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Overpressure detection from seismic amplitude versus offset response: An application to gas-hydrates

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The seismic amplitude versus offset (AVO) analysis is an important tool for quantification of gas-hydrates and/or free-gas across a bottom simulating reflector (BSR). The high overpressure in the free-gas zone underlain by gas-hydrated sediments changes the seismic velocity and hence affects the AVO response appreciably. So the effect on AVO due to overpressure is to be evaluated before making quantitative assessment of gas-hydrates and free-gas across a BSR. Besides, knowledge of overpressure helps in planning the drilling process to avoid potential geo-hazard due to abnormally high pressures. Here we compute the AVO response of both *P–P* and *P–S* reflections from a BSR

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for possible detection of overpressure in the free-gas-bearing zone. The theoretical computation shows that high and negative AVO anomalies for *P–P* reflected waves indicate a high overpressure condition. Normal AVO trend for *P–P* reflected wave and relatively high maximum *P–S* reflection amplitude indicate the presence of overpressure.

SEISMIC methods have been proved to be the best tool for detecting gas-hydrates in the marine environments by mapping the bottom simulating reflector (BSR), a marker for gas-hydrates, on the seismic section based on various characteristic properties. The BSR corresponds to the base of gas-hydrate stability field that is controlled by the local geothermal gradient, salinity and the presence of other gases. BSR is a high-amplitude negative-polarity seismic event with respect to the seafloor reflection. High-velocity hydrated sediments underlain by low-velocity sediments containing free gas or brine cause phase reversal. The high amplitude at BSR is due to the contrast in acoustic impedance since the *P*-wave velocity of gas-hydrates is high compared to the velocity of free-gas or brine-saturated sediments below, while the density is almost unchanged. The BSR, being a physical boundary, mimics the shape of the seafloor and cuts across the dipping strata. The methane trapped within and below the hydrated sediments may be regarded a potential energy resource. On the other hand, methane, being a greenhouse gas, may cause global warming upon dissociation[1]. The dissociation of gas-hydrates also reduces the shear strength of sediments and hence causes slope failure. Therefore, the study of gas-hydrates has various important implications on energy potential, global warming, geo-hazard, etc. The presence of gas-hydrates and/or 'free-gas' in sediments influences the physical properties of sediments, which is manifested in the seismic data. The amplitude versus offset (AVO) response plays an important role in quantifying the amount of gas-hydrates and hence in measuring the energy potential and hazard assessment.

The AVO analysis of a BSR is an important tool to understand whether the hydrated sediment is underlain by brine or gas-saturated sediment. It also helps to predict the type of distribution of hydrates (non-contact or contact models) and to quantify the amount of gas-hydrates by analysing both the *P*- and *S*-waves[2,3]. However, the problem of estimating free-gas lying below the hydrated sediments has been difficult due to the combined effect of 'presence of free-gas' and 'overpressure in the free-gas zone'. In fact, both the effects cause the low compressional velocity that is observed below the BSR. Several geological and geophysical parameters indicate favourable condition for the formation and occurrence of gas-hydrates in the vast offshore regions of India[4,5]. Gas-hydrates form in the upper few hundred metres of the rapidly accumulating submarine sediments. Since hydrates are not stable at normal pressure and temperature, not much is known about their *in situ* properties. The physical properties have mostly been derived from seismic experiments. Here, we attempt to find the possibility of discriminating the effect caused by the presence of free-gas from the effect caused by an anomalous pressure in the pores, following the approach of Tinivella[6].

The study of pore-pressure is important for both the academic community and the oil industries. Since high pressure may cause a high risk for drilling, knowledge of the same is useful for optimum casing in drilling programmes. A prediction of overpressure can be used to develop fluid migration models and to improve seismic interpretation. Various workers[7–10] have attempted to predict the pore-pressure regime using seismic data. The overpressure is caused by the free-gas trapped below the gas-hydrates, which act as seal to prevent the escape of gas from underneath. Predicting overpressure in the free-gas zone helps to better understand the migration of fluids, physical properties of sediments and the origin of BSR. Here we investigate the effects of pore-pressure in free-gas underlain by gas-hydrates based on analysing the AVO response of a BSR.

