Viscous Fluid Effects on Guided Wave Propagation in a Borehole

by

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ABSTRACT

In order to investigate the effect of borehole fluid viscosity on the attenuation and dispersion of the guided waves present in full waveform acoustic logs, the problem of wave propagation in a borehole containing a viscoelastic fluid surrounded by an infinite elastic formation is solved using boundary layer theory. The results indicate that the losses due to viscous drag along the borehole wall are a small component of the overall guided wave attenuation for the frequencies of interest in full waveform acoustic logging (2–15kHz) and for reasonable viscosity values (1-1000cP). These losses, however, can be significant at low frequencies. In addition, the variations in viscosity have a negligible effect on the guided wave dispersion for this range of frequency and viscosity. These findings indicate that friction between grains in fluid suspension may be the dominant attenuation mechanism in the drilling fluids present in boreholes.

INTRODUCTION

In most previous formulations of the borehole wave propagation problem, the fluid which fills the borehole is assumed to be perfectly elastic, that is, inviscid. However, it is often found that in order to match synthetic microseismograms to actual full waveform acoustic log field data, the fluid must be lossy. Fluid attenuation is most commonly included by assuming a constant Q value for the fluid (Cheng et al., 1982; Tubman, 1984). Although these assumptions simplify the analysis and result in good agreement with field data, there are physical reasons for questioning their validity. First, by neglecting viscosity in the fluid, there is no boundary condition at the borehole wall for the axial displacement, that is, the axial displacement is allowed to be discontinuous. Such behavior suggests that the fluid molecules can slide past the solid borehole wall more easily than they can slide past themselves (Lamb, 1945). Fluid mechanical observations also indicate that the 'no-slip' condition is observed in practice no matter how small the viscosity (Lu, 1977). It seems reasonable, then, to investigate the effect of imposing the additional boundary condition on axial displacement. The second reason concerns the fluid attenuation mechanism. The most reasonable attenuation mechanism for a fluid in a borehole would be viscous drag at the borehole wall. In the absence of any viscosity, the assumption of constant Q for the fluid is somewhat difficult to justify. One possible justification for the use of a constant Q is based on the narrow frequency band commonly used in full waveform sonic logging. If the frequency dependence of Q for the fluid is not too great, it is reasonable to approximate it with a constant value over some limited frequency band. This explanation also carries the implicit assumption that the axial displacement boundary condition is not critical for the fluids and frequencies of interest in borehole logging situations. The commonly used drilling fluids, however, are fairly complicated in composition and dynamic behavior. These fluids can be viewed as suspensions of barite (or some other high density material) and other compounds (including clay minerals). Drilling fluids are also thixotropic, that is, the viscosity of the fluid is low when the fluid is flowing, as during drilling operations, and is higher when the fluid is stationary so that cuttings will remain in their proper spatial positions within the fluid stream. Besides viscous losses, then, attenuation due to frictional sliding of the suspended grains past one another is one possible loss mechanism. These questions of boundary conditions and attenuation mechanisms are critical enough to warrant an investigation of the effects of viscous borehole fluid on full waveform acoustic logs.

There has been very little work done on borehole wave propagation in the presence of a viscous fluid. Stevens and Day (1986) briefly discussed the possible effects of fluid viscosity and concluded that the effects would be negligible for any reasonable values of viscosity and frequency. Schoenberg et al. (1986) quantified the effects of viscosity by deriving an effective dispersion equation for low frequency Stoneley waves. The acoustic literature also contains the solution of similar wave propagation problems (Pierce, 1981). Biot (1956a,b), in his derivation of wave propagation in porous media, treated energy dissipation due to the relative motion between a viscous pore fluid and the solid framework of the porous material. He modelled the pore structure by cylindrical tubes, which is analogous to the present problem. Comparison of the results obtained for the viscous borehole fluid with those obtained via the Biot theory (Burns and Cheng, 1986) highlights the similarity.

In this paper, the dispersion equation for a simple, open borehole filled with a visco-elastic fluid will be derived. This is a boundary layer type problem due to the fact that as viscosity approaches zero, the axial displacement becomes discontinuous at the borehole wall. Such problems are referred to as singular perturbation problems because the nature of the problem changes dramatically when some small parameter, viscosity

(η) in this case, becomes zero. If the fluid is assumed to be 'perfectly' elastic, only three boundary conditions are imposed at the borehole wall: continuity of radial stress and displacement, and vanishing of axial stress. When viscosity is introduced, the axial stress is continuous at the borehole wall and it is non-zero in the fluid. In addition, a fourth boundary condition is imposed: the continuity of axial displacement. In order to satisfy this fourth boundary condition, a viscous boundary layer is formed in the fluid adjacent to the borehole wall. The boundary layer manifests itself in the azimuthal component of the vector potential of the fluid, that is, the fluid supports shear motion in the boundary layer. A zeroth order (in η) uniform solution for this shear potential in the fluid allows the period equation to be derived and dispersion and attenuation to be calculated for Stoneley and pseudo-Rayleigh modes. The results are in agreement with the conclusions of Schoenberg et al. for low frequency Stoneley waves. Calculations of radial and axial stress and displacement as functions of radial distance from the borehole axis are also carried out to illustrate the structure of the viscous boundary layer. Higher order solutions for the shear potential can be obtained, but for the range of viscosities and frequencies of interest in acoustic logging, the errors ($O(\eta)$) are small.

THEORY

In this section, the period equation for guided waves in a borehole containing a viscoelastic fluid is derived. The geometry of the borehole is assumed to consist of a cylindrical borehole filled with a viscoelastic fluid surrounded by an elastic formation of infinite extent. The problem is assumed to be axisymmetric. By assuming a viscoelastic fluid, the stress components in the fluid are proportional to strains and strain rates. More specifically, the fluid is assumed to be Newtonian viscous, that is the shear stress is equal to the product of viscosity and shear strain rate:

$$\tau = \eta \frac{\partial \epsilon}{\partial t} \tag{1}$$

Problem Formulation

For the simple open borehole geometry, the dilatational and shear potential solutions to the wave equation for an elastic formation are:

$$\begin{aligned} \phi &= \left[A' I_0(lr) + A K_0(lr)\right] e^{i(kz-\omega t)} \\ \psi &= \left[B' I_1(mr) + B K_1(mr)\right] e^{i(kz-\omega t)} \end{aligned} \tag{2}$$

where:

$$l = k\left(1 - \frac{c^2}{\alpha^2}\right)^{1/2}$$

$$m = k\left(1 - \frac{c^2}{\beta^2}\right)^{1/2}$$

r	= radial distance
z	= axial distance
k	= axial wavenumber
ω	= angular frequency
ϕ	= scalar potential
ψ	= azimuthal component of the vector potential
I_i	= i^{th} order modified Bessel function of the first kind
K_i	= i^{th} order modified Bessel function of the second kind
A, B	= amplitudes of outgoing waves
A', B'	= amplitudes of incoming waves

