the Petro-Sonde deconvolutes the charge Q(t) by indicating the solution of Formula 2. The operator tunes the filter to decrease the cutoff frequency and, thereby, to increase the depth. Because of the soft roll-off characteristics of the tunable filter, the transient is enhanced and deconvolution is obtained.

As shown in Formula 5, the Petro-Sonde indicates a solution of this problem by continuously adjusting the tunable filter to depth 2d and determining the cutoff frequency, or vice versa. The error is minimized due to the steepness and linearity of the conductivity curves in Fig. 1. The error amounts to approximately +25 to 50 feet and is defined by:

$$\Delta d = \left(\frac{(2d)^3\sigma}{7.34 \times 10^6}\right) \Delta fc \longrightarrow 0$$

Formula 6

The tunable filter is first set to a certain depth, based on a well log. The remaining deconvolution of the information consists of audibly determining the lithologic nature of the underground formation. Each formation tends to have its characteristic audio signature.

For a fixed depth, the cutoff frequency changes strongly as a function of the conductivity of the strata. With the Petro-Sonde, the capacitance 540, 542, 544, and 546 (see Fig. 2) is selectively added to the tunable RC filter to reduce the bandwidth of the circuit from f_C into the direction of arrow 670 (see Fig 3). When capacitor 546 is adjusted to increase the capacitance and frequency f_1 is reached, there is immediate change in the cutoff frequency f_2' which is not due to the tunable circuit, but rather related to the change in conductivity because of the limestone-shale interface. This is because there is a piece-wise discontinuity between 6_2 and $6_1'$ along line 630. Hence, this change can be audibly detected.

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The Petro-Sonde at this stage has generated analog information indicative of both the identity of the lithologic information and the depth of the formation as well as the presence of any inhormogenities such as porosity contained therein. This output, while not actually solving Formula 2, provides an audible indication of its solution. The answer is an approximation and that is why the accuracy is + 50'.

Audio System

The human ears are used as an ergonomic recognition system. It is recognized that the human mind can localize sound sources in space. The localization of stereo sound sources in space by the human mind represents the best "field portable" recognition system. Hard copy has been tried, but to date no computer analysis has been able to equal the human ear. Eventually improvements will be made, and the logs will be printed out by a computer.

The purpose of the cross-over circuit of the Petro-Sonde is to enhance the human ear's bandwidth recognition by using a high-low cross-over band pass filter to generate stereo sound in the operator's ears. Hence, two outputs are provided to the left and right ears of the operator. The left earphone receives the low band pass response, and the right earphone receives the high band response. The cross-over point is between 1200 and 1600 Hz. Essentially, a stereo sensation in the operator's ears is created in which changes in the band width localize the sound impression as wandering from the right ear to the left and vice versa. This permits the operator to plot the conductivity changes in the same manner as in a borehole electric log, and then the two logs will correlate.

What is being heard is generally white noise in stereo. Three signatures are to be detected. First is the presence of a change of frequency' suddenly occurring in the white noise, the second is the characteristic of the white noise itself, and third is the detection of any pulsating signals present in the white noise. The latter is associated with the presence of fluids, particularly oil. Gas does not have much of a signature and cannot normally be detected with the Petro-Sonde directly. However, I have measured the thickness of a gas column by noting the location of the first water reading in a zone of porosity. However, I use these hydrocarbon readings with considerable reservation at any time, because the ability to detect hydrocarbons varies widely between operators.

It is important to recognize that, overall, the environment is extremely noisy. The Petro-Sonde provides an analog output in stereo mode that is extremely sensitive to these differences even in the presence of a noisy background. Thunderstorms in the area usually terminate field work because the logs then become non-repeatable.

Digital Recording of Ground Wave

The basic ground wave collected by the antenna can now be recorded by Geophysics International’s new Japanese digital recorder. This provides playback opportunities because all the frequencies from 0-20,000' or 0-40,000 are recorded. Those tapes can be played and passed through the Petro-Sonde filtering system again and again. This has helped to overcame one of the principal problems of the tool, operator error. Those errors become correctable by replication. At critical stations, I often obtain readings from a second operator.

Having used Geophysics International's new recorder on three field areas so far, it is evident that the recorder represents a quantum jump in the level of confidence I have in the accuracy of the logs. It facilitates using different operators for reading the same stations. Previously, I had used different operators to read the same station in the field on different days. Unfortunately, the magnetotail is variable enough so that one might not know for sure why there are variations on the log at the same station read on different days. Now with the ground wave being recorded at the same time as the field reading, there is no reason for non-repeatability. Properly used, the Petro-Sonde now appears to deliver better than 85% accuracy on depths and lithologies, but Petro-Sonde hydrocarbon readings have a lower confidence level. Hydrocarbon readings require a great deal more training and expertise by the Petro-Sonde operator, and the quality of the reading can vary throughout the day. I prefer to work on prospects that do not rely heavily on oil readings for evidence of closure. Oily source rocks commonly appear on the Petro-Sonde log as possible pay zones. In the Permian basin, for example, the Woodford shale is often confused with Siluro-Devonian porosity because it is an oily source rock especially when the Siluro-Devonian reservoir is non-porous.

Field Checking the Petro-Sonde

Many geologists and geophysicists have rejected the Petro-Sonde without any field checking. That seems surprising because the tool is almost as easy to check for accuracy in the field as is a Brunton compass. All one has to do to gauge its accuracy is to take readings at well sites where there are electric logs available. The Petro-Sonde operator should be able to replicate the log of any selected interval, but the results are best when you select well-defined lithologic breaks for them to read. In sections such as in deltas where there are many variations in stratigraphy, miscorrelations are easily made. If electric logs are hard to correlate, Petro-Sonde logs are even less reliable.