Before studying the effect of overpressure, it is necessary to know the pressures that may exist in a reservoir medium. A detailed description of pore-pressure terminology can be found in Bruce and Bowers[11]. We recall these for our convenience (Figure 1). 'Pore-pressure' or formation pressure is the *in situ* pressure of fluids in the pores of the rock. Normal or 'hydrostatic pressure' is the pore fluid pressure of a column of formation fluid extending up to the surface. In this case the pore fluids only support the weight of the overlying pore fluids (primarily brine) present in a porous formation, with pore spaces continuously connected to the surface. The pressure exerted by all overlying materials, both solid and fluid, is called 'lithostatic pressure' or 'overburden pressure'. In such cases, the pore fluids of the sediments support all the

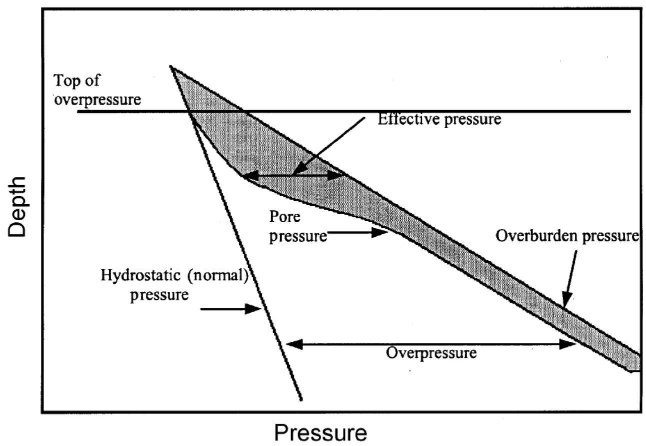

Figure 1. Definition of various pressure terminologies[11].

weight of the overlying sediments (brine as well as mineral grains). It is also called as 'confining pressure'. 'Effective pressure' is the difference between overburden pressure and the pore-pressure. It is the amount of overburden pressure that is supported by the rock grains.

Another term frequently used is the differential pressure, which is the difference between confining pressure and the 'pore-pressure'. When the pressure exerted by the formation fluids is significantly greater than the normal hydrostatic pressure, the medium is said to be in overpressure condition. The difference between the pore-pressure and the hydrostatic pressure for a given depth is called overpressure. In overpressure condition, fluids are trapped in the pores and bear part of the weight of the overlying solids.

Overpressure may occur due to the following reasons: (i) Chemical reactions whose products are more voluminous than their reactants, e.g. formation of oil and gas from kerogen; (ii) thermal expansion of water and (iii) failure of sediments to compact on burial, to a porosity where the framework of rock grains can support all the weight of the overlying sediments. This situation arises when the permeability of sediments is so low that the pore fluids cannot be squeezed out fast enough. However, it is generally opined that the third process is the predominant cause of most large overpressures observed in the sediments.

Pore-pressure strongly affects compaction-related geophysical properties such as density, resistivity and sonic velocity[12]. The reason behind this is the change of porosity and saturation with increase in pressure. Carcione and Tinivella[8] calculated the porosity (ϕ) and water (S_w) and gas (S_g) saturation by changing the pore-pressure at constant confining pressure (or depth) and temperature. The changes, as explained by them, are due to the compressibility effect only.

The porosity (ϕ) and pore-pressure are related as:

$$\phi = A\phi_i/[1 - \phi_i(1 - A)],$$

where ϕ_i is the porosity at the initial state at normal hydrostatic pressure. The parameter A depends on the pore-pressure and can be obtained if the pore compressibility versus effective pressure is known[8]. The porosity versus pressure relationship can be obtained using the relationships between the velocity versus effective pressure and the velocity versus porosity in marine sediments. Figure 2 shows the variation of porosity with pore-pressure ranging from hydrostatic pressure (25.5 MPa) to the limit of confining pressure (28.2 MPa) at 500 m below the seafloor lying 2000 m beneath the water column.

The water (S_w) and free gas (S_g) saturation are related to pore-pressure as[6]:

$$S_w = S_{wi}[\exp(-C_w\Delta p)/A],$$

and

$$S_g = 1 - S_w,$$

where S_{wi} is the initial water saturation, Δp is the amount of overpressure (pore-pressure minus hydrostatic pressure) and C_w is the water compressibility. Figure 3 shows the water (solid line) and free gas (broken line) saturation versus pore-pressure. Initial gas saturation is assumed to be 10%.