The radiation condition requires that A' and B' both equal 0. In order to obtain the solutions for the fluid, the equations of motion must be reformulated. The equation of motion based on the radial forces acting on an elementary volume in cylindrical coordinates is (assuming axial symmetry) (White, 1983):

$$\frac{\partial P_{rr}}{\partial r} + \frac{P_{rr} - P_{\theta\theta}}{r} + \frac{\partial P_{zr}}{\partial z} = \rho \frac{\partial^2 u_r}{\partial t^2} \tag{3}$$

where:

P_{ij}	= elements of the stress tensor
ρ	= density
u_r	= radial displacement

For a viscoelastic fluid as described above, the stress-strain equations of interest are given by:

$$P_{rr} = \lambda \left[\frac{\partial u_r}{\partial r} + \frac{u_r}{r} + \frac{\partial u_z}{\partial z} \right] + 2\eta \frac{\partial}{\partial t} \left[\frac{\partial u_r}{\partial r} \right] \tag{4}$$

$$P_{\theta\theta} = \lambda \left[\frac{\partial u_r}{\partial r} + \frac{u_r}{r} + \frac{\partial u_z}{\partial z} \right] + 2\eta \frac{\partial}{\partial t} \left[\frac{u_r}{r} \right]$$

$$P_{zr} = \eta \frac{\partial}{\partial t} \left[\frac{\partial u_z}{\partial r} + \frac{\partial u_r}{\partial z} \right]$$

where:

η = fluid viscosity
λ = Lame's constant of the fluid
u_z = axial displacement

Substituting Equations (4) into Equation (3) results in :

$$\lambda \left[\frac{\partial^2 u_r}{\partial r^2} + \frac{1}{r}\frac{\partial u_r}{\partial r} - \frac{u_r}{r^2} + \frac{\partial^2 u_z}{\partial z \partial r} \right] + \tag{5}$$

$$2\eta \frac{\partial}{\partial t} \left[\frac{\partial^2 u_r}{\partial r^2} + \frac{1}{r}\frac{\partial u_r}{\partial r} - \frac{u_r}{r^2} + \frac{1}{2}\frac{\partial^2 u_z}{\partial z \partial r} + \frac{1}{2}\frac{\partial^2 u_r}{\partial z^2} \right] = \rho \frac{\partial^2 u_r}{\partial t^2}$$

The dilatational potential in the fluid can be derived by substituting the following expressions into Equation (5):

$$u_r = \frac{\partial \phi}{\partial r} \tag{6}$$

$$u_z = \frac{\partial \phi}{\partial z}$$

Which results in :

$$\left[\frac{\partial^2\phi}{\partial r^2}+\frac{1}{r}\frac{\partial\phi}{\partial r}+\frac{\partial^2\phi}{\partial z^2}\right]+\frac{2\eta}{\lambda}\frac{\partial}{\partial t}\left[\frac{\partial^2\phi}{\partial r^2}+\frac{1}{r}\frac{\partial\phi}{\partial r}+\frac{\partial^2\phi}{\partial z^2}\right]=\frac{1}{\alpha_f^2}\frac{\partial^2\phi}{\partial t^2} \tag{7}$$

where:

$$\alpha_f=\left(\frac{\lambda}{\rho}\right)^{1/2}$$

Solving by separation of variables yields the following solutions:

$$\phi_{fluid}=\left[CI_0(fr)+C'K_0(fr)\right]e^{i(kz-\omega t)} \tag{8}$$

where:

$$f=\left[k^2-\frac{\omega^2}{\left(\alpha_f^2-\frac{2i\omega\eta}{\rho}\right)}\right]^{1/2}$$

The solution must remain finite on the borehole axis, therefore, C' must equal 0. The solution given in Equation (8) reduces to the elastic solution when $\eta=0$.

Because we have four boundary conditions which must be satisfied at the borehole wall, a solution for the shear potential must also exist in the fluid. The straight forward approach to finding the shear potential solution is to substitute the following expressions into Equation (5):

$$u_r=-\frac{\partial\psi}{\partial z} \tag{9}$$

$$u_z=\frac{\partial\psi}{\partial r}+\frac{\psi}{r}$$

The resulting equation can be solved by separation of variables and yields:

$$\psi_{fluid}=\left[DI_1\left(\bar{f}r\right)+D'K_1\left(\bar{f}r\right)\right]e^{i(kz-\omega t)} \tag{10}$$

where:

$$\bar{f} = \left[k^2 - \frac{i\omega\rho}{\eta}\right]^{1/2}$$

Again, the solution must be finite on the borehole axis, and therefore D' must equal 0.

An obvious problem exists with this solution. As η gets small the radial wavenumber $(\bar{f})$ gets very large, and the Bessel function becomes infinite. This behavior is not too surprising since the problem is actually a singular perturbation problem. When $\eta = 0$, the axial displacement boundary condition is dropped and $\psi = 0$ in the fluid. As soon as η is non-zero, however, the nature of the problem abruptly changes to include the axial displacement boundary condition. The problem must be solved by using boundary layer theory. The fluid develops a thin boundary layer along the borehole wall in which the viscous drag occurs. In this boundary layer the axial displacement is rapidly changing. The rapid change in the axial displacement is due to the shear potential of the fluid rapidly changing in this zone. It is reasonable to expect that the solution outside the boundary layer will be equal to the non-viscous solution, that is, $\psi = 0$, and only be non-zero within the boundary layer.

Boundary Layer Formulation

The shear potential is found by substituting Equations (9) into Equation (5). Assuming an oscillatory function of the form:

$$\psi_{fluid} = \xi(r)\, e^{i(kz-\omega t)} \tag{11}$$

the resulting ordinary differential equation in terms of the radial distance r is:

$$\frac{d^2\xi}{dr^2} + \frac{1}{r}\frac{d\xi}{dr} - \xi\left(\frac{1}{r^2} + k^2 - \frac{i\omega\rho}{\eta}\right) = 0 \tag{12}$$

To find the outer solution of this equation, that is the solution outside of the boundary layer (Figure 1), Equation (12) is rewritten as:

$$\eta\frac{d^2\xi}{dr^2} + \frac{\eta}{r}\frac{d\xi}{dr} - \xi\left(\frac{\eta}{r^2} + \eta k^2 - i\omega\rho\right) = 0 \tag{13}$$

Letting $\eta \rightarrow 0$ results in:

$$(i\omega\rho)\,\xi = 0 \tag{14}$$

or:

$$\xi = 0$$

The outer solution, then, is the same as the solution for the case of a non-viscous fluid.

