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An Interactive Drilling Simulator for Teaching and Research

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Abstract

An interactive program has been constructed that allows a student or engineer to simulate the drilling of an oil well, and to optimize the drilling process by comparing different drilling plans.

The program operates in a very user-friendly way, with emphasis on menu and button-driven commands. The simulator may be run either as a training program, with exercises that illustrate various features of the drilling process, as a game, in which a student is set a challenge to drill a well with minimum cost or time under constraints set by an instructor, or as a simulator of a real situation to investigate the merit of different drilling strategies.

It has three main parts, a Lithology Editor, a Settings Editor and the simulation program itself. The Lithology Editor allows the student, instructor or engineer to build a real or imaginary sequence of rock layers, each

characterized by its mineralogy, drilling and log responses. The Settings Editor allows the definition of all the operational parameters, ranging from the drilling and wear rates of particular bits in specified rocks to the costs of different procedures. The simulator itself contains an algorithm that determines rate of penetration and rate of wear of the bit as drilling continues. It also determines whether the well kicks or fractures, and assigns various other "accident" conditions. During operation, a depth vs. time curve is displayed, together with a "mud log" showing the rock layers penetrated. If desired, the well may be "logged", casings may be set and pore and fracture pressure gradients may be displayed. During drilling, the total time and cost are shown, together with cost per foot in total and for the current bit run.

A demonstration version of the program is available on the World Wide Web at the Berkeley Petroleum Engineering Page. Its current address is: mse16.mse.berkeley.edu

Figures and References at end of paper.

Introduction

Various types of equipment have been developed in recent years to simulate the drilling of hydrocarbon wells for training, operational or research purposes. Some simulators include elements of "real" drilling hardware, in which the operator controls the simulator via a realistic brake, throttle and other controls, and sees the output of the simulator displayed on gauges and meters that are typical of real drilling equipment (1, 2). This type of simulator is mainly intended for the use of rig personnel, often to train drillers in the techniques of dealing with kicks or blow-outs. Its principal intention is to give as real an impression as possible of the situation on the rig floor.

Other types of simulator have been more directed towards simulating the drilling of a particular well, in order to optimize the drilling process or to predict the effects of changing the operating parameters (3, 4). In these simulators, the objective is more to make an accurate simulation of the drilling process within the computer, and to examine the results in terms of numerical output, than to generate a realistic "real time" response for the driller. It should, however, be noted that such simulators have been used to model and optimize the drilling of specific wells as they are being drilled, and also in the design of rigs (5) and rig equipment (6). Probably the greatest use of drilling-related simulators has been to model well kicks (7 - 10).

A disadvantage of the first type of simulator is that, since the intention is to make an accurate material simulation of the real life situation, the equipment is necessarily bulky and expensive, and although portable versions of such equipment are available, the more portable they are made, the less "realistic" they become. Simulators of the second type, that are intended to make simulations of specific real wells, are inevitably very complex in the way that the simulation program is

constructed, since the main objective in using them is to make an accurate model of the entire drilling process. This requires the specification of a large number of input parameters, from the properties of the rocks being drilled to the mechanics of the drilling process, the properties of the drilling fluid and many other factors. This complexity has meant that such simulators are only used when substantial resources are available to determine the set of input parameters that are required, and skilled personnel are available as operators.

We have taken a third approach, in which the objective has been to make a simple simulator that is above all easy to use, and that conveys a realistic "feel" to the operator while being entirely within the computer. This has meant constructing a drilling model that, while being adjustable so that many different drilling situations can be reproduced, gives a physically reasonable and easily understood response under almost any conditions that are applied. It has also required the construction of a simple, intuitive and largely visual user interface, with the objective of making the simulator attractive to the operator.