Seismic velocity in a rock depends upon porosity and saturation, and therefore is sensitive to pore-pressure. Dvorkin[13], through laboratory experiments, has shown that in a rock formation with gas in its pore spaces, the velocity of seismic wave increases with increasing differential pressure (confining minus pore-pressure), while it decreases with increasing pore-pressure (Figure 4). The decrease in P-wave velocity with increasing pore-pressure can be used for overpressure detection[13]. However, overpressure cannot be detected precisely from velocity alone, as velocity depends on many other factors like porosity, mineralogy, texture of the rock materials, etc.

Poisson's ratio can be calculated from the velocities of $P(V_P)$ and $S(V_S)$ waves as:

$$\sigma = 0.5(V_p^2/V_s^2 - 2)/(V_p^2/V_s^2 - 1).$$

A precise relation exists between the Poisson's ratio, pore-pressure and fluid type[14]. Values of Poisson's ratio for dry samples are significantly smaller than those for fluid saturated samples, especially in soft formation. Figure 5 shows the variation of Poisson's ratio with increasing pore-pressure. Except at very high pore-pressure, Poisson's ratio decreases with pore-pressure. As is evident from Figure 5, the decrease in Poisson's ratio with pore-pressure is more pronounced at low gas saturation.

AVO analysis has been an important tool for the detection of gas-bearing sediments. The theoretical basis for AVO is governed by Zoeppritz's equation[15], which describes the variation of reflection coefficients or amplitudes with increasing angles or offset for various component

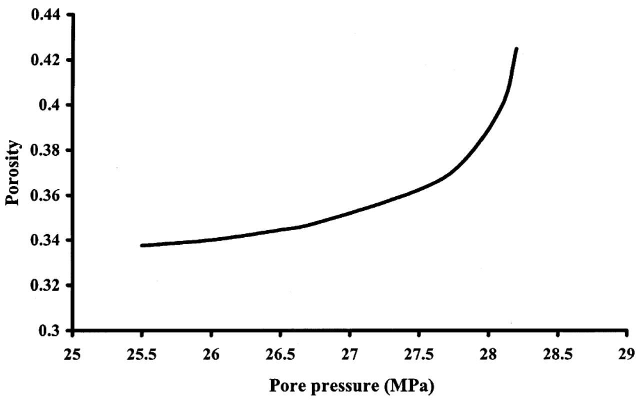

Figure 2. Porosity versus pore-pressure[6].

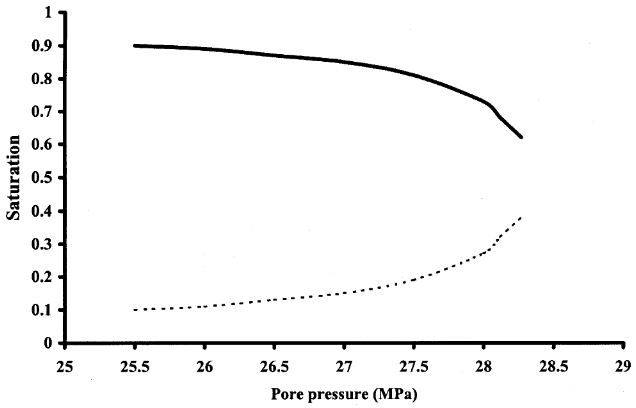

Figure 3. Water (solid line) and free gas (broken line) saturation versus pore-pressure[6].

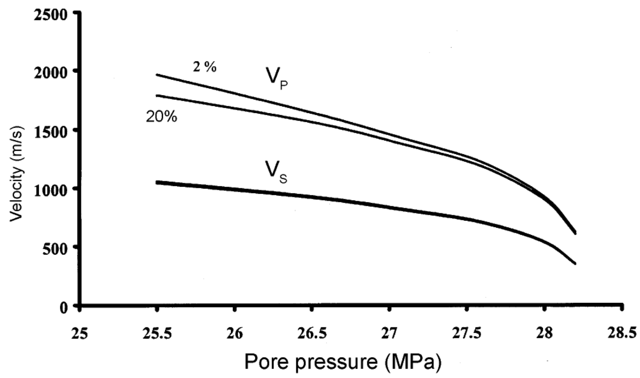

Figure 4. Compressional and shear wave velocity versus pore-pressure at 2% and 20% gas saturation below the BSR[6].