The inner solution, that is the solution within the boundary layer, is somewhat more complicated. Because the solution is rapidly changing in this narrow region it is best to rescale the problem (Bender and Orzag, 1979). The natural choice is:

$$r' = \frac{R - r}{\delta} \tag{15}$$

where:

R	= borehole radius
r	= radial distance
δ	= boundary layer thickness

In terms of this new variable, as $r \rightarrow R$, $r' \rightarrow 0$, and as $r \rightarrow 0$, $r' \rightarrow \frac{R}{\delta}$ which approaches infinity as δ goes to zero. Equation (13) can be rewritten in terms of r' by noting that:

$$\frac{d\xi}{dr} = -\frac{1}{\delta}\frac{d\xi}{dr'} \tag{16}$$

$$\frac{d^2\xi}{dr^2} = \frac{1}{\delta^2}\frac{d^2\xi}{dr'^2}$$

The resulting equation in terms of the inner variable, r', is:

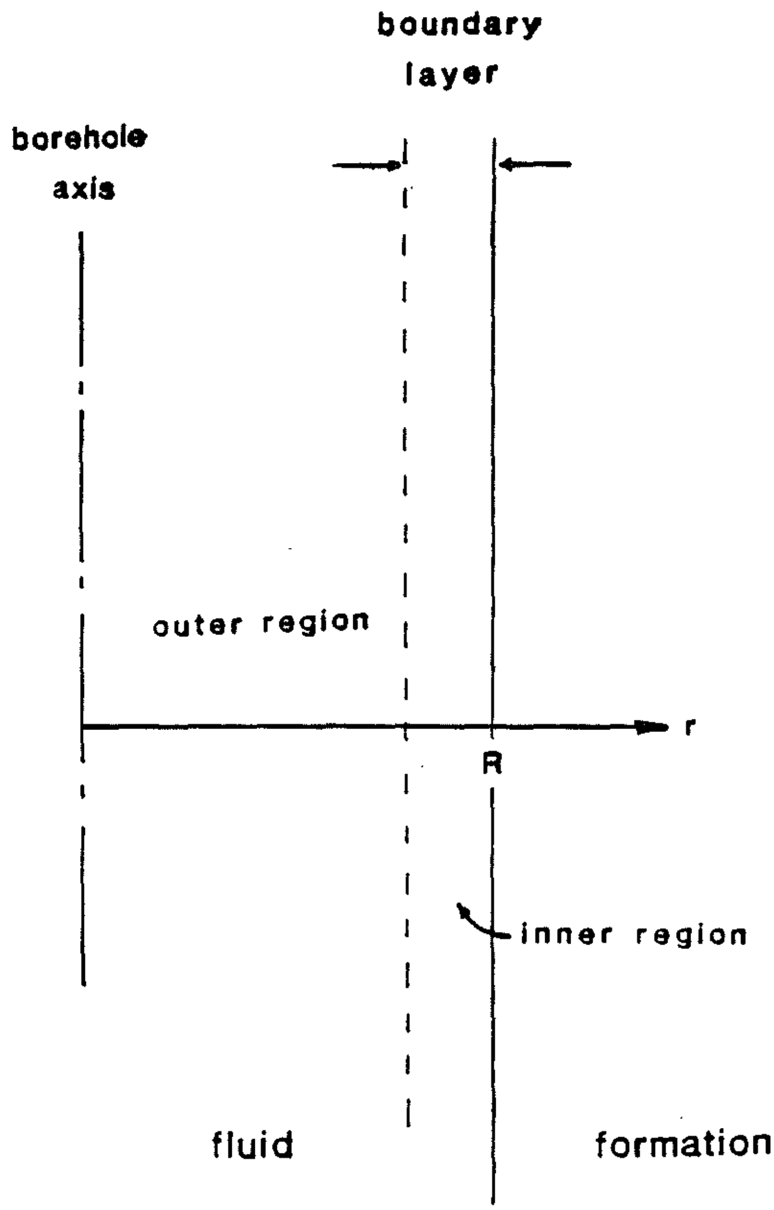

Figure 1: Boundary layer structure of the viscous fluid

$$\frac{\eta}{\delta^2}\frac{d^2\xi}{dr'^2} - \frac{\eta}{\delta\left(R-\delta r'\right)}\frac{d\xi}{dr'} - \xi\left(\frac{\eta}{\left(R-\delta r'\right)^2} + \eta k^2 - i\omega\rho\right) = 0 \tag{17}$$

Dominant balance arguments indicate that $\delta \sim \sqrt{\eta}$ which leaves:

$$\frac{d^2\xi}{dr'^2} - \frac{\eta^{1/2}}{\left(R-\delta r'\right)}\frac{d\xi}{dr'} - \xi\left(\frac{\eta}{\left(R-\delta r'\right)^2} + \eta k^2 - i\omega\rho\right) = 0 \tag{18}$$

Letting η and δ go to zero reduces the equation to :

$$\frac{d^2\xi}{dr'^2} + i\omega\rho\xi = 0 \tag{19}$$

The solution of this equation can be written as:

$$\xi\left(r'\right) = D_1\, exp\left[\sqrt{-i\omega\rho}\, r'\right] + D_2\, exp\left[-\sqrt{-i\omega\rho}\, r'\right] \tag{20}$$

The inner solution must match the outer solution as r' approaches ∞, therefore $D_1 = 0$. Noting that:

$$\sqrt{-i} = \frac{1-i}{\sqrt{2}} \tag{21}$$

Equation (20) is reduced to (the subscript on the constant D_2 is dropped):

$$\xi\left(r'\right) = D\, exp\left[-(1-i)r'\sqrt{\frac{\omega\rho}{2}}\right] \tag{22}$$

And, using Equation (15), the inner solution can be recast in terms of the original variables as follows:

$$\xi\left(r\right) = D\, exp\left[-(1-i)\left(R-r\right)\sqrt{\frac{\omega\rho}{2\eta}}\right] \tag{23}$$

The uniform approximation to shear potential in the fluid is represented by the sum of the inner and outer solutions minus the matching solution. In our case, the uniform solution is equal to the inner solution. The total, zeroth order, uniform approximation for the shear potential in the fluid, is therefore given by:

$$\psi_{fluid} = D\ exp\left[-(1-i)\,(R-r)\sqrt{\frac{\omega\rho}{2\eta}}\,\right] e^{i(kz-\omega t)} \tag{24}$$

The boundary layer thickness, or viscous skin depth, is given by:

$$\delta = \sqrt{\frac{2\eta}{\omega\rho}} \tag{25}$$

The boundary layer thickness is very small for almost any reasonable viscosity and frequency values of interest. As an example, for a frequency of 1kHz and a viscosity of 1000cP, $\delta = 0.0056$ of the borehole radius (R). The form of the solution in Equation (24) indicates that when r=R, ψ_{fluid} takes on its maximum amplitude, which is the constant D, and decreases exponentially away from the borehole wall.

