Thoughts on detecting wormholes in cold production of heavy oil using time-lapse seismology

Qiaozhi (Sandy) Chen and Larry Lines

ABSTRACT

During the heavy-oil cold production process, producing sand and oil simultaneously causes a dramatic increase in oil recovery. The reason for the higher oil recovery is due to the wormhole development during production, where wormholes create interconnections between the boreholes in the reservoirs. Therefore, detecting the distribution of the wormholes is very significant for designing the well spacing and infill drilling locations. Time-lapse seismology could be a useful new technique to monitor wormholes based on the physical characteristics of wormholes, such as high porosity, unconsolidated sand-free channels, and foamy oil with gas saturation. This paper will discuss some ideas on how to detect wormhole distribution by employing the Vp/Vs ratio and AVO anomalies in time-lapse seismology techniques.

INTRODUCTION

The heavy-oil cold production process is a non-thermal process, in which sand and oil are produced simultaneously in order to enhance oil recovery. The reason that the oil recovery rate increases rapidly compared with conventional production without sand, is due to foamy oil flow and wormhole network growth (Sawatzky and Lillico, 2002).

Foamy oil flow

The cold production process involves the depressurization of the live heavy oil in the reservoir. When oil production increases, and the sand cut tends to be very low and stable, the pressure declines in the reservoir. This causes the exsolution of dissolved gases as bubbles within the oil. The formation of gas bubbles increases the fluid volume within the reservoir, forcing both oil and gas to the well. Gas saturation in the wormholes is an advantage for seismology, because the seismic response is very sensitive to gas saturation, compared to other fluids.

Wormhole network growth

During cold production, the production of sand from an unconsolidated heavy-oil reservoir generates a network of high-permeability channels – wormholes. It is believed that the growth of wormholes depends on the following conditions (Sawatzky et al. 2002):

1) Wormholes grow in the unconsolidated, clean (no cementation, less clay and shale, high porosity) sand reservoirs, because clean sand has a much weaker cohesive strength. This leads to an easier movement of sand with the high-viscosity heavy oil.

2) A criterion for wormhole growth is the pressure gradient between the borehole and the tip of the wormhole. Generally, wormholes tend to grow more rapidly as the pressure gradient increases.

3) Also, the higher the porosity and oil saturation, the higher the rate of wormhole growth will be.

In cold production, sand and heavy-oil are always produced simultaneously. However the growth of wormholes develop in two stages. During the first six months of the wormhole growth, the sand cut is relatively high. After that, the sand-cut rapidly drops and tends to be stable. At this time, the wormhole growth tends to be mature and the sand-free channels are formed on the top of wormholes with a possible high porosity of 50 percent or more (Figure 1). Although the size of a single wormhole is only about a few centimetres (Tremblay, 1999a), they can extend 200 m or more around the original borehole in the pay zone. Therefore, the wormhole growth not only enhances the oil recovery, but also creates the interconnections between the wells.

Therefore, knowing the distribution of wormholes is very important in planning and designing the development of reservoir exploitation strategies for cold production pools. This knowledge will influence well-spacing, infill locations, and the prediction of production profiles and estimates of reservoirs. Reservoir simulation has modeled cold production footprints. Another alternative approach could be time-lapse seismic imaging. This paper will present some thoughts on how to detect the distribution of wormholes by employing time-lapse seismic techniques. These techniques are based on the mechanisms of cold production, such as the physical characteristics of wormholes and gas-saturated foamy oil.

GEOLOGICAL MODELS OF WORMHOLES

During cold production, wormholes are very likely to grow into a network within the pay zone. The mechanism would be similar to the growth of a root system (Yuan et al. 1999). Figure 2 illustrates the top view of the wormhole zone. Yuan et al. introduced the Probabilistic Active Walker (PAW) model to describe the growth of wormholes.