Overall layout of the simulator

When the simulator is used as a teaching tool, it reproduces the behavior of a drilling rig under sets of conditions that allow the trainee to observe and react to the response as he or she changes the operating parameters. In this mode, the simulator calculations start from a defined compilation of the properties of the rocks to be drilled (the Lithology), and the output is their drilling and log responses. It is therefore different from some field simulators that work in the opposite sense, whose purpose is to infer the formation properties from the measured drilling and log data. Further, the simulator usually does not calculate or suggest what should be done to optimize the drilling operation, since a major teaching objective is to make a trainee

engineer learn how to carry out such optimizations by him- or herself. The simulator thus differs from some other simulators that have been developed to help field engineers calculate answers to particular engineering problems. Such simulators tend to be of the type in which once all the necessary parameters are input, the simulator outputs a "recommended course of action" or value without necessarily explaining why. The instructional value of such simulators is therefore much more limited.

If the simulator is to be used to optimize a real field operation, it must first be used to deduce the properties of the rocks that are being drilled. This is done essentially by running it "in reverse" i.e. setting the simulator operating conditions to match field conditions, and then "tuning" the rock and other properties so that the simulator response corresponds to the field results for the known field conditions. Once the simulator is tuned to reproduce this response, the operating conditions may be changed to investigate a range of "what if" scenarios in order to optimize the field operation.

User interface

In designing the user interface, we have aimed for simplicity. We have also tried to prevent the operator entering unrealistic values of the operating parameters, and generating "impossible" results. The operator choice is therefore limited by various means, for example, when selecting weight on bit, rotary speed or mud flow rate, the value is input via a slide bar whose upper and lower limits cannot be exceeded. When the operator has to choose the bit type and diameter, the nozzle sizes and similar parameters, the choice is frequently made via "radio buttons" that allow a defined choice of options - for example, the nozzle sizes have to be in integral $1/32$ " increments (see Fig 6, for example). Other parameters can only be input in selected ranges. Alternatively, the operator is warned

that values exceeding certain limits are unacceptable. In this way, even a novice operator is more or less guaranteed of obtaining a physically reasonable response.

Output is largely graphical, with the main result being a depth-time curve that plots the progress of the operation. In addition, a "mud log" is presented, showing the rocks encountered as a function of depth as they are penetrated, together with symbols showing casings that have been set. Further graphs may be displayed that show pore fluid pressure gradient and fracture pressure gradient, and wireline logs may also be shown. Some data, however, must be numerical. Thus overall costs, cost per foot, current depth, pump pressure and horsepower and other data are presented numerically. Such figures are essential for the operator to be able to make engineering and economic calculations.

The entire operation of the simulator is accompanied by a simple accounting procedure that calculates total cost and time, cost per foot for the current bit run, and cost per foot for the entire well.

Construction of the simulator

The simulator is programmed in "C", and runs on Macintosh computers. It is composed of five linked modules. These are the Lithology Editor, Settings Editor, Drilling Simulator, Exercise Editor and "Run An Exercise". When the program is launched, a window appears from which each of the above modules can be opened by clicking the appropriate button (Fig 1). "Help" and "Quit" are also available. When any one of the modules is opened, further windows appear, with choices and actions to be taken as appropriate.

Lithology Editor.

This editor allows the construction of the sequence of rocks that are to be drilled. When

the editor is activated, a window appears listing each of the rock layers in sequence (Fig. 2). Each layer can have its particular properties changed, or layers can be cut, copied or pasted as required. Parameters to be specified include first the thickness of the layer and its mineralogy (from a choice of five types - shale, hard or soft sandstone, limestone or chert). Two parameters govern the drilling response. These are the "Softness Factor" (S) that determines the initial rate of penetration, and the "Wear Factor" (W) that determines the rate of bit wear. Thus, although the choice of rock types is limited to five "mineralogies" the range of possible rates of penetration and wear is very large. Next, the pore fluid pressure gradient and the fracture gradient at the bottom of the layer can be set; these values are made to change linearly through the layer from the values set at the bottom of the layer above. In this way, any desired profile of pressure with depth can be constructed. The nature of the pore fluid can be set to be gas, oil, water or "nothing" and three "wireline log" parameters can also be set. These are a "Sonic porosity" the "Natural gamma ray emission value" and a "Formation resistivity". The values are plotted against depth when the command "log well" is activated during operation of the simulator, and the log and pressure graphs can be "previewed" while constructing the Lithology Editor (Fig. 3 shows the pressure gradient preview). Once a suitable sequence of layers has been constructed, it can be saved and called up subsequently to be drilled by the simulator.