Before moving on to the derivation of the period equation, a short discussion of the approximate nature of the solution obtained for the shear potential is in order. The solution given in Equation (24) is the zeroth order (in η) solution which means that the correction terms to this solution are of order η ($O(\eta)$). The error introduced by neglecting these correction terms can be estimated by comparing the magnitude of the zeroth order solution (Equation (24)) to the magnitude of η for the range of parameters of interest. This has been done by comparing the maximum value of Equation (24), that is the constant D, to the dimensionless (normalized) value of η. For a frequency of 1kHz and a viscosity of 1000cP, the errors are less than 1 percent. Errors are much less than 10 percent even for frequencies as low as 100 Hz with this very high value of viscosity. These error values indicate that the zeroth order solution is an excellent approximation for the probable range of viscosities and frequencies of interest in acoustic logging.

Derivation of the Period Equation

In order to derive the period equation for guided waves in a borehole containing a viscous fluid, four boundary conditions must be satisfied at the borehole wall:

i) continuity of radial displacement

ii) continuity of radial stress

iii)continuity of axial displacement

iv) continuity of axial stress

The radial and axial displacement in terms of potentials are given by:

$$u_r = \frac{\partial \phi}{\partial r} - \frac{\partial \psi}{\partial z} \tag{26}$$

$$u_z = \frac{\partial \phi}{\partial z} + \frac{\partial \psi}{\partial r} + \frac{\psi}{r}$$

and the radial and axial stresses in terms of potentials are:

$$\sigma = P_{rr} = \rho \frac{\partial^2 \phi}{\partial t^2} - 2\mu \left[\frac{1}{r}\frac{\partial \phi}{\partial r} + \frac{\partial^2 \phi}{\partial z^2} + \frac{\partial^2 \psi}{\partial z \partial r} \right] \tag{27}$$

$$\tau = P_{zr} = \rho \frac{\partial^2 \psi}{\partial t^2} - 2\mu \left[\frac{\partial^2 \psi}{\partial z^2} - \frac{\partial^2 \phi}{\partial z \partial r} \right] \tag{28}$$

For the viscous fluid, the rigidity (μ) in Equations (27) and (28) is replaced by $-i\omega\eta$. By using the potentials given in Equations (8) and (24), the displacements and stresses in the fluid are (the exponential propagation term is dropped for clarity):

$$u_r = CfI_1(fr) - ikDe^{\varsigma} \tag{29}$$

$$u_z = CikI_0(fr) + D\left[(1-i)\sqrt{\frac{\omega\rho}{2\eta}} + \frac{1}{r}\right] e^{\varsigma} \tag{30}$$

$$\sigma = C\left[-\rho_f\omega^2 I_0(fr) + 2i\omega\eta\left[\frac{f}{r}I_1(fr) - k^2 I_0(fr)\right]\right] + iD\left[2i\omega\eta k(1-i)\sqrt{\frac{\omega\rho}{2\eta}}e^{\varsigma}\right] \tag{31}$$

$$\tau = C\left[2\omega\eta k f I_1(fr)\right] + D\left[-\rho_f\omega^2 - 2i\omega\eta k^2\right] e^{\varsigma} \tag{32}$$

where:

$$\varsigma = -(1-i)(R-r)\sqrt{\frac{\omega\rho}{2\eta}}$$

The displacements and stresses in the formation are calculated by using the potentials from Equation (2):

$$u_r = -AlK_1(lr) - iBkK_1(mr) \tag{33}$$

$$u_z = AikK_0(lr) - BmK_0(mr) \tag{34}$$

$$\begin{aligned}\sigma = A\left[-\rho\omega^2 K_0(lr)\right] + 2\mu\left[\frac{l}{r}K_1(lr) + k^2 K_0(lr)\right] \\ +iB\left[2\mu k\left[mK_0(mr) + \frac{1}{r}K_1(mr)\right]\right]\end{aligned} \tag{35}$$

$$\tau = -A\left[2\mu iklK_1(lr)\right] - B\left[\rho\omega^2 K_1(mr) + 2\mu k^2 K_1(mr)\right] \tag{36}$$

Equating terms at the borehole wall (r=R) results in the following system of equations:

$$\mathbf{Ya} = \mathbf{0} \tag{37}$$

where:

$$\mathbf{a}^{\mathbf{T}} = [A \;\; iB \;\; C \;\; iD]$$

and $\mathbf{Y}$ is a 4 x 4 matrix whose elements are given by the terms in Equations 30 - 37. A non-trivial solution to this system exists when:

Table 1: Fluid and formation parameters used in calculations

LAYER	V_p (m/sec)	V_s (m/sec)	ρ (g/cm^3)	η (cP)
fluid	1500	0	1.0	0 1 10 100 1000
formation	3670	2170	2.4	

$$|\mathbf{Y}| = 0 \tag{38}$$

which is the period equation. By solving for the complex wavenumber roots of Equation (38) over a range of frequencies, the dispersion and attenuation of Stoneley and pseudo-Rayleigh waves are found for any given fluid and formation parameters.

RESULTS AND DISCUSSION

The dispersion and attenuation of Stoneley and pseudo-Rayleigh waves are calculated for a range of viscosity values in the presence of a fast formation (that is, formation shear velocity greater than the borehole fluid velocity). The parameters are given in Table 1. Before presenting these results, however, plots of displacement and stress terms near the borehole wall will be shown. Figures 2 through 5 illustrate the variations in displacements and stresses in the vicinity of the borehole for the Stoneley wave (1kHz) and several values of viscosity. The axial displacement profiles (Figure 3) show the boundary layer behavior of the fluid particularly well. In order to make these calculations without imposing a source term, the constant C (the fluid dilatational potential amplitude) was set equal to one. As a result, the displacement and stress values are arbitrary. In addition, all calculations have been carried out with dimensionless input parameters, and, as such, the displacement and stress values are also dimensionless.

The complex wavenumber roots of the period equation have been calculated for viscosity values of 0, 1, 10, 100, and 1000 centipoise (cP). Phase velocity dispersion and attenuation are calculated from the real and imaginary parts of the roots of the period equation. The results for the Stoneley wave are given in Figures 6 and 7, while the