Probabilistic Active Walker (PAW) seismic model

In the PAW model, the walker modifies the landscape surrounding him while walking, and the landscape in turn influences the walker's decision on the direction of the next step.

In addition, the walker is partially drunk and would most likely choose a direction that costs less energy, but he would not be able to always find the desired direction. We can consider the mechanism of the wormhole growth to be similar to the walker. During the

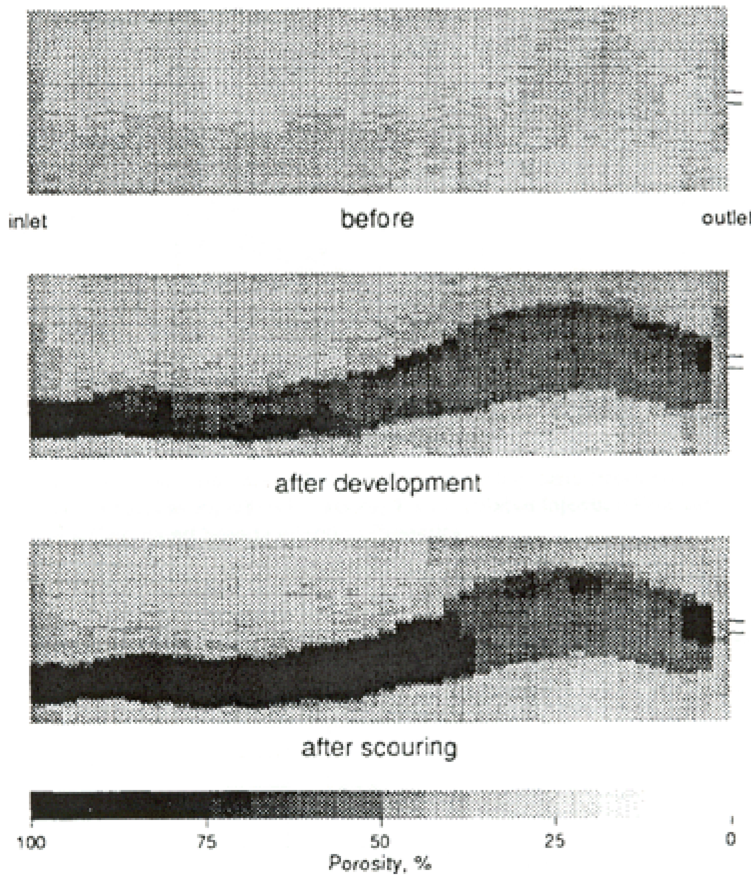


FIG. 1. The development of the wormhole with porosity changes (Tremblay, 1996)

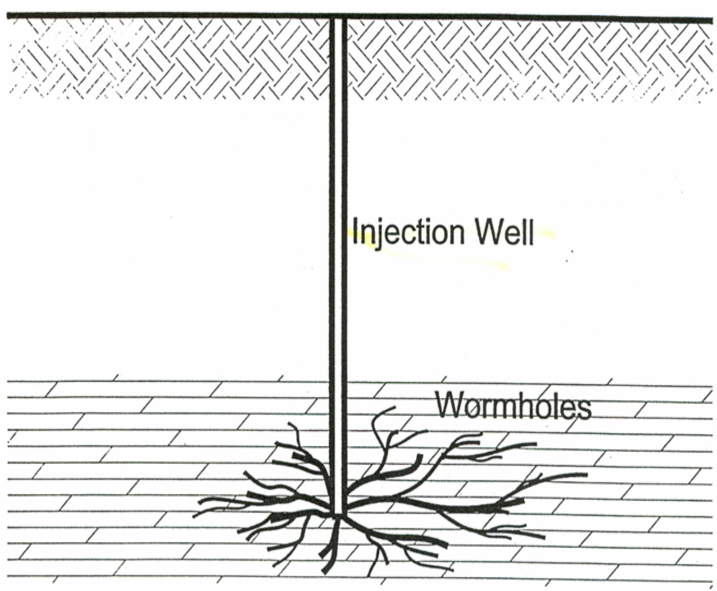


FIG.2. Schematic of wormholes following cold production of heavy oil (from Miller et al. 2001)

