PETROLEUM EXPLORATION AND DEVELOPMENT
Volume 44, Issue 5, October 2017
Online English edition of the Chinese language journal

Available online at www.sciencedirect.com
ScienceDirect

Cite this article as: PETROL. EXPLOR. DEVELOP., 2017, 44(5): 789–796.

RESEARCH PAPER

Evaluation method of the least horizontal principal stress by logging data in anisotropic fast formations

LIU Zhonghua[1,*], SONG Lianteng[1], WANG Changsheng[2], SUN Ting[3], YANG Xiaoming[2], LI Xia[1]

1. PetroChina Research Institute of Petroleum Exploration & Development, Beijing 100083, China;
2. Exploration and Development Research Institute, Changqing Oilfield Company, Xi'an 710018, China;
3. Research Institute of Zhanjiang Branch, CNOOC China Limited, Zhanjiang 524057, China

Abstract: For transverse isotropic fast formations, the evaluation method of the least horizontal principal stress by using logging data is an important unresolved issue. An innovative method is proposed to solve this problem by derivation of five independent stiffness coefficients (C_{11}, C_{33}, C_{44}, C_{66} and C_{13}) in this kind of formation. Based on the functional relations between acoustic anisotropy coefficients and clay volume, and that between different stiffness coefficients, which are all approved by the assorted experiment data, an effective method is built to calculate the stiffness coefficients and the least horizontal stress of anisotropic fast formations. Successful applications in the Ordos Basin illustrate that the method is complementary to that based on the horizontal shear wave velocity which is only fit for slow formations, and is applicable to evaluating rock mechanical parameters of tight oil and gas reservoirs and selecting intervals for fracturing and testing oil.

Key words: rock mechanical parameters; well logging evaluation; anisotropy; fast formation; stiffness coefficients; least horizontal principal stress

Introduction

Core samples of tight oil & gas reservoirs in the Ordos, Jungar, Songliao and Sichuan Basins were collected for assorted experimental measurements, including acoustic anisotropy, porosity, permeability, XRD, casting thin sections and so on. The results show that they are elastic anisotropic because of fine grained sedimentary environment and horizontal formations. Elastic parameters in vertical direction (such as Young's modulus) are clearly different from those in horizontal direction. Most samples belong to fast formations, in which the shear wave velocity is larger than acoustic velocity of drilling mud and the brittleness index is relatively high. This kind of formation is generally called fast formation with transverse isotropy. How to calculate the least horizontal principal stress of this kind of formation is an unresolved problem in borehole geophysics. Especially in tight formations, the calculation of least horizontal principal stress is of great practical significance for selecting oil test intervals to be fractured, optimizing completion design, reducing cost and enhancing profit[1–5].

According to the formulas given by Shannon[6], if elastic stiffness of C_{11}, C_{33}, C_{44}, C_{66} and C_{13} are all derived, the least horizontal principal stress can be calculated when the other parameters are known. Among them, C_{33} and C_{44} can be easily computed by using bulk density log and compressional and shear wave velocities from array acoustic logging data. C_{66} can be obtained by using the method to invert horizontal shear wave velocity from Stoneley wave presented by Tang Xiaoming[7]. Then C_{11} and C_{13} can be calculated with C_{33}, C_{44} and C_{66} according to ANNIE approximation and the relationship between C_{11}, C_{33}, C_{44} and C_{66}[7–8]. By this way five independent stiffness can be determined. However, in fast formations with TI character, the sensitivity of Stoneley wave to horizontal shear wave velocity decreases greatly and even disappears, leading to sharp drop of the accuracy of calculated C_{66}, and in turn the calculation accuracy of C_{11} and C_{13}. Sinha presented a method[9] to obtain the least and maximum horizontal principal stress using three shear wave moduli C_{44}^{∞}, C_{55}^{∞} and C_{66}^{∞} (the three shear wave moduli, C_{44}, C_{55} and C_{66} in original formation which is infinite far from the centerline of borehole). This method also depends on the horizontal shear wave velocity and does not fit for fast TI formations.

This study tries to build relations among different stiffness based on experiment data and a new method that does not depend on horizontal shear wave velocity to characterize anisotropy of compressional and shear waves, and eventually to realize evaluating stiffness and the least horizontal principal

Received date: 31 May 2016; **Revised date:** 20 Jul. 2017.
*** Corresponding author.** E-mail: lzh2004@petrochina.com.cn

stress in fast TI formations.

1. Experiment analysis

The objective of experiment analysis is to develop a new method to characterize anisotropy coefficients of compressional and shear wave velocity, and mathematical functions between different stiffness coefficients based on wave velocity anisotropy measurement of full diameter cores from different formations of different exploration areas. This work will lay a solid foundation for evaluating stiffness and the least horizontal principal stress in fast TI formations. The specific information of the collected full diameter cores is shown in Table 1, including place and lithology etc. Three core plugs were drilled from every full diameter core sample in the directions parallel with, perpendicular to, and 45 degree with the symmetry axis of the sample. The plugs were then fully water saturated and their compressional and shear wave velocities were measured as shown in Fig. 1[10–11].