Errors cropping up on the Petro-Sonde log are generally not from the reading itself, but from incorrect correlations after the log is constructed. The geologist accompanying the Petro-Sonde operator is responsible for those correlations-the operator only delivers the log. Remember that these are crude conductivity logs, measuring somewhat different physical properties than does an electrical log, and, thus, one may have to learn how to correlate them properly. For example, I first found it difficult to correlate the old ES logs and gamma ray neutron logs, but now, those correlations seem easy. Even after several years of use, I still don't trust my field Petro-Sonde correlations completely. I always layout the logs on cross-sections before finally picking my formation tops.

In the deep basins where I work, boreholes are seldom perfectly vertical. If there is a poor correlation with the electric log, I have often found it is not the Petro-Sonde operator's fault. A borehole seldom ends up directly under the surface location, so there should be some poor correlations. In mapping faulted structures, one finds all kinds of small structural features such as step faults, rabbit ears, etc., which most of us subsurface geologists and seismologists never were aware of before. Repeated field checking has satisfied me that the Petro-Sonde consistently records readings from directly below the station. Thus, there may be serious discrepancies between the electric and Petro-Sonde log depths, but repeated Petro-Sonde readings at the same station seldom indicate differences of more than 10-15'. When there is a particularly poor correlation between electric and Petro-Sonde logs, I often can locate the true bottom hole location nearby, where the depth readings coincide.

My structural research in the Permian basin shows that so-called anticlinal structures almost always consist of a series of tilted fault blocks. This is because the brittle basement was fractured prior to uplift, and, not being isotropic any longer, this brittle rock does not often bend. Continental crust does not fold the way most published maps and sections tend to display. If the apparent Petro-Sonde structure does not fit your structural interpretation, it could well be that your subsurface map is not properly contoured. We will learn a great deal more about the structures of the Permian basin now that we can accurately measure vertical depth!

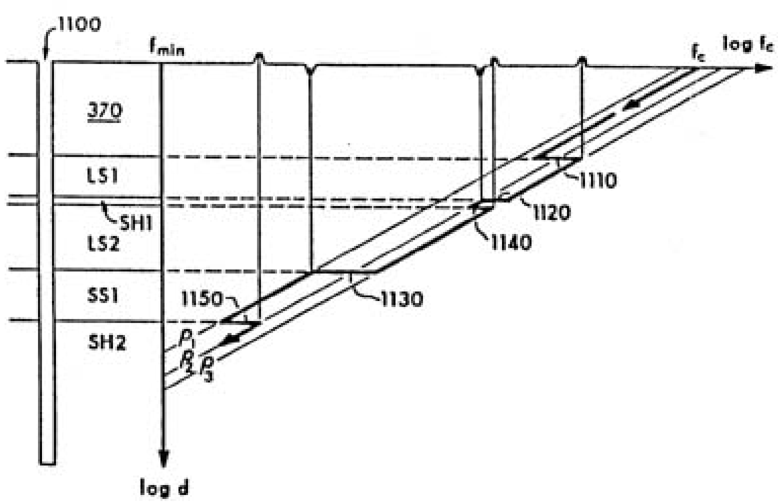
One of the primary uses for the Petro-Sonde is in producing TVD readings for seismic sections. The two are very complementary tools. The Petro-Sonde helps in separating reflections from diffractions. In the deep Permian basin, many, if not most deep seismic dry holes are dry because the geophysicist could not distinguish the two. Geophysical prospects validated by both tools should be near certain discoveries because each uses independent variables.

The Petro-Sonde promises to revolutionize exploration at the time we badly need to reduce the wildcat risk to survive as explorationists into the next century. Those who ignore its strengths take unnecessary risks in exploring today.

<u>Conclusions:</u>

The Petro-Sonde represents a major new addition to our array of exploration tools. It is not difficult to learn to use properly, but a geologist should never use it to create prospects that do not stand on their own geological and geophysical merit. Wishful thinking can easily lead to dry holes, as I can testify. At first, most geologists attempt to use the Petro-Sonde beyond its capabilities, but a few dry holes will cure that tendency. There is no substitute for experience. It took me over a year to fully appreciate the Petro-Sonde.

<u>Fig. 4</u>



This figure illustrates what the Petro-Sonde operator logs in the field. The depths to the specific lithologic breaks are recorded initially by the operator, along with the direction of the breaks. Sandstone, with the greatest conductivity, is shown with the greatest break or porosity. Remember it is conductivity that controls the Petro-Sonde. The operator plots it up to look as much like an electric log as possible, and it is best to keep the same scale. These Petro-Sonde logs record far fewer breaks than a conventional electric or radioactivity log. However, formations do have characteristic signatures, and these signatures become most apparent when the logs are laid out jammed correlation sections. A formation becomes apparent in gross detail, even though at first a novice might think that those correlations look like fabrications. The Petro-Sonde operator should acquaint himself with these signatures at an existing borehole. Usually I try to tie to two or three producers first, if they are present.

The safest way to use the Petro-Sonde is to validate a previously contoured interpretation. It needs to be a valid geologic prospect first. Unless the prospect map and the Petro-Sonde map are nearly identical, I don't consider that I have a drillable prospect. I tend to restrict my field work to areas where my rift model applies. These rift anticlinoria are simple and repetitive and easy to contour properly with very sparse well control.

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