Predicting Fracture Orientations with Volumetric Curvature Gradient Analysis*

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Abstract

Seismic curvature gradient is a useful third-order geometric attribute that has demonstrated its value for subsurface structure analysis, especially fracture detection in fractured reservoirs. However, most recent efforts have been primarily focused on predicting fracture intensity by this attribute; and little has been published on applying it to predict most likely fracture orientation, which is crucial and essential for efficient fracture characterization and modeling. This study presents an algorithm to evaluate both the principal value and principal direction of curvature gradient. First, we develop a computational equation for azimuthal curvature gradient that measures curvature gradient along any given azimuth in 3D space. Then, we implement an azimuth-scanning approach to find local maximums of curvature gradient. The proposed technique allows us to simultaneously generate two volumes of curvature gradient and curvature gradient azimuth. We apply curvature gradient analysis to a fractured reservoir at Teapot Dome in Wyoming and find lineaments not discernable from coherence or curvature attributes. The example demonstrates the potential of this new technology to predict mode and orientation of fractures in the reservoirs.

Introduction

Detecting faults and fractures from three-dimensional (3D) seismic is one of the most significant tasks in subsurface exploration. The coherence attribute (Bahorich and Farmer, 1995) has been widely used for fracture detection. However, coherence is limited to detection of faults that are already discernable from seismic data. By evaluating local changes in the geometry of 3D seismic reflectors, curvature analysis (e.g. Lisle, 1994; Roberts, 2001; Al-Dossary and Marfurt, 2006; Chopra and Marfurt, 2007) and curvature gradient analysis (Gao, 2013) provide the potential to delimit faults and fractures in a more quantitative manner at both seismic and subseismic scale. Physically, fractures are most likely to develop in zones of abnormal strains, and fracture orientation is often associated with most extreme (signed maximum) curvature gradient. Thus, a fracture reservoir can be better characterized by combining most extreme curvature gradient along with its azimuthal directions.

This paper presents a new efficient method for computing both the magnitude and direction of most extreme curvature gradient attribute. First, we derive an equation of computing azimuthal curvature gradient along any specified azimuth in 3D space. Then we implement an azimuth-scanning algorithm to find most extreme curvature gradient. We apply our proposed method to a seismic survey from Teapot Dome in Wyoming, and demonstrate the added value of most extreme curvature gradient as well as their associated directions in fractured reservoirs.

Methodology

Curvature gradient, as a new geometric attribute of seismic data, is defined as a spatial derivative of seismic curvature along reflectors (Gao, 2013). At any point of a two-dimensional curve, curvature gradient evaluates the changes in the radius of circles that are tangent to the curve with respect to the arc length at that point; thereby a fault is highlighted as a peak associated with two sidelobes of opposite signs (Figure 1). In this paper, starting from the definition of apparent dip (Marfurt and Kirlin, 2000), we derive a computational equation of azimuthal curvature gradient, which represents the curvature gradient measured along any given azimuth on a three-dimensional surface.

$$k'_{\varphi} = \frac{\cos\varphi}{[1+A_1^2+A_2^2]} \cdot \frac{(C_1+3C_3\tan\varphi+3C_4\tan^2\varphi+C_2\tan^3\varphi)}{[(1+A_1^2)+(1+A_2^2)\tan^2\varphi+2A_1A_2\tan\varphi]} - \frac{\cos\varphi}{[1+A_1^2+A_2^2]^2} \cdot \frac{[B_1+B_2\tan^2\varphi+2B_3\tan\varphi]}{[(1+A_1^2)+(1+A_2^2)\tan^2\varphi+2A_1A_2\tan\varphi]^2} \cdot [(3A_1^3B_1 + A_1^2A_2B_3 + 2A_1A_2^2B_1 + 3A_1B_1 + A_2B_3) + (5A_1^3B_3 + 4A_1^2A_2B_2 + A_1^2A_2B_2 + 6A_1A_2^2B_3 + 5A_1B_3 + A_2B_2 + 2A_2B_1 + 2A_2^3B_1)\tan\varphi + (2A_1^3B_2 + 6A_1^2A_2B_3 + A_1A_2^2B_1 + 4A_1A_2^2B_2 + A_1B_1 + 2A_1B_2 + 5A_2B_3 + 5A_2^3B_3)\tan^2\varphi + (2A_1^2A_2B_2 + A_1A_2^2B_3 + A_1B_3 + 3A_2B_2 + 3A_2^3B_2)\tan^3\varphi] \quad (1)$$