Settings Editor

The Settings Editor allows all the operating parameters of the rig and drilling system to be set. There are two purposes. The first is to allow the simulator to be tuned to match a particular type of operation, and the second is to govern the complexity of the simulation so that the operator may work selectively with particular aspects of the drilling process. Thus

a student may start in a simple way and increase simulation complexity as he or she learns, or an engineer may limit the simulation to a restricted set of parameters to emphasize the effects of a particular set of variables.

The choices are presented in a suite of six windows that cover different aspects of the simulation. One window controls the drilling model that lies at the heart of the simulator (Fig 4). Here one may decide on the complexity of the simulation by selecting or not the different factors in the drilling model itself. Each of these determines the response of the model to a particular input parameter. If all of the factors are deactivated, the model generates a constant rate of penetration for which changing any of the operating parameters has no effect, and for which bits never wear out, and all bits behave identically in all rocks. As each factor is activated, the model becomes more complex, with rate of penetration and wear eventually reacting to the specific bit, the bit size and bit nozzles being used, the rock being drilled, weight on bit, rotary speed, and the mud density and its flow rate.

Another window in the Settings Editor deals with the characteristics of each of the four bit types that is available (PDC, Milled Tooth, Tungsten Carbide Insert and Natural Diamond). This part of the editor allows the setting of typical rates of penetration and rates of wear for each bit in the different rocks, and the number, cost and size of each bit type that is available (the latter for "missions" in which the operator has to do his best under time, money or materials constraints).

Other windows deal with the costs and availability of other services, for example, whether wireline data can be obtained, or whether it is possible to have information on pore and fracture pressures. Other adjustable features concern the introduction or exclusion of certain "accident" phenomena - for

example, the well may be allowed to fracture or kick, the borehole may collapse a certain time after entering a shale if the correct choice of mud was not made, or cones may be lost from roller cone bits after a certain fraction of the bit life is consumed.

Drilling Simulator

Clicking the Drilling Simulator button launches the simulation program itself. The display is composed of a main window, in which are shown a depth-time plot, the "mud log" and casing data, and some smaller windows that allow controls to be set or output data to be displayed (Fig. 5).

Before commencing drilling, the operator must choose the rock sequence that is to be drilled, and then select a drill bit. Bit selection is made from a control panel that concerns operations that are to be conducted with the bit "Out of Hole" (see Fig. 5). These include selecting or changing the bit (Fig. 6), running and cementing casing, logging the well, carrying out a fracture test, fishing junk and of course "running in hole". Having selected a bit, the operator chooses "run in hole", which closes the "Out of Hole" control panel and presents the "Drilling Control" panel (Fig 7). Here the operator sets the operating parameters and then clicks "Start Drilling". This starts the simulation, which then calculates and displays a graph of depth versus time, displays the "mud log" and calculates and displays depth, time, cost and cost per foot, and the mud hydraulic parameters of standpipe pressure, pump horsepower, and hydraulic horsepower per square inch of bit area.

At any time the display may be scaled or scrolled to allow viewing of specific details of the display, and the simulation speed may be adjusted to allow rapid drilling through straightforward sections or slow drilling when special attention is required.

The Drilling Model

As drilling proceeds, the drilling model is continuously calculating the state of wear of the bit and its rate of penetration. The wear algorithm starts by calculating a "wear factor". The "wear factor" is the result of first combining the two wear parameters mentioned above, set in the Settings Editor and the Lithology Editor respectively, that are specific to the particular combination of bit and rock. This result is then combined with two factors that represent, respectively, the effects of weight on bit and rotary speed on the rate of wear of the bit. Both factors cause the rate of wear to increase more than in proportion to increases in the weight on bit and rotary speed. Finally the combined parameter is scaled to give a value somewhat less than unity.

The state of wear of the bit is associated with a remaining "Life". All bits, when new, are assigned 100% "Life". At each time step the "Life" is multiplied by the "wear factor", (less than unity), that reduces the "Life" by a certain fraction of its current value. This has the effect of reducing the "Life" asymptotically towards zero as time increases.