cold production, wormholes will very likely grow into a network away from the original borehole. Wormhole growth could be very random like the growth of the root system of a plant, but tends to extend along the weakest cohesive strength (clean sand) and along the greatest pressure gradient between the tip of wormholes and reservoir sands. In other words, the wormhole could grow in any direction around the borehole laterally and vertically in the reservoir sands under the control of the cohesive strength and pressure gradient. This describes the PAW model employed to build 2D geological models of wormholes.

In this paper, a simple 2D geological model of wormholes is built as in Figure 3. This model is 800m by 800m in horizontal and vertical directions, and consists of three layers denoted layer 1, layer 2, and layer 3, from top to bottom. The three layers are assigned P-wave velocities of 1900m/s, 2027m/s and 2200m/s respectively, from top to bottom with constant density. Layer 2 is a sandstone reservoir with a porosity of 30 percent, where wormholes are developed randomly with a relatively high porosity of 50 percent and a lower velocity of 1800m/s (as shown in Figure 3). The wormholes can extend about 200 m long around the borehole at coordinate of (400,500). A single wormhole width in this model is set at one meter, which may be optimistically large but not impossible.

Based on the model, synthetic seismograms with and without wormholes are created by using Ricker wavelets with dominant frequencies of 120Hz, 60Hz and 30Hz respectively. Figures 4,5,6, respectively, show the synthetic data with and without wormholes, as well as the differences, which are plotted by subtracting wormhole synthetic seismograms from non-wormhole synthetic seismograms. Notice that the high frequency content gives more detail of the wormholes characteristics. However, when the dominant frequency of the wavelet is 30Hz, the only seismic response is produced by the average effect of all of the wormholes.

In the field, with a vertical size of a few centimetres, a single wormhole can only be seen on surface seismic data by using frequencies in the KHz range. It is very difficult for surface seismic data to detect a single wormhole. According to the three synthetics above, we could consider detecting the average response of the wormholes instead of a single wormhole. In addition, knowing the distribution zone of wormholes could satisfy the requirements of reservoir engineering. Therefore, the above wormhole model of Figure 3 will be modified as shown in Figure 7. The effective wormhole zone would have a size of a couple of meters. This model will be applied to future study. In this model, the velocities of Layer 2 are calculated using Wyllie's time average equation.