in which $A_1 = \frac{dz}{dx}$ and $A_2 = \frac{dz}{dy}$ denote the first derivatives of the reflector along x- and y-directions, also known as apparent dips, respectively. $B_1 = \frac{d^2z}{dx^2}$, $B_2 = \frac{d^2z}{dy^2}$ and $B_3 = \frac{d^2z}{dxdy}$ denote the reflector second derivatives. $C_1 = \frac{d^3z}{dx^3}$, $C_2 = \frac{d^3z}{dx^3}$, $C_3 = \frac{d^3z}{dx^2dy}$ and $C_4 = \frac{d^3z}{dxdy^2}$ denote the reflector third derivatives. Using this equation, we plot the curve of curvature gradient related to the azimuthal direction (Figure 2). We notice that curvature gradient is periodic with a period of 180 degree; but its sign reverses when azimuth exceeds 180 degree, since it measures the gradient from the opposite direction.

To find the signed maximums of azimuth curvature gradient, the best approach is to take a derivative of equation 1 with respect to azimuth and solve the generated derivative equation, whose roots are related to a local maximum or minimum. However, this approach leads to a fifth-order derivative equation that cannot be solved algebraically. Therefore, we propose scanning all possible azimuths to compute most extreme curvature gradient. First, at any given sample location in a seismic volume, we compute the first, second and third derivatives of the seismic reflector; second, using equation 1, a set of azimuthal curvature gradients are calculated by increasing the measuring azimuth from 0 degree to 360 degree; finally, we compare all the curvature gradients, and output the signed maximum as most extreme curvature gradient and the associated azimuth as most extreme curvature-gradient azimuth. After repeatedly executing the above steps from one sample location to another, a seismic amplitude volume is transformed into two volumes, one of most extreme curvature gradient and the other of most extreme curvature-gradient azimuth.

Application

To illustrate the added value of the most extreme curvature gradient and their associated azimuth in fracture characterization, we apply our method to a 3D seismic data set from Teapot Dome in Wyoming. We begin by generating a suite of attribute cubes for Teapot Dome, Wyoming, and extracting the attribute values along an interpreted horizon approximately at 4400 ft. As a baseline, we plot the structure contour map of the picked horizon in Figure 3a, which clearly depicts the northwest-trending anticline and associated three northeast-striking major faults (denoted by arrows). After processing the amplitude volume by the semblance-based coherence method (Marfurt et al., 1998), we display the corresponding coherence slice in Figure 3b, in which zones of low coherence correspond to the cross-regional faults that are already visible from the structure contour map. Figure 3c displays the corresponding most extreme curvature map.

We generate two attribute cubes: one of most extreme curvature gradient and the other of most extreme curvature-gradient azimuth. Figure 4 displays both attributes corresponding to the horizon shown in Figure 3a. We notice an enhanced spatial resolution of most extreme curvature gradient (Figure 4a) when compared to most extreme curvature (Figure 3c). This is particularly the case with the northeast-trending cross-regional faults that have been previously reported based on outcrops and well logs (Cooper et al., 2006; Schwartz, 2006). Integrating both magnitude and azimuth of most extreme curvature gradient provides new insight into the fractured reservoir.

Conclusions

Most extreme curvature gradient is a useful attribute for detecting faults and fractures in the subsurface. An integration of most extreme curvature gradient and the associated azimuth helps define the fracture intensity and fracture orientation well. Our results indicate that the most extreme curvature gradient provides a new perspective for fracture reservoirs.