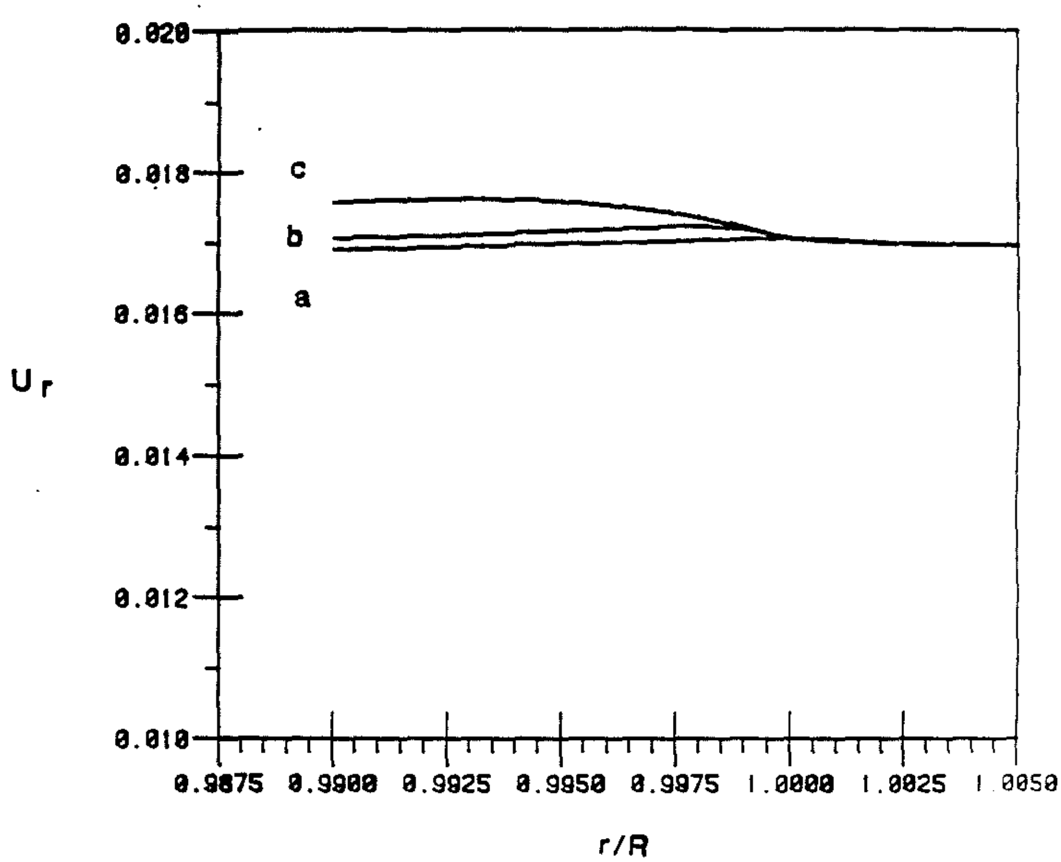

Figure 2: Stoneley wave radial displacement as a function of radial distance (normalized to the borehole radius) for viscosity values of (a) 1, (b) 100, and (c) 1000 cP

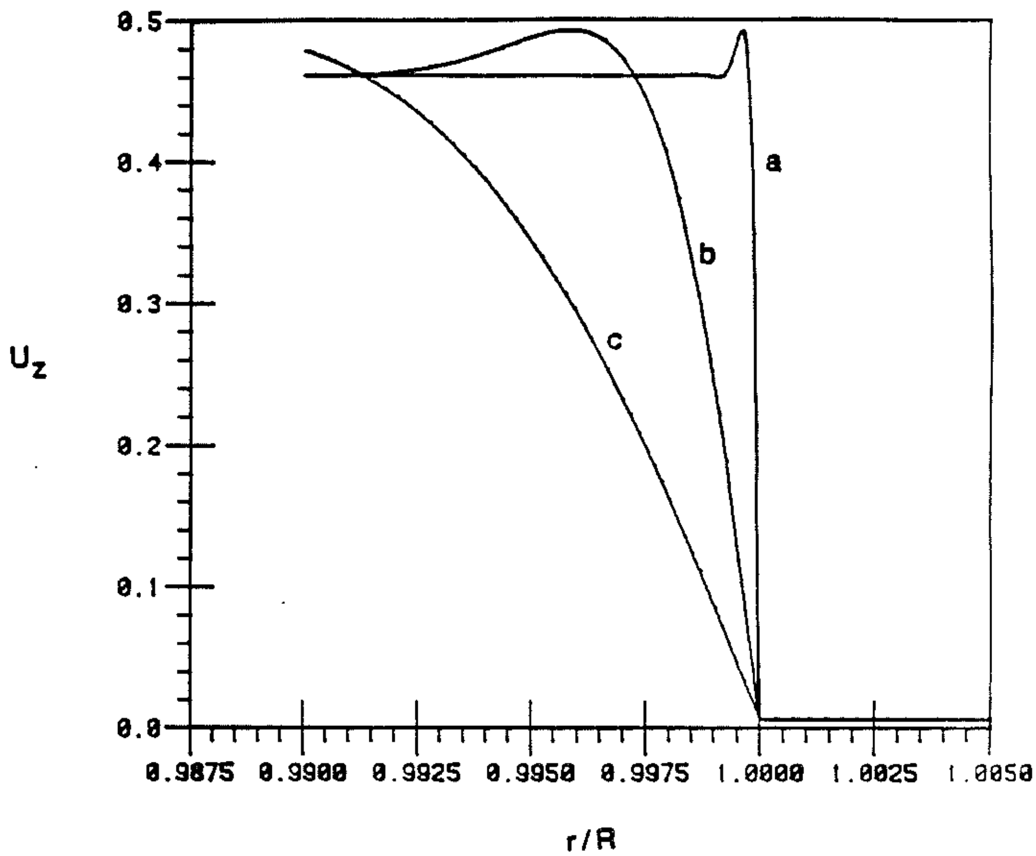

Figure 3: Stoneley wave axial displacement as a function of radial distance (normalized to the borehole radius) for viscosity values of (a) 1, (b) 100, and (c) 1000 cP