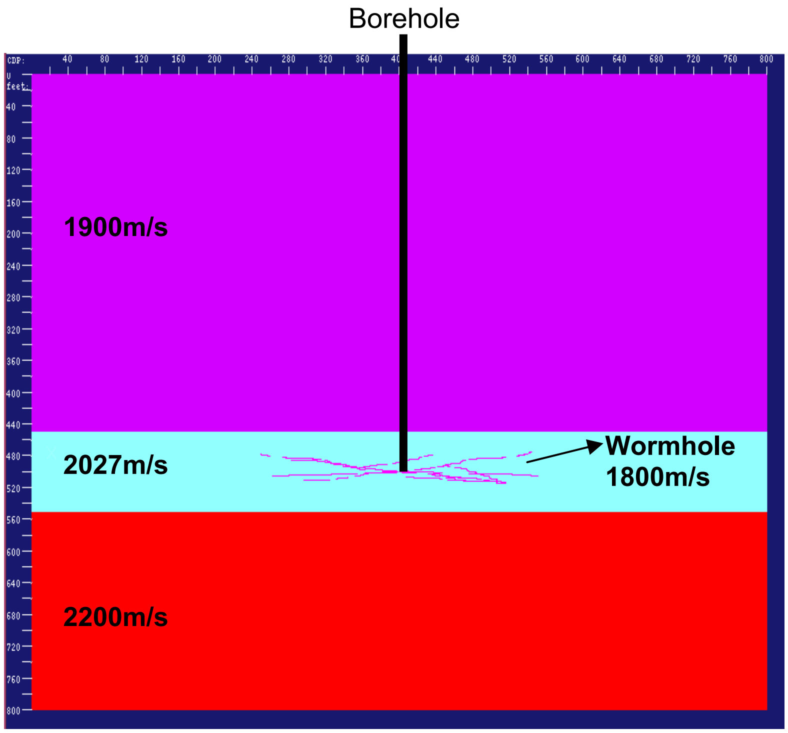
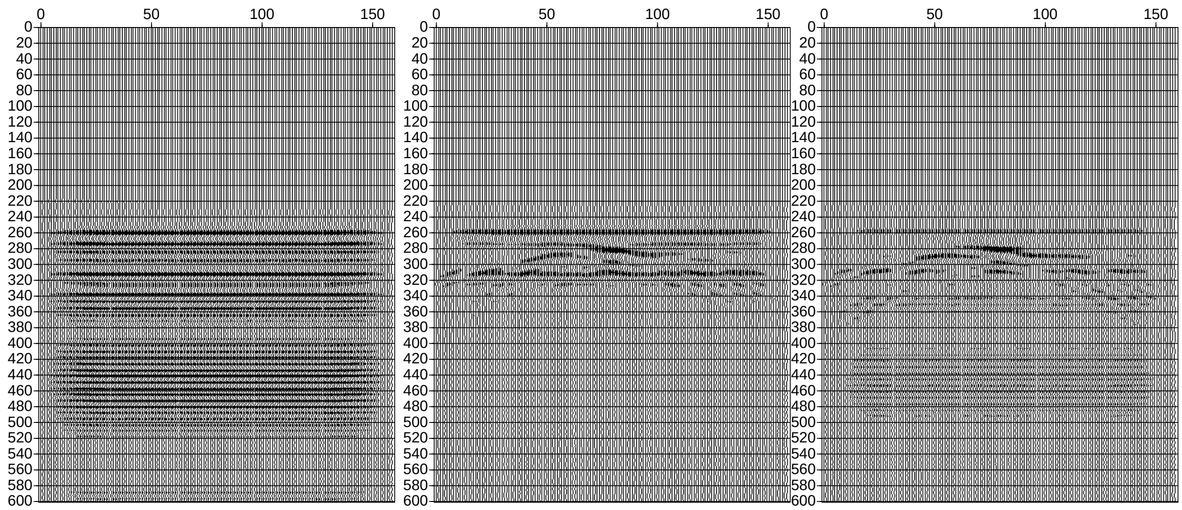


FIG. 3. Wormhole geology model based on PAW

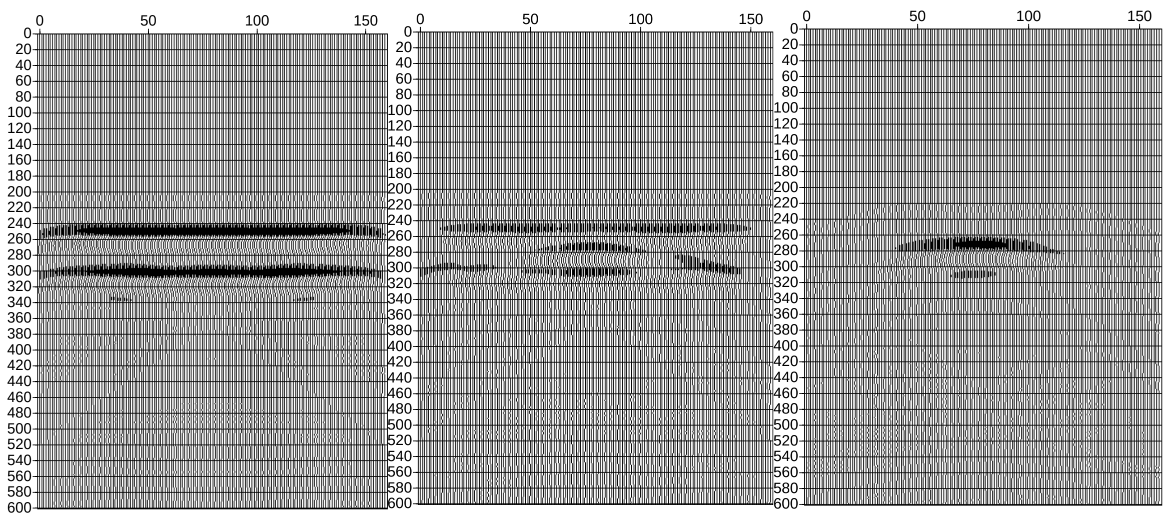
a) without wormholes b) with wormholes c) difference