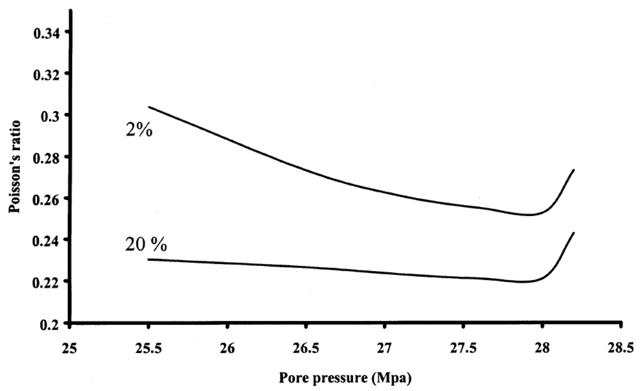

Figure 5. Poisson's ratio versus pore-pressure at different free-gas saturations[6].

waves, i.e. reflected and transmitted waves both *P–P* and *P–S* at a plane boundary. The AVO response has important implications in (i) estimating the amount of free-gas and gas-hydrates, and (ii) studying the internal structure of hydrated sediments.

Table 1. Material properties of marine sediments above the BSR containing gas-hydrates

Hydrate concentration	Effect on the sediments	V_P (m/s)	V_S (m/s)	Density (kg/m^3)
Low	No cementation	2314	1042	2104
High	Cementation	3256	1698	2071

Table 2. Material properties of marine sediments below the BSR containing free-gas at different pore-pressures. The two values correspond to free-gas saturation equal to 2 and 20% of the pore space

Pressure (MPa)	V_P (m/s)	V_S (m/s)	Density (kg/m^3)
25.5	1964–1787	1043–1058	2097–2041
26.5	1640–1562	916–929	2073–2017
27.1	1419–1370	807–818	2049–1994
27.6	1219–1183	699–708	2021–1967
28.0	923–899	531–538	1968–1915
28.2	623–604	348–352	1883–1832

So far as pore-pressure is concerned, seismic velocity of both *P*-wave and *S*-wave decreases with increasing pore-pressure but the degree of reduction in *S*-wave velocity is different from that in *P*-wave velocity. So, the reflection coefficients show some anomaly in the presence of overpressure. We consider the reflection of the *P*-wave (*P–P*) as well as the mode-converted wave (*P–S*). Values of the physical properties of the sediments used in the analysis are taken from Tinivella[6]. Tables 1 and 2 list the material properties of the sediments containing gas-hydrates and free-gas at different pore-pressures respectively.

The reflection coefficients are computed at different pore-pressures for different free-gas saturations. Both the cementation as well as non-cementation models of hydrates are considered. We assume the compressional and shear quality factors equal to 200 and 100 respectively, within the zone of gas-hydrates and free-gas-bearing sediments[16]. Figure 6 *a* shows the variation of reflection coefficients against angles for the *P–P* wave reflected from the BSR. The concentration of gas-hydrates is taken to be less, so that there is no cementation of the sediments above the BSR. The concentration of free-gas is also taken to be small, i.e. only 2%. Figure 6 *a* shows that the *P–P* amplitude at normal incidence increases with the increase in pore-pressure. At low overpressure, the AVO trend is normal (negative amplitude increases with angle), but at high overpressure the AVO effect is strong and negative. Thus, in the case of low saturation of gas-hydrates, the high overpressure can be detected from the *P–P* AVO analysis of the BSR. Figure 6 *b* shows that the amplitudes of *P–S* waves reflected from the BSR are small at normal incidence angles even at high overpressure, but the variation of reflection coefficients with angle is quite signifi-