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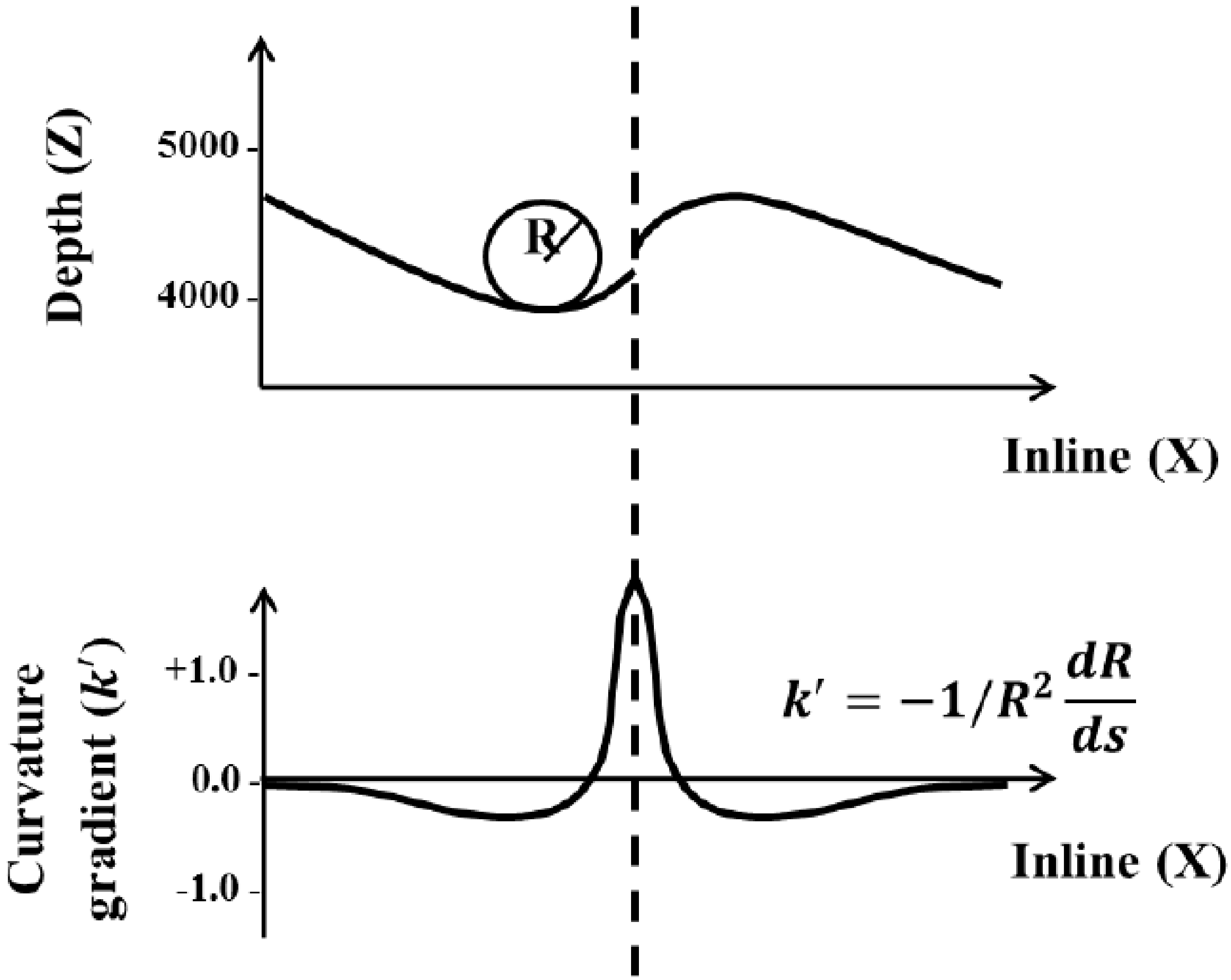

Figure 1. Curvature gradient attribute of a curve in two dimensions. Note that curvature gradient k of a curve at a particular point evaluates the changes in the radius of circles tangent to that curve at that point, and a fault is expressed by a local maximum of curvature gradient with two sidelobes (modified from Gao 2013).