To obtain the current rate of penetration, the present "Life" is combined with two more factors that represent the interaction of the particular bit with the rock being drilled, and influence the underlying rate of penetration. The factors are set in the Lithology Editor and the Settings Editor respectively. The result is further combined with factors that depend on the weight on bit, the rotary speed and the mud density. These operations result in the calculation of a rate of penetration that would be characteristic of a bit for which the cuttings are removed as soon as they are formed, i.e. perfect cleaning of the workfront. At this point, the effect of the mud flow is introduced, and a final rate of penetration is calculated based on the effectiveness of the mud flow in cleaning the cuttings away from the hole

bottom. This procedure is adopted because it is believed that the effectiveness of the mud flow is partially dependent on the quantity of cuttings that need to be removed, i.e. the greater the rate of penetration, the greater the mud flow must be to attain "perfect cleaning". Thus it is necessary to calculate a theoretical rate of penetration based on all the other operating parameters before the effect of the mud flow can be calculated. Once this is done, however, the final rate of penetration for the present timestep is known, and the distance drilled can be calculated and added to the depth-time plot.

If the operating parameters are held constant, the effect of multiplying the present "Life" by the wear factor at each timestep is to produce an exponential decrease in rate of penetration with time. This function appears to be a reasonable approximation to the behavior of real bits operating under field conditions, provided that the wear process is uniform. Failure by "catastrophic" processes is not well modeled in this way, but provision is made in the simulator for at least one such behavior, by allowing sudden failure by "cone loss" in roller cone bits at a fraction of "Life" remaining that can be set in the Settings Editor.

As drilling proceeds, the drilling model checks at each timestep to see if the well has kicked or fractured, or if an uncased shale interval has collapsed. If any of these events occur, an alarm message is sent to the operator. Alarms also occur if the mud flow rate is inadequate to lift the cuttings, or if the mud pump maximum pressure and/or horsepower are exceeded. If an alarm is triggered, drilling is stopped until the appropriate remedial action is taken.

The pore pressure gradient and fracture gradients to the depth drilled may be displayed at any time if these facilities have been allowed in the Settings Editor, and their graph may be

matched in scale to the depth-time plot, or printed for later reference.

The drilling assembly may be pulled out of hole at any time, and various "Out of Hole" activities carried out. These include setting casing and logging the well. Log data is graphed in a similar manner to that used to present the pressure information, and the graphs may be matched to the depth-time plot, and scaled, scrolled or printed as desired. It should be noted that if the well is "logged" after a casing has been set, the porosity and resistivity values will not be displayed over the cased interval, although the natural gamma ray data is always available. This behavior is shown in Fig 8.

At any time during operation of the simulator, a "Note" may be added to the depth-time plot (three examples are shown on Fig 8), and the current status of the well may be saved for future reference or re-drilling.

Exercise Editor

This editor allows an instructor to build specific exercises for the students or trainees. Access to the editor is limited by the use of a password that prevents the students from obtaining restricted information, or from changing the exercise parameters. To create an exercise, the instructor follows a sequence of operations. These are: 1) Select or create a lithology in the Lithology Editor, 2) Set the desired settings in the Settings Editor, 3) Set the starting conditions for the well (the exercise may begin in a part-drilled well, for example), 4) Set module availabilities (e.g. is the student allowed to examine the Lithology or change the Settings ?) 5) Set various exercise options (for example, printing a "summary sheet" at the end of the exercise), 6) Write a set of instructions, and finally 7) Save the exercise.

"Saving" the exercise has the effect of packaging the entire set of instructions listed

above into a single file that the student can run by clicking "Run an Exercise" in the Module Chooser window (Fig 1). (see below).

Run an Exercise

When "Run an Exercise" is selected in the Module Chooser window, the operator is given a choice of all available exercise titles. By selecting a particular exercise, the complete set of instructions, lithology and operating parameters that were set in the Exercise Editor are loaded into the simulator, allowing the student to commence the exercise without having to "set up" the simulator beyond choosing the exercise that is to be run. In particular, when the exercise is launched, a window appears that displays the set of instructions for the exercise. This may be printed to form a reference text. In many cases, we have made this text form a self-contained chapter that not only explains the requirements of the exercise but includes a quantity of background information that will help the student to understand the larger context of the exercise.