FIG. 4. Synthetic seismic data using a Ricker wavelet with 120Hz dominant frequency



a) without wormholes b) with wormholes c) difference

FIG. 5. Synthetic seismic data using a Ricker wavelet with 60Hz dominant frequency



a) without wormholes b) with wormholes c) difference

FIG. 6. Synthetic seismic data using a Ricker wavelet with 30Hz dominant frequency

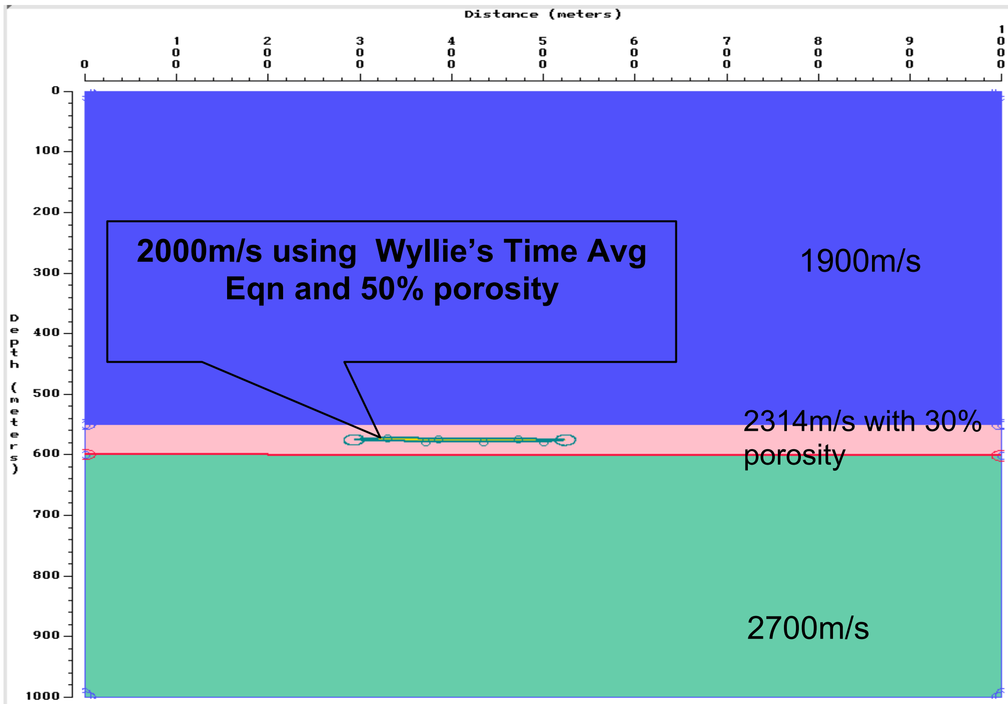


FIG. 7. Wormhole zone model modified from FIG.3

WORMHOLE PHYSICAL CHARACTERISTICS

Although detecting wormhole zones rather than individual wormholes is more possible on surface seismic data, thin beds are still very hard to distinguish from seismic data. However, some unique characteristics of wormholes would be very useful, such as the dramatically high porosity and foamy oil saturation.