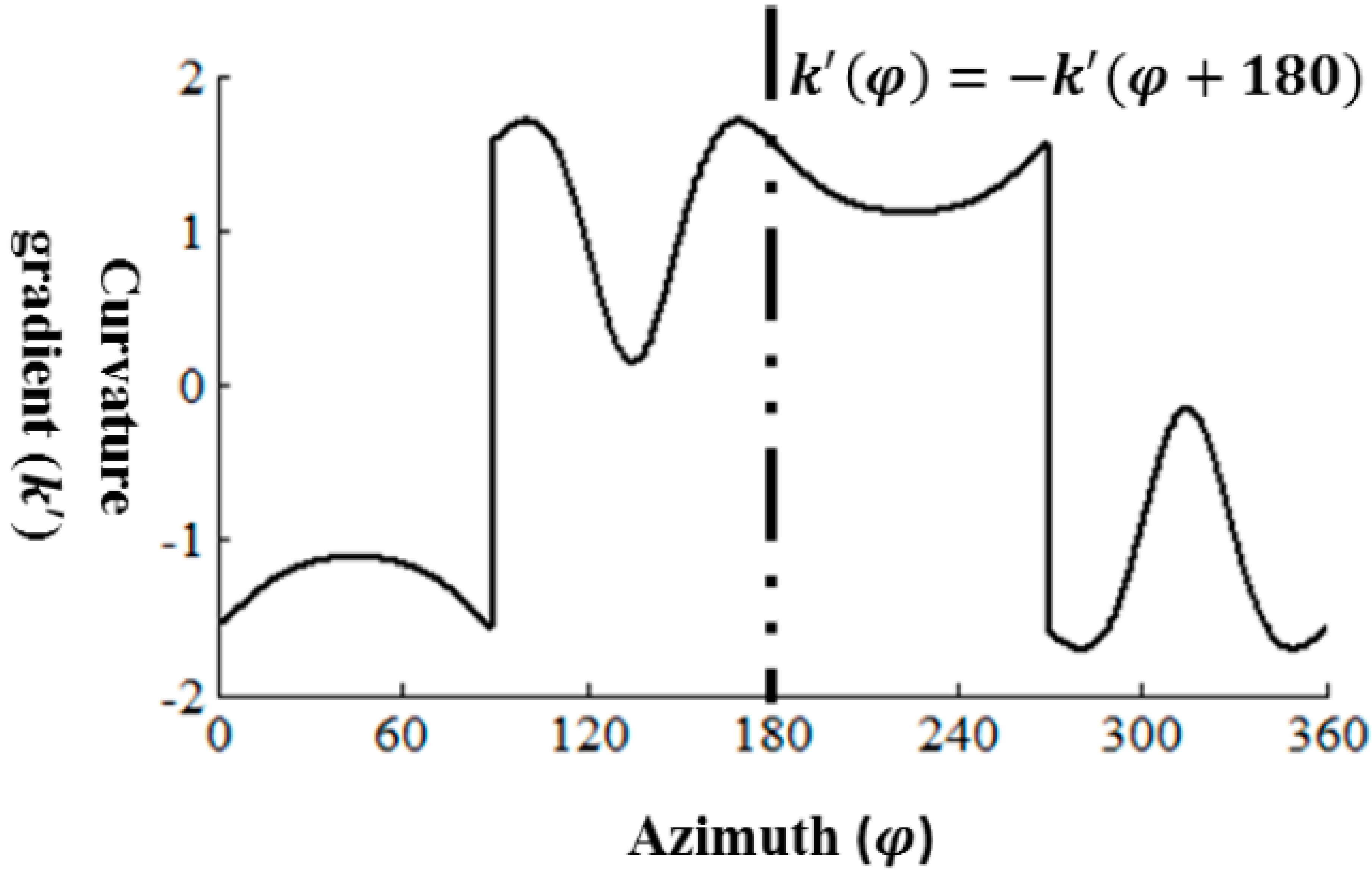

Figure 2. The relationship curve of azimuthal curvature gradient k' with respect to the measuring azimuth φ, demonstrating the periodic property of curvature gradient.