Other features

The program contains various supporting features, such as the ability to append notes to the drilling plot, mentioned above, printing text and graphs, a "Help" section etc. Overall, the objective has been to make the simulator easy to use and to understand.

Conclusions

In this paper, we have reviewed some of the main features of our drilling simulator program. The main philosophy underlying the construction of the simulator has been to make a program that is simple to understand and use, and in which the effects of changing particular operating parameters are obvious.

We believe that these features will make the simulator not only a useful teaching tool, but

also a vehicle through which drilling engineers concerned with field operations can experiment with the effects of changing the operating parameters in order to optimize drilling operations.

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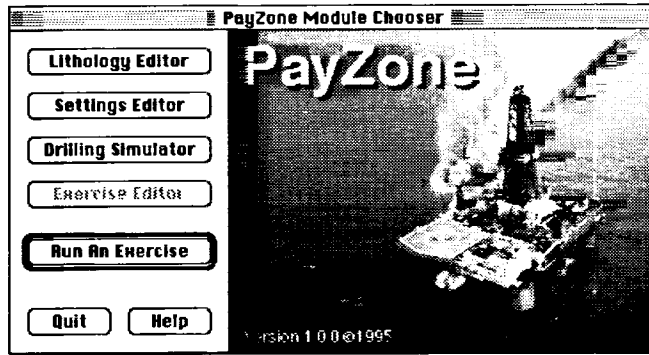


Figure 1: Module Chooser window.

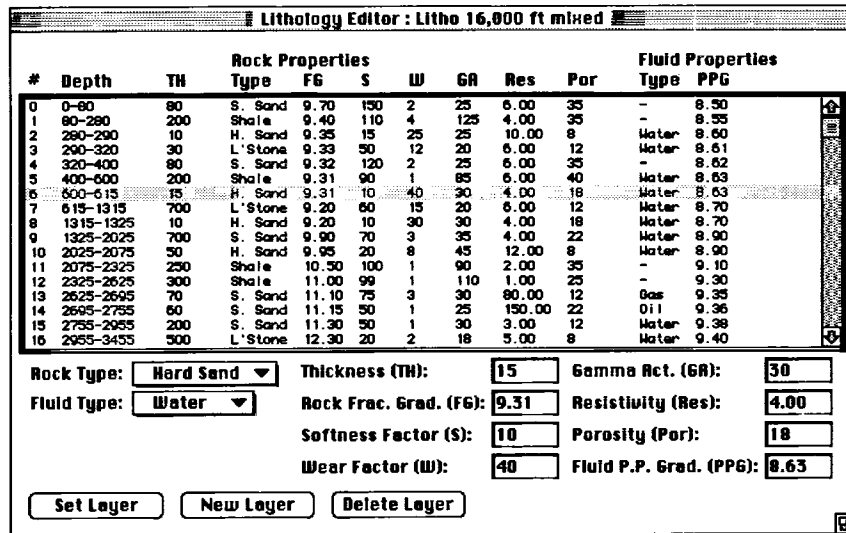


Figure 2: The Lithology Editor, with layer number 6 being edited.

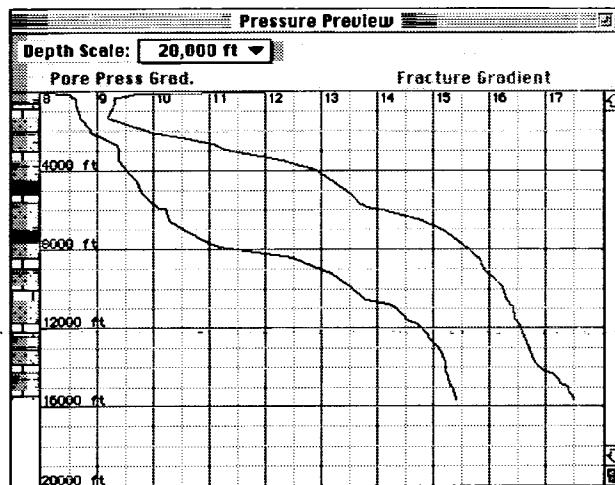


Figure 3: Preview of the Lithology and Pressure Gradients.