High Vp/Vs anomaly response to the high porosity of wormholes

With the development of wormholes, one of the most obvious changes in reservoir physical properties is the porosity of sandstones, varying from 30% to 40%. Once the growth of the wormholes becomes mature, and the depletion or erosion of the wormholes occurs, channels are formed on top of the wormholes. These channels are filled with heavy oil and unconsolidated sands. The porosity of wormholes can reach 50% or higher (Tremblay et al. 1996). The increasing porosity could result in both P- and S-wave velocity decreases. However, with a high porosity of 50%, the sands exist in a suspended state within the heavy oil. In this case, the change of the shear-wave velocity could be more observable than the P-wave velocity. Shear-wave velocity could drop dramatically and lead to a high Vp/Vs anomaly. This unique characteristic of Vp/Vs change could cause significant seismic responses.

AVO responses of wormholes

The Vp/Vs ratio of hydrocarbon-bearing sediments normally deviates from the Vp/Vs trend of the background rocks. This causes anomalous reflection amplitude variations with offset (AVO) in the seismic data (Dong, 1999). Also, the condition of the high anomalies of Vp/Vs ratios and shallow unconsolidated sands in the wormholes, will cause strong variations of AVO intercept and gradient.

In addition, when the pressures of the borehole and the wormholes decrease with the increase of sand productions, gas bubbles will occur in the reservoir. This creation of foamy oil could lead to a variety of AVO anomalies, because AVO is very sensitive to the presence of gas.

Therefore, the AVO responses caused by wormholes could be another useful tool in detecting the distribution of the wormholes from seismic data.

THOUGHTS ON DETECTING WORMHOLE ZONES

Based on the assumption that the wormhole zones could have seismic responses, the following flow-chart (FIG.8) outlines the approaches that will be followed for this research project.

Step 1: By using the time-lapse dipole sonic logs, we can calculate the P-wave and S-wave velocities, as well as the Vp/Vs ratios. By comparing Vp/Vs ratios before, during and after production, we can find the Vp/Vs anomalies indicating where the wormhole zones could possibly exist. Then we create the synthetic seismograms to match the seismic data, in order to detect the corresponding zone of wormholes.

Step 2: Build a geological model before production (without wormholes), using the seismic data and well logs. Then, based on the geology model, build a wormhole zone model by employing the Vp/Vs anomalies from the time-lapse dipole logs.

Step 3: Create synthetic seismograms of models both with and without wormholes. Also, according to the Vp/Vs relationships derived from time-lapse sonic logs, generate PP and PS synthetic seismic data for both models.

Step 4: Apply velocity analysis to both PP and PS synthetic data. The purpose is to detect the differences of Vp/Vs ratios between the synthetic data and the well logs. In addition, by conducting velocity analysis on the synthetics, we can obtain the Vp/Vs relationships on the whole seismic section instead of only a few values from the boreholes. Then we calculate the Vp/Vs relationships in the whole section to find the distribution of Vp/Vs anomalies.

Step 5: AVO can be employed to detect wormhole zones by calculating the anomalies of amplitudes, intercepts and gradients, as well as Poisson's ratios. In addition, seismic inversion can be applied to compute the PP and PS impedances by using the density and sonic logs. It is possible that strong anomalies on PS impedances could demonstrate the presence of the wormhole zones.

Above, we have presented some ideas on how to detect wormholes using surface seismic data. Other data, such as VSP and cross-borehole profiling, could provide higher resolutions, improving an ability to detect wormholes. However, if we can combine all the information from dipole sonics and multicomponent surface-seismic data, it is possible to detect wormhole zones from conventional high- resolution seismic. Also, this procedure is economical and practical. In order to apply and test, therefore, strong supports from the industry, such as seismic data, logs and advice, are greatly appreciated.