Stiffness coefficients were then calculated based on the measured wave velocities and bulk density of water saturated core plugs. These parameters reflect the functional relationship between stresses applied on cores and induced strains. For a TI system with vertical symmetrical axis, the relationship between stress and strain follows the generalized Hook's law[12]:

$$\boldsymbol{\tau} = \boldsymbol{C} \cdot \boldsymbol{\varepsilon} \tag{1}$$

$$\boldsymbol{C} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \tag{2}$$

Because the C_{12}, C_{11}, C_{66} satisfy the relation expressed by equation (3), the five independent stiffness coefficients, C_{11}, C_{33}, C_{44}, C_{66} and C_{13}, need to be calculated to describe the relationship between stress and strain of TI formations with vertical symmetrical axis. Their calculation formulas based on experiment data are as follows[12]:

$$C_{12} = C_{11} - 2C_{66} \tag{3}$$

$$C_{11} = \rho v_{\mathrm{p},90}^2 \tag{4}$$

$$C_{33} = \rho v_{\mathrm{p},0}^2 \tag{5}$$

$$C_{44} = \rho v_{\mathrm{s}1,90}^2 \tag{6}$$

$$C_{66} = \rho v_{\mathrm{s}2,90}^2 \tag{7}$$

$$C_{13} = \left[\frac{\left(4\rho v_{\mathrm{p},45}^2 - C_{11} - C_{33} - 2C_{44}\right)^2 - \left(C_{11} - C_{33}\right)^2}{4} \right]^{\frac{1}{2}} - C_{44} \tag{8}$$

C_{11} represents the correlation between normal stress of horizontal direction and normal strain of the same direction. C_{33} characterizes the correlation between normal stress of vertical direction and normal strain of the same direction. C_{44} describes the relationship between shear stress of vertical direction and shear strain of the same direction. C_{66} represents the relationship between shear stress of horizontal direction and

Table 1. Specific information of core samples

Origin of sample	Lithology
Chang7 Member of Triassic Yanchang Fm in Jiyuan area of Ordos Basin	Tight sandstone
Cretaceous Qishankou Fm in Fuyu area of Songliao Basin	Tight sandstone
Permian Lucaogou Fm in Jimusaer area of Jungar Basin	Tight dolomitic limestone
Paleogene Ziniquanzi Fm in Huoerguosi area of Jungar Basin	Tight siltstone
Silurian Longmaxi Fm in Yibin area of Sichuan Basin (outcrop)	Shale

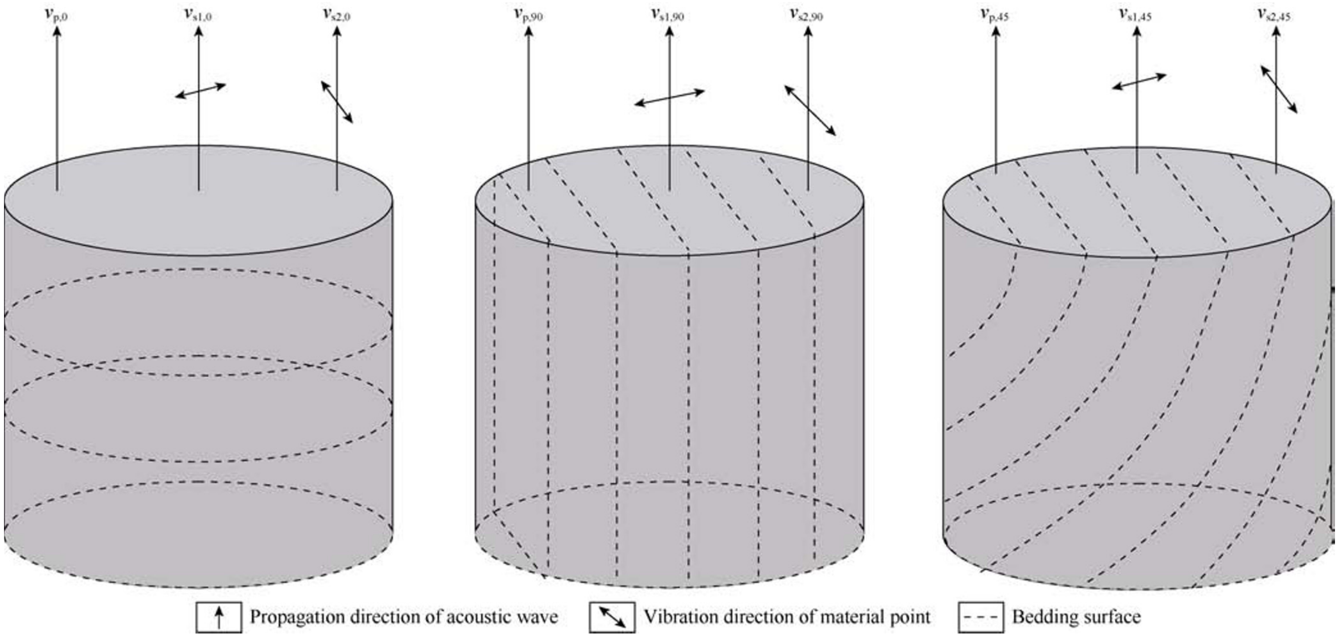

Fig. 1. Schematic diagram of acoustic wave velocity measurement.