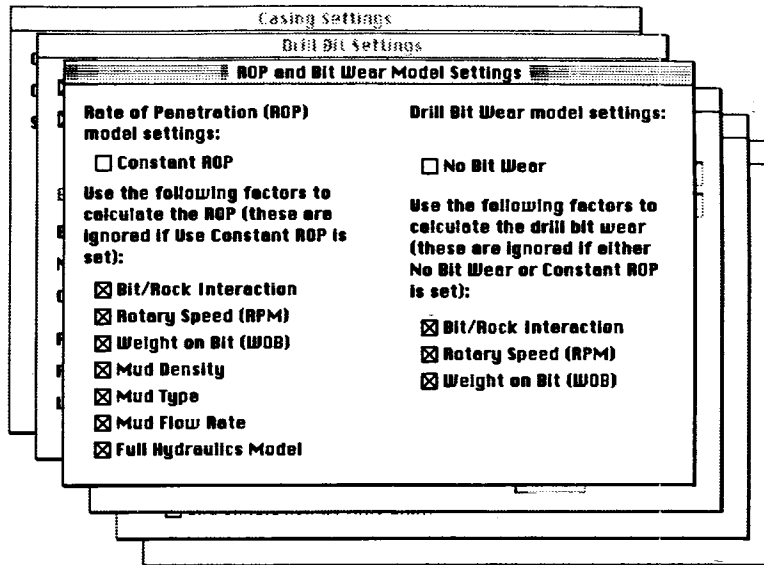


Figure 4: The Settings Editor, with the ROP and Bit Wear Model window active.

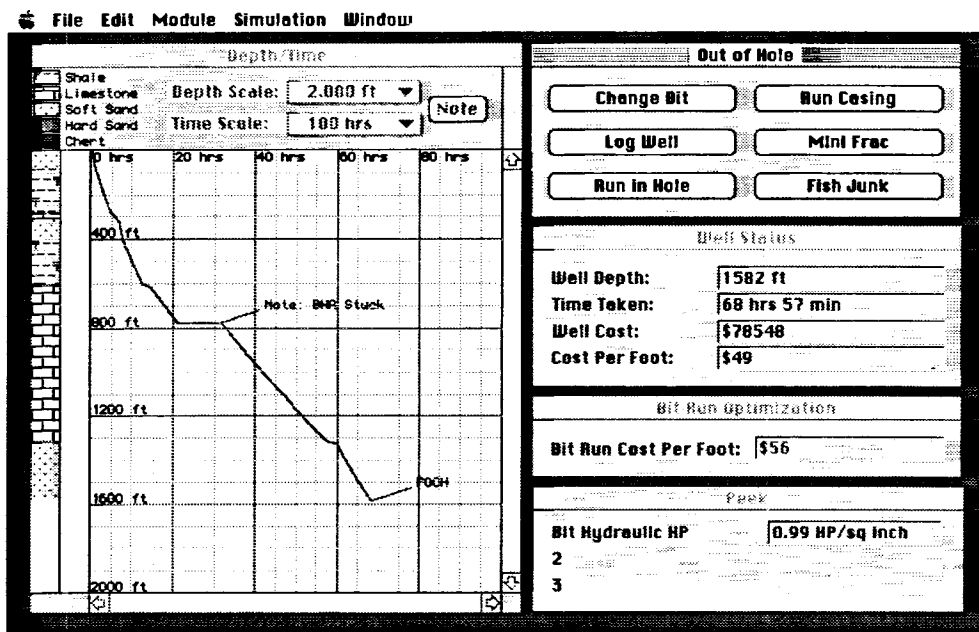


Figure 5: Overall view of the simulator layout, showing the depth vs time window and some of the control and diagnostic windows.