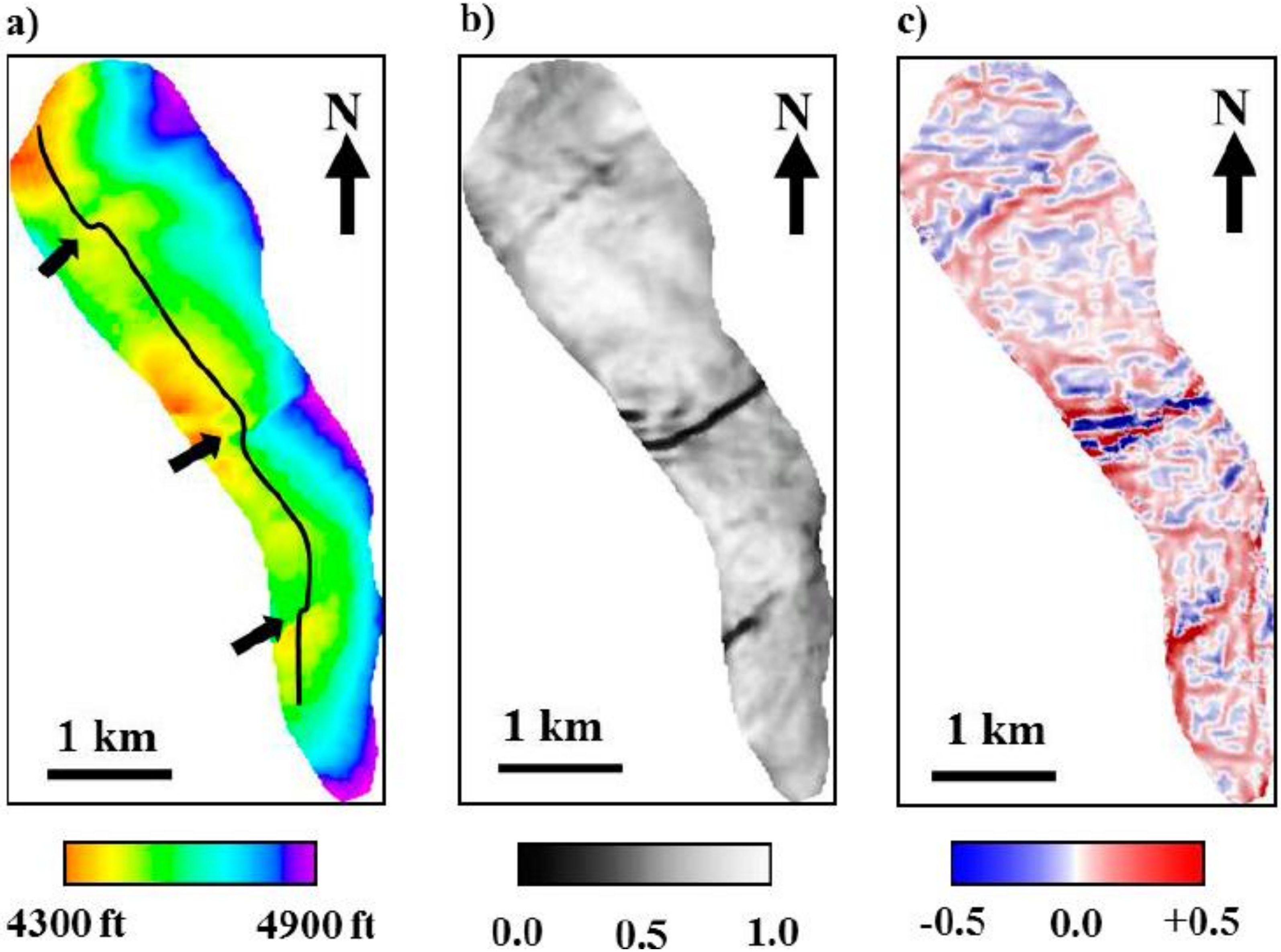

Figure 3. Application of our method to the 3D seismic volume over Teapot Dome in Wyoming. (a) Structure contour of the horizon approximately at 4400 ft., demonstrating a northwest-trending anticline (the fold hinge is denoted by curve) and associated northeast-striking faults (denoted by arrows). (b) The corresponding semblance-based coherence slice (Marfurt et al., 1998). (c) The corresponding most extreme curvature slice.