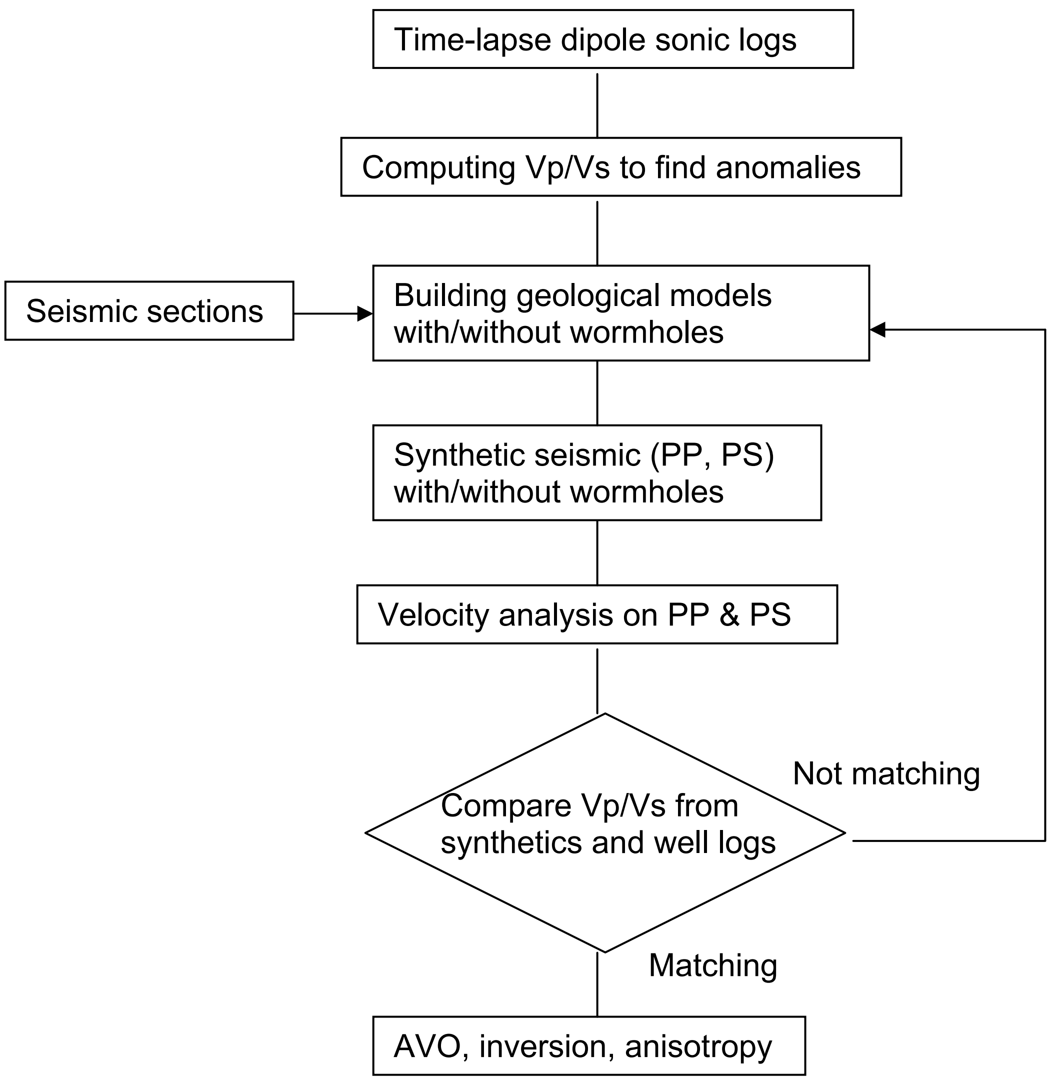


FIG. 8 Flow-chart for detecting wormholes using time-lapse seismology

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