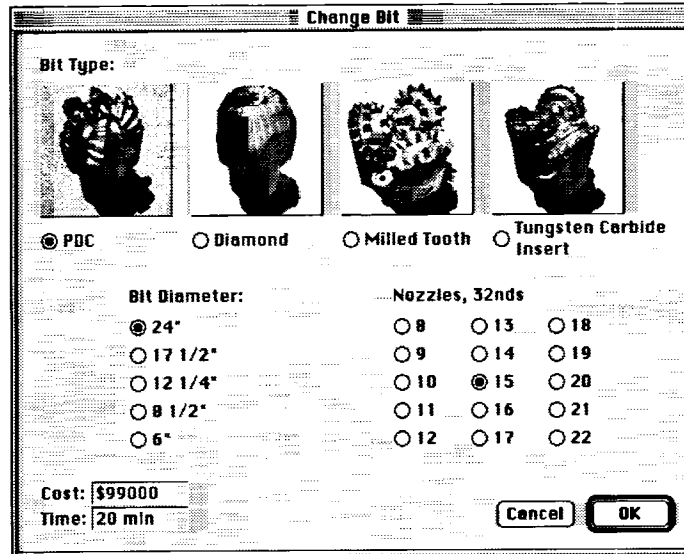


Figure 6: Drill bit selection window.

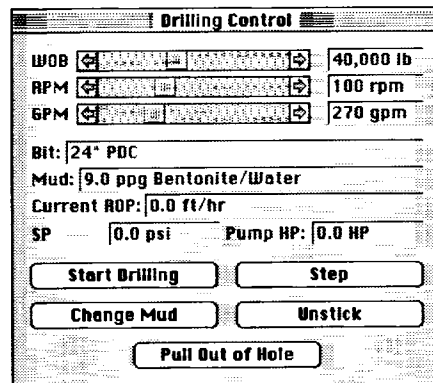


Figure 7: The Drilling Control Panel.

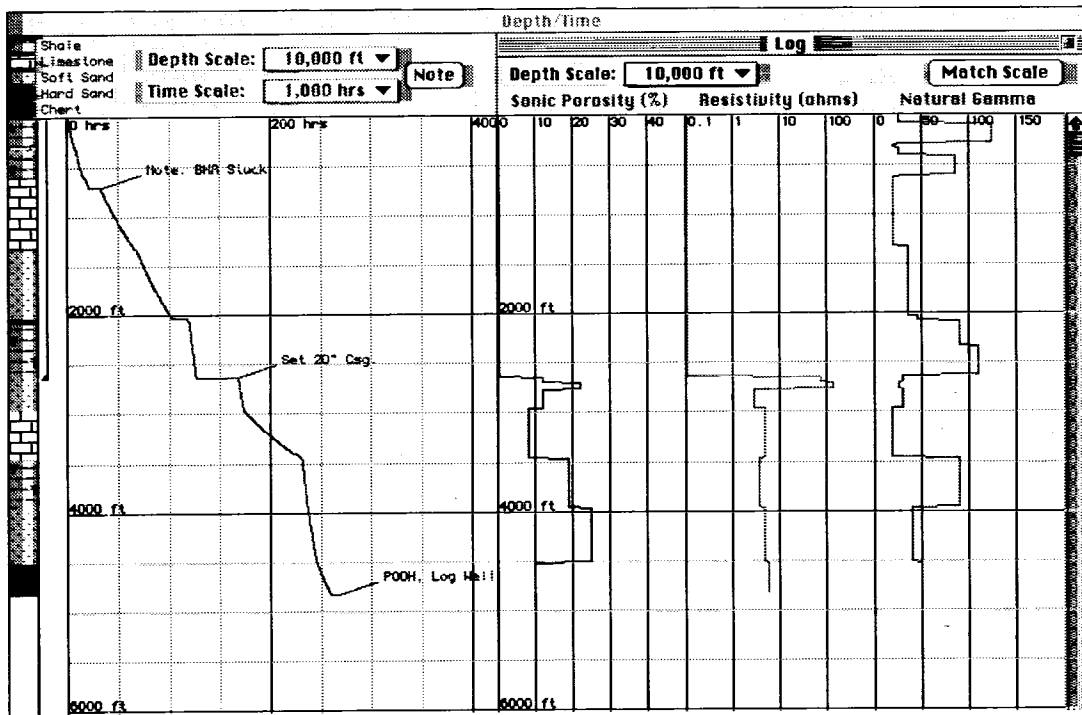


Figure 8: The Depth-Time window with the Well Log window superposed.