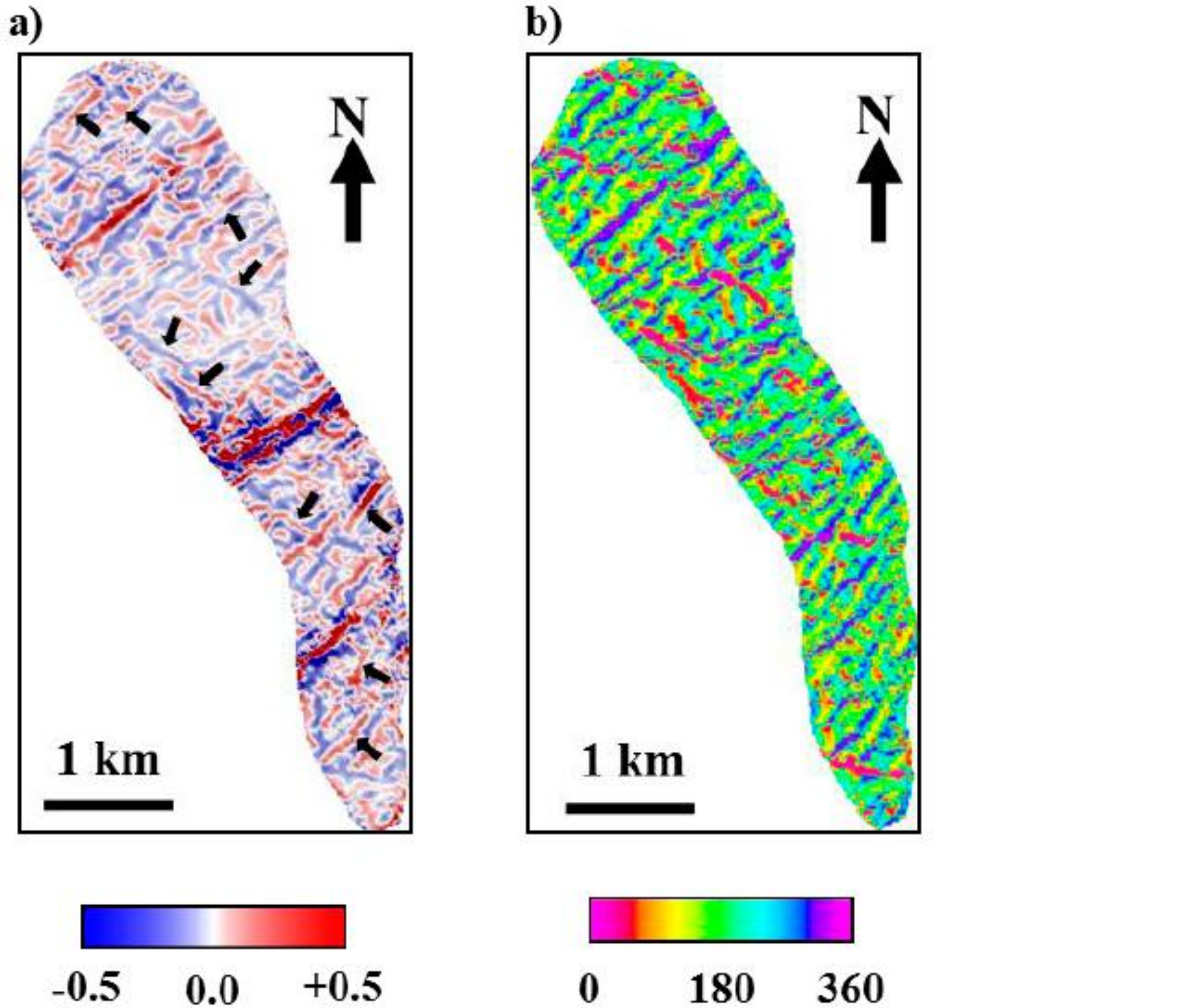

Figure 4. (a) Most extreme curvature gradient. (b) Most extreme curvature-gradient azimuth.