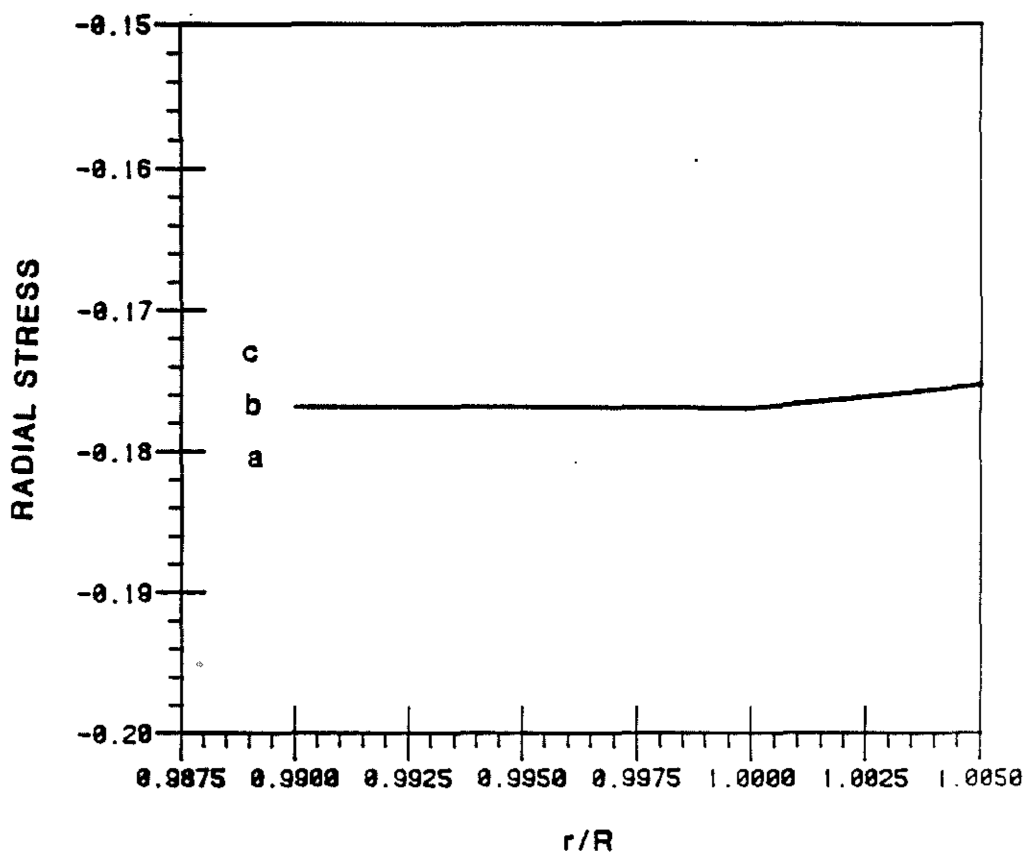

Figure 4: Stoneley wave radial stress as a function of radial distance (normalized to the borehole radius) for viscosity values of (a) 1, (b) 100, and (c) 1000 cP

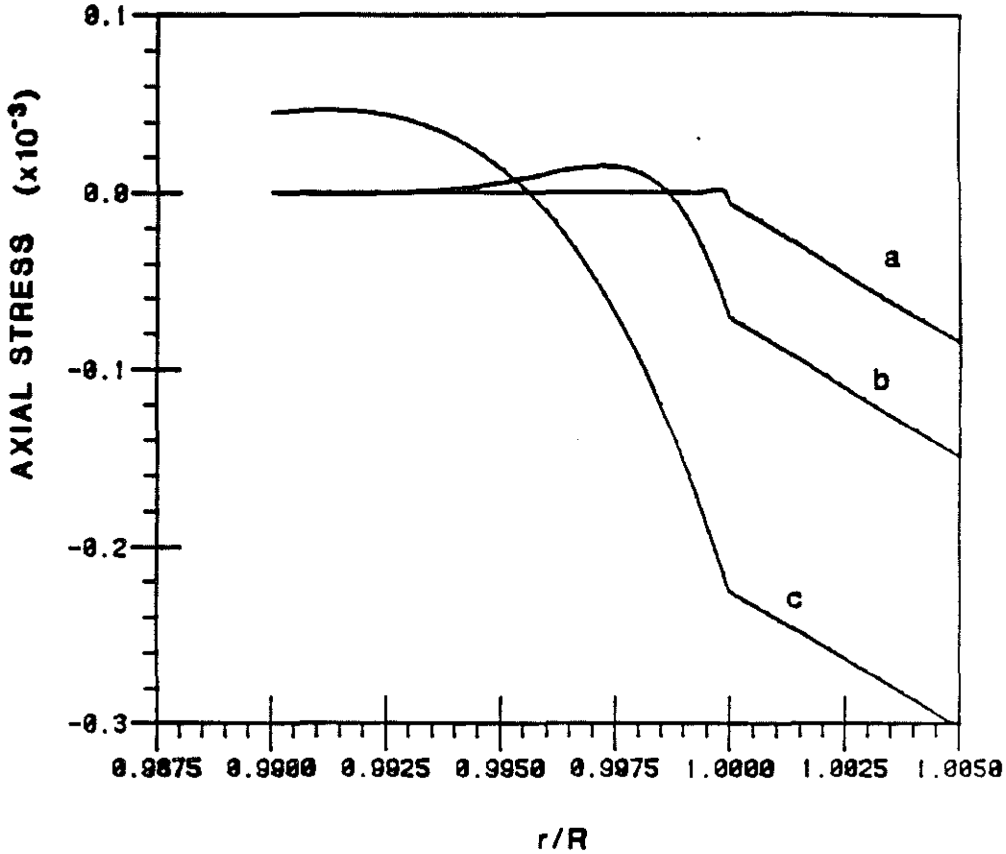

Figure 5: Stoneley wave axial stress as a function of radial distance (normalized to the borehole radius) for viscosity values of (a) 1, (b) 100, and (c) 1000 cP

results for the fundamental mode of the pseudo-Rayleigh wave are given in Figures 8 and 9.

The dispersion and attenuation curves generated for the Stoneley and pseudo-Rayleigh waves indicate that the effects of a viscous borehole fluid are quite small. Stoneley wave dispersion is only negligibly affected in the normal logging frequency range (2-15kHz) and the pseudo-Rayleigh wave dispersion is completely unaffected. The Stoneley wave attenuation due to viscous drag at the borehole wall, although increasing dramatically at low frequencies (the attenuation varies as $\omega^{-1/2}$), is quite small even for very large viscosity values. For a frequency of 1kHz and a viscosity of 1000cP the attenuation is about 0.005 which corresponds to a Q value of 200. By contrast, studies of guided wave attenuation in the presence of a fast formation indicate that the Stoneley wave attenuation is primarily controlled by the fluid attenuation (Cheng et al, 1982). As stated earlier, most modelling of acoustic logs requires fluid attenuation values of about 0.05 or a Q of about 20. Viscosity values greater than 10,000 cP are necessary to even approach Stoneley wave Q values of 20 (for example, for $\eta = 10000$ and a frequency of 1000 Hz, the Stoneley wave attenuation is 0.02 (Q = 50)). Comparison of such values with the viscous loss values computed here indicates that the viscous losses are quite small and can generally be neglected. The psuedo-Rayleigh wave attenuation values reach a maximum value less than 0.001 (Q of 1000) for a viscosity value of 1000cP, again indicating that the viscous losses are much smaller than the attenuation values normally needed in modelling.