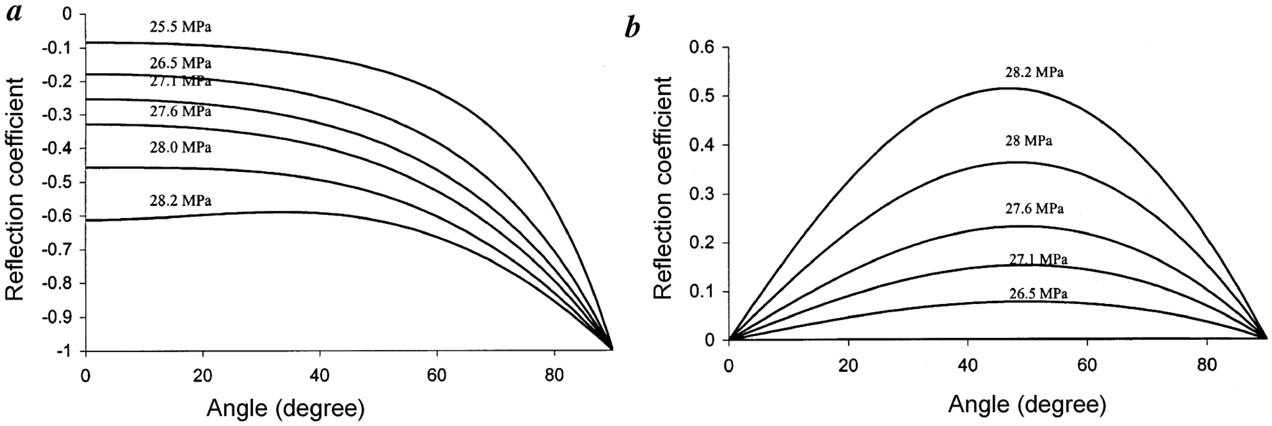

Figure 6. Variation of (***a***) *P–P* and (***b***) *P–S* reflections coefficient with angle of incidence for different pore-pressure conditions. Sediments below the BSR are assumed to contain 2% free gas.

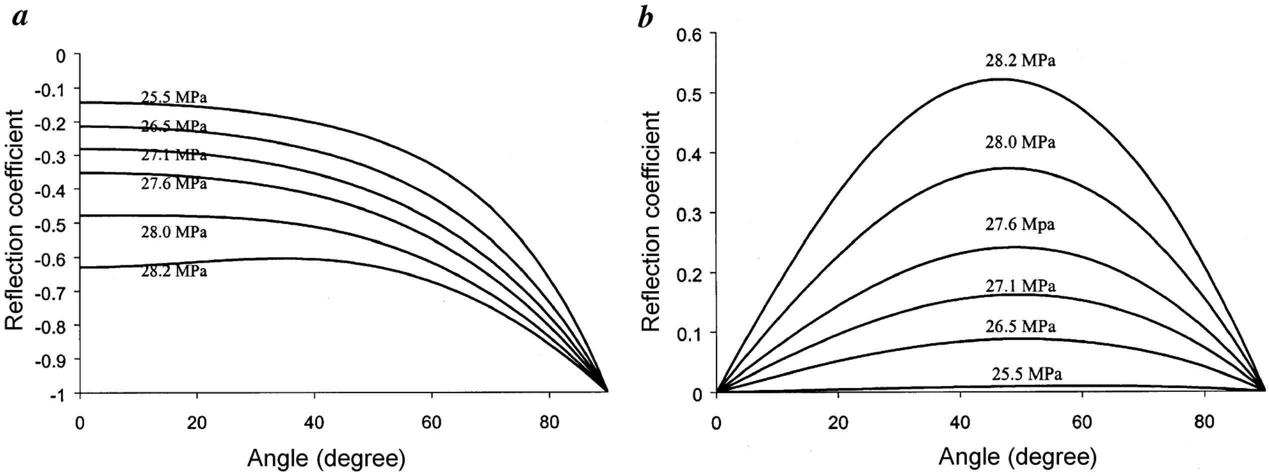

Figure 7. Variation of (***a***) *P–P* and (***b***) *P–S* reflections coefficient with angle of incidence for different pore-pressure conditions. Sediments below the BSR are assumed to contain 20% free gas.

cant in the presence of overpressure. So we can detect overpressure from the AVO analysis of *P–S* reflected phases in the case of low saturation of gas-hydrates.

For the case of 20% free-gas in the pore spaces, the AVO effects are shown in Figure 7*a* and *b* for the *P–P* and *P–S* reflected phases respectively. The results are similar to those described in Figure 6*a* and *b*, but the magnitudes are higher.

When the concentration of gas-hydrates above the BSR is high enough to cement the sediments, this has an effect to increase the seismic velocity above the BSR (Table 1) appreciably. This, in turn, produces more prominent AVO response due to greater impedance contrast between the hydrated layer above and the free-gas zone below. Figure 8*a* depicts the results of *P–P* reflection coefficients versus angle for a cemented model of gas-hydrates, where saturation of free-gas is taken to be 2%. The AVO curves show negative anomalies at high pore-pressure. These negative anomalies increase with pore-pressure and are strong at high overpressure. The variation of *P–S*-reflection coefficients with angle is shown in Figure 8*b*. The curves are strongly affected by the cementation of gas-hydrates and the anomalous pore-pressure conditions and are significant. But in this case, the amplitudes are high enough at normal pressure itself.

The joint analysis of *P*-wave velocity, Poisson's ratio and AVO responses of both *P–P* and *P–S* waves can be utilized to detect the presence of overpressure in the free-gas-bearing sediments below the BSR. From the theoretical considerations we draw the following points:

(i) Velocity of *P*-wave decreases with overpressure. *S*-wave velocity also decreases with overpressure, but to a different degree.

(ii) The Poisson's ratio decreases with increasing pore-pressure, but at high pore-pressure it again increases.

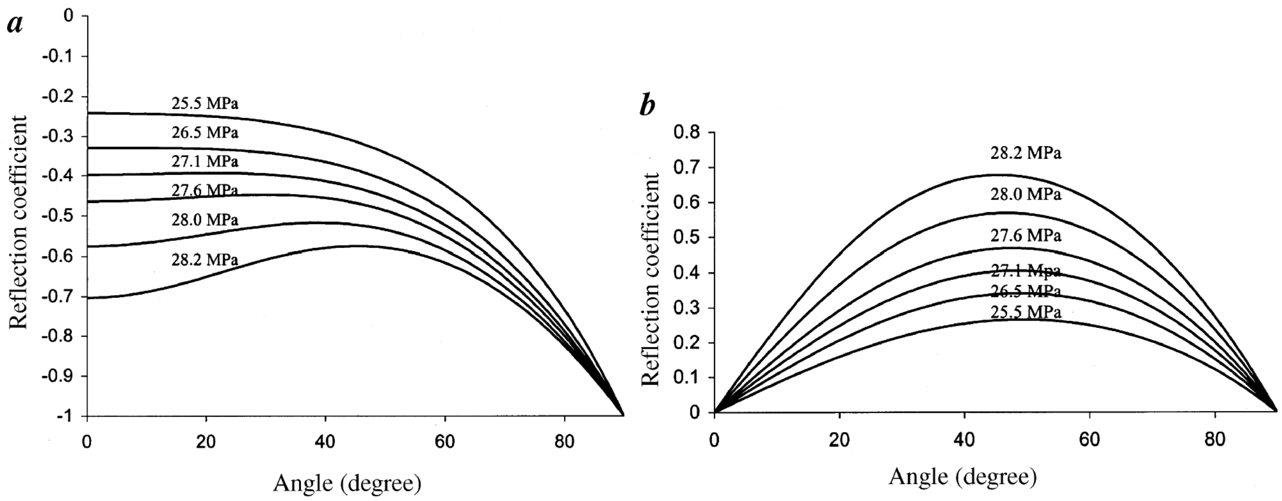

Figure 8. Variation of (***a***) *P–P* and (***b***) *P–S* reflections coefficient with angle of incidence for different pore-pressure conditions considering cementation of hydrates above the BSR. Sediments below the BSR are assumed to contain 2% free gas.

(iii) The amplitudes or reflection coefficients of *P–P* reflected phases are high and increase with overpressure at normal incidence angles. The AVO response at high overpressure shows negative trends.

(iv) The amplitudes or reflection coefficients of *P–S* reflected phases steadily increase with angles followed by negative anomalies at higher angles and the trends are stronger at high overpressure. The values are relatively high compared to those of *P–P* reflected phases at high overpressures.

(v) For high concentration of gas-hydrates causing cementation, the *P–P* reflection amplitude is high and it shows highly negative anomaly at high overpressure.

(vi) The *P–S* amplitudes for high concentration of hydrates is high even at normal hydrostatic pressure and the analysis to differentiate high pore-pressure should be carried out along with the amplitudes of *P–P* reflected phases.

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