Although 1000cP represents a very viscous fluid (for example, at 20^oC : the viscosity of glycerin is 1490cP; the viscosity of olive oil is 84 CP; and the viscosity of water is 1cP), the range of representative viscosity values for drilling fluid must be addressed. The rheological properties of drilling fluids are of prime importance to the drilling process. Drilling fluid primarily acts as a medium to transport rock cuttings away from the drill bit and to the surface. It also maintains pressure on any subsurface pore fluids. Most drilling fluids contain clay minerals which will adhere to the borehole wall (as the fluid invades the subsurface formations) creating a mudcake which seals in formation fluids and aids in maintaining the integrity of the borehole. Drilling fluids, in general, are either water or oil base mixtures containing clays in suspension, barite or some similar high density material to add weight, and a host of other possible chemical additives to adjust the fluid's dynamic or chemical properties. The viscosity of the borehole fluid is of particular importance. A viscosity value that is too low may not hold the drill cuttings in their proper relative positions in the flow line when fluid circulation is stopped, while a value that is too high may result in difficulty in pumping of the fluid. A number of authors have investigated the dynamic behavior of drilling fluids, with particular emphasis on viscosity (Hiller, 1963; McMordie et al., 1975; Messenger, 1963; and Walker and Mays, 1975). Hiller (1963) performed laboratory measurements of viscosity for a range of drilling fluids as functions of temperature and pressure. His results indicate that oil base drilling fluids exhibit Newtonian behavior and have viscosities in the range

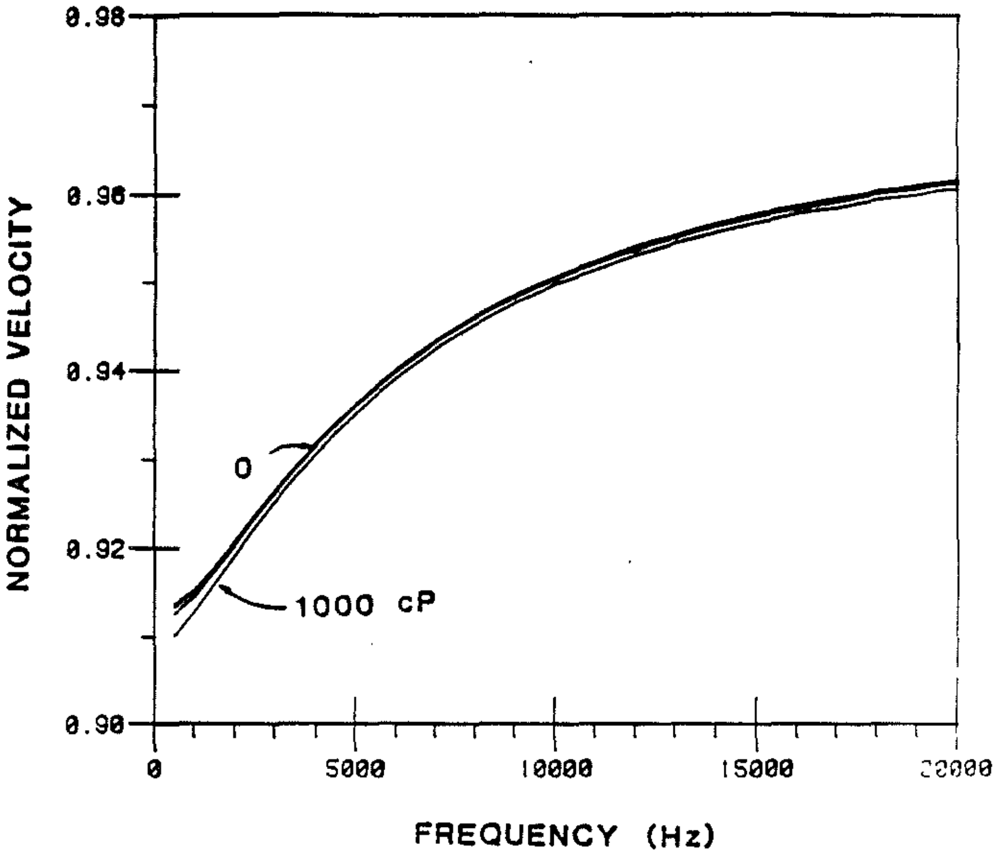

Figure 6: Stoneley wave phase velocity dispersion (normalized to the borehole fluid velocity) for viscosity values of 0, 1, 10, 100, and 1000 cP

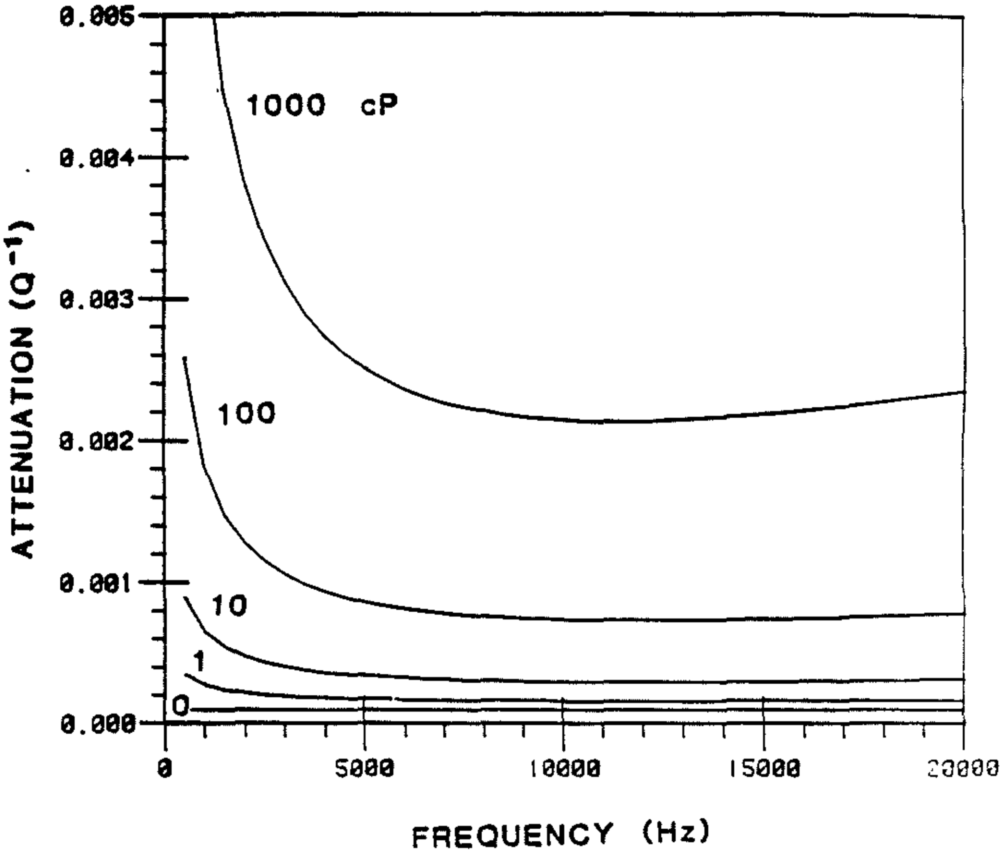

Figure 7: Stoneley wave attenuation (Q^{-1}) for viscosity values of 0, 1, 10, 100, and 1000 cP

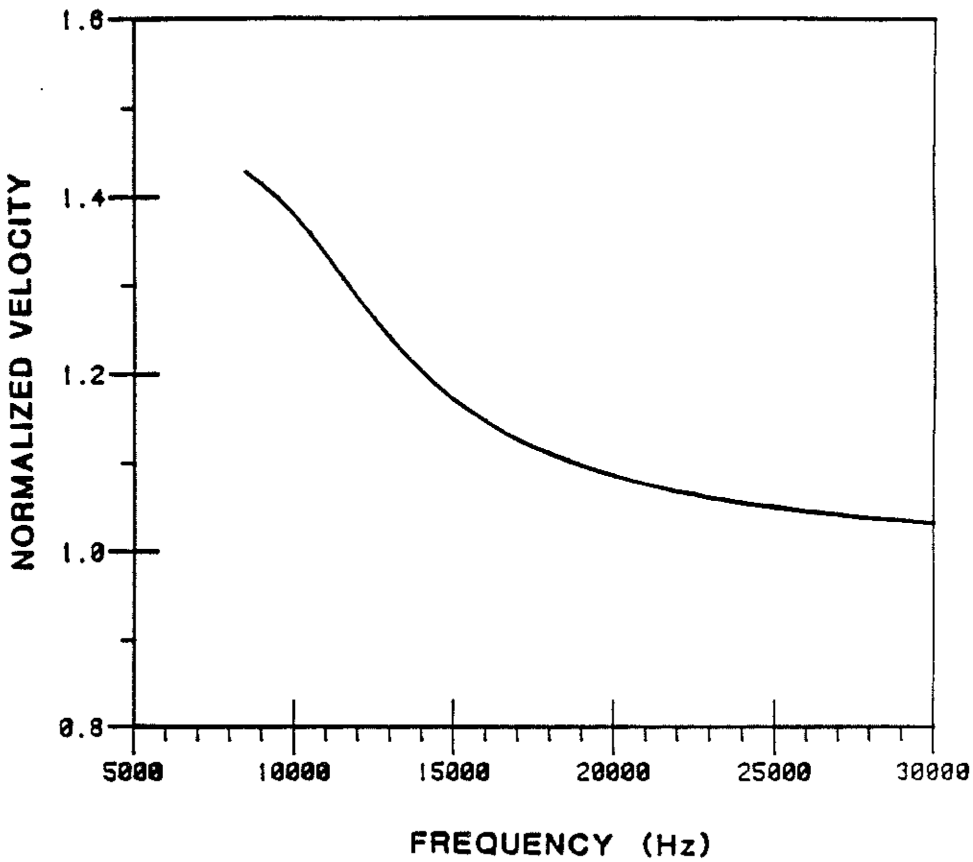

Figure 8: Pseudo-Rayleigh wave phase velocity dispersion (normalized to the borehole fluid velocity) for viscosity values of 0, 1, 10, 100, and 1000 cP

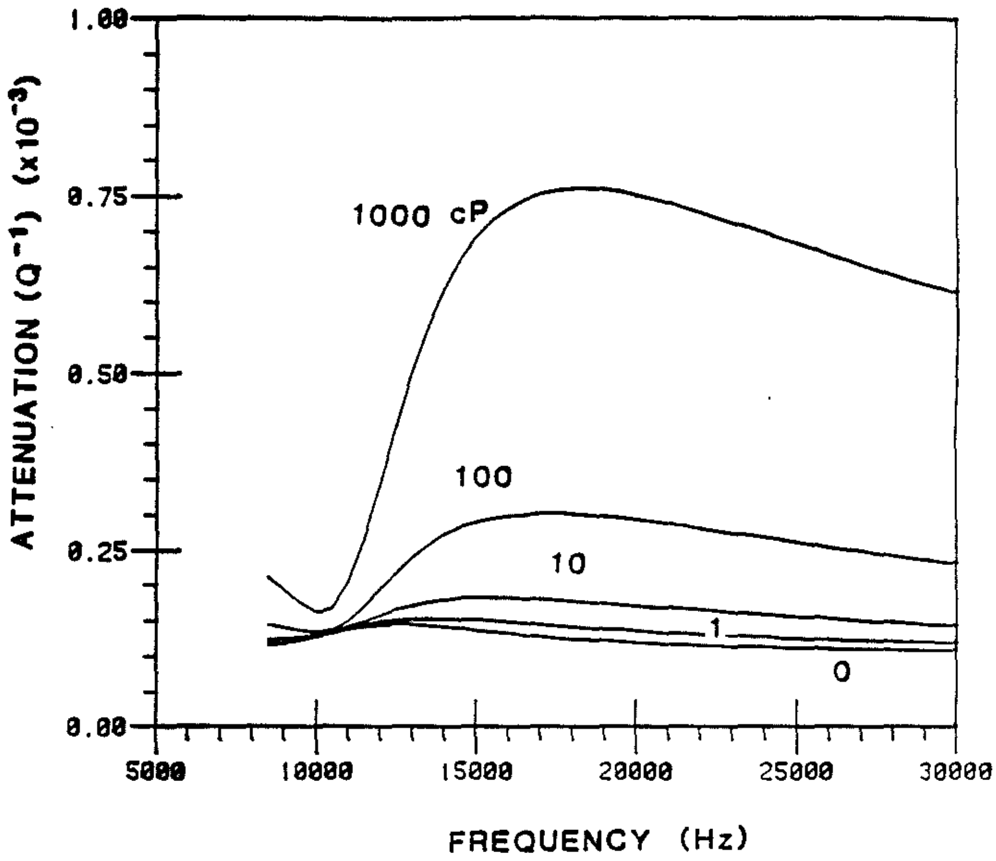

Figure 9: Pseudo-Rayleigh wave attenuation (Q^{-1}) for viscosity values of 0, 1, 10, 100, and 1000 cP

of 30 to 200 cP, depending on the temperature and pressure. A number of water base drilling fluids which were tested exhibited Newtonian behavior only at higher strain rates. That is, these fluids behave in a thixotropic manner, the viscosity values are higher when the fluid is at rest, and lower when the fluid is flowing. In the Newtonian regions, the water base fluids have viscosity values between 6 and 30 cP. Hiller (1963) also studied the effect of clay suspensions in water and found that the amount (and type) of clay can have a large effect on the viscosity behavior. In most examples he measured viscosity values of between 5 and 40 cP, however in one example containing a high concentration of swelling clay, the viscosity at low strain rates increased dramatically at high temperatures (to 600cP at 150^oC) due to clay flocculation.

CONCLUSIONS

In conclusion, published studies of drilling fluid viscosity indicate that values of 5 to 200 cP are typical, with a possibility of values reaching 1000cP in extreme cases. The typical values (5-200cP) result in viscous losses that are small in magnitude for the Stoneley and pseudo-Rayleigh waves. This result, coupled with a recent laboratory measurement of drilling fluid Q which was frequency independent (a water based mud containing clay was found to have a constant Q value of 30 over a frequency range from 100kHz - 1MHz (Tang and Toksöz, personal communication), and the agreement between synthetic and real microseismograms using a frequency independent fluid Q value, indicates that friction between solid particles in a suspension may be an important loss mechanism. A more detailed study of the properties of drilling fluids, particularly their viscosity and attenuation values over a wide range of frequencies, is needed to fully understand the actual loss mechanisms involved.

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