Tectonophysics xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Continuous estimation of 3-D reflector orientations along 2-D deep seismic reflection profiles

Andrew J. Calvert

Department of Earth Sciences, Simon Fraser University, 8888 University Drive, Burnaby, British Columbia V5A 1S6, Canada

ARTICLE INFO

Article history:
Received 23 August 2016
Received in revised form 17 October 2016
Accepted 4 November 2016
Available online xxxx

Keywords:
Seismic reflection
Crustal seismology
Archean tectonics

ABSTRACT

Interpretation of 2-D deep seismic reflection data can be limited by the recording of out-of-plane reflections that cannot be readily distinguished from those originating beneath a seismic line. Here I present a method analogous to semblance velocity analysis that utilizes varying source-receiver azimuths to derive continuous estimates of 3-D reflector orientations along onshore 2-D reflection profiles. For each zero-offset time within a common depth point supergather, the semblance is calculated along 3-D travel time curves, and the dip and strike of the most coherent reflection is determined. Relative errors in these angles are derived from the range of travel time curves that have semblance values greater than a specified fraction, for example 90%, of the maximum. The method is illustrated using a section from line 10GA-YU1 from the Youanmi terrane of the Yilgarn craton in Australia in which the original field data have been replaced with synthetic in-line and cross-line reflections. Reflector orientations are generally well recovered where the range of available source-receiver azimuths is greater than 20°, but the method fails at lower ranges where the seismic line is almost linear, and this behavior is also observed in analysis of the field data. Nevertheless when using a realistic 1-D velocity function the orientation of upper crustal shear zones can be readily determined, and on unmigrated sections subhorizontal sills can be distinguished on the basis of their geometry from the mid-crustal reflectivity. In future surveys, reflector orientations can be determined along the near-linear sections of a seismic profile by deploying additional receivers, perhaps as cross-line recording spreads, to supplement the limited range of azimuths available from the in-line acquisition. The method can in principle be extended to marine reflection surveys, and more complex sub-surface velocity models.

1. Introduction

Over the past 40 years, deep seismic reflection profiling has provided an unparalleled view of the variation with depth of the continental crust. The success of this method has come from the continuous acquisition of near normal incidence reflection data along surface profiles using 2-D common midpoint (CMP) profiling and the typical use of frequencies that provide temporal resolution equivalent to 100 m or so. At late times, dipping reflections can originate many kilometers from their position on a stack section, which makes interpretation of the unmigrated data challenging. Migration processing moves reflections to their true subsurface positon if the seismic velocities are known and the reflections originate in the plane of the 2-D profile. Artefacts can, however, arise from the use of wave-equation migration algorithms due, for example, to reflection truncation by near-surface static anomalies or signal attenuation (Warner, 1987), but these wave-equation artefacts can be avoided by the use of algorithms that are based on the characterization of the dip and repositioning of reflection segments (Raynaud, 1988; Alsdorf, 1997; Calvert, 2004; Bauer et al., 2013). In practice, the interpretation of migrated sections can be problematic due to the presence of cross-cutting reflections, which arise when some reflections originate out-of-the plane of the section profile. If out-of-plane reflections can be identified, or better, if the true dip and strike of subsurface reflectors can be determined, then some of this ambiguity that limits the interpretation of crustal reflection profiles can be reduced.

In this paper, I describe an approach that can be employed to continuously estimate the true 3-D dip and strike of reflectors along a crooked onshore seismic profile. This method is similar to that previously employed to determine local reflector orientations at sharp bends in Lithoprobe seismic profiles shot across the Abitibi and Opatica belts of the Canadian Superior Province (Bellefleur et al., 1997; Bellefleur et al., 1998). Previously the more general application of the method was limited by its computational cost, which is less of a barrier today. I apply the method to a fairly straight section of line 10GA-YU1, which was shot in the northern part of the Australian Yilgarn craton, and additionally quantify the relative errors in the dip and strike estimates,

E-mail address: acalvert@sfu.ca.

http://dx.doi.org/10.1016/j.tecto.2016.11.002
0040-1951/© 2016 Elsevier B.V. All rights reserved.

demonstrating that, as expected, the errors in the estimated reflector orientations become large where the seismic line is almost linear. In future 2-D surveys, this limitation can be avoided if additional cross-line receiver spreads are deployed to increase the range of recorded source-receiver azimuths. The method can also be applied to 2-D marine surveys where there is significant streamer feathering or multiple streamers are deployed.

2. Estimation of reflector dip and strike

On land, most deep crustal reflection profiles are shot along existing roads that can be quite crooked. For processing, common depth point (CDP) bins are defined at regular intervals along a CDP slalom line that is a smoothed version of the acquisition profile, and the bins are extended away from the CDP line in an approximately perpendicular fashion. Seismic traces are allocated to the CDP bin in which their common midpoint (CMP) lies. For a given source and receiver, the travel time of a reflection from an arbitrarily oriented planar reflector (Fig. 1) is approximated by:

$$T = \sqrt{T_0^2 + \frac{X^2\left(1-\sin^2\theta\cos^2\phi\right)}{{V_{rms}}^2}}$$

where T_0 is the zero-offset time at the source-receiver midpoint, X is the source-receiver offset, V_{rms} is the usual root mean square (RMS) velocity of a horizontally layered medium, θ is the reflector dip, and ϕ is the angle between the source-receiver azimuth and the perpendicular to reflector strike (Levin, 1971). An additional time correction shifts the zero offset reflection time from the source-receiver midpoint to the zero offset time from the CDP bin centre, which provides a common reference point for all traces within a CDP gather. In the case of a linear reflection profile, it is impossible to distinguish the angles representing dip and strike from one another, because the angle ϕ has the same value for all source-receiver pairs; any effect of reflector dip on travel time could equally be due to reflector strike. If the seismic line is crooked, however, a range of source-receiver azimuths will be recorded, allowing, in principle, the independent determination of the reflector's dip and strike.

The method presented here for the determination of reflector dip and strike, which was implemented as a module in the ProMAX software package, is similar to that presented by Bellefleur et al. (1997), except that the angle estimates are output as a function of two-way zero offset time from the CDP bin centre rather than depth. Within a CDP gather, and assuming a RMS velocity function, the semblance (Neidell and Taner, 1971) is calculated at each zero offset time for a range of trial angles of dip and strike, which is measured from north, and using a given time window, for example 48 ms as commonly used for velocity spectra (Taner and Koehler, 1969). At each zero offset time, the estimated dip and strike correspond to the angles with the maximum semblance, i.e. the most coherent reflection. Although the searched strike angle varies from −180° to +180°, only values between 0° and 180° are output because negative values are increased by 180° to ensure that the same value is output for reflectors with the same strike direction but opposite sense of dip; for example, reflectors dipping to the north and south will both be assigned a strike of 90°. It is additionally possible to repeat the estimation of an optimal dip and strike angle for a range of trial RMS velocity values, which can increase the computational cost by more than an order of magnitude, but when applied to subsets of the full dataset the velocity search can help constrain the dip-independent RMS velocity function used along the seismic line. As with conventional stacking velocity analysis, the ability to accurately estimate the RMS velocity function decreases with increasing time due to the limited range of available source-receiver offsets. Estimates of dip and strike, however, are not really limited by the maximum offset, but by the range of available source-receivers azimuths; for example, reflector orientation can be estimated at the intersection of two orthogonal zero-offset seismic profiles.

The error in the dip is characterized by defining a threshold, for example 90% of the maximum semblance, and finding the largest difference in dip from the maximum to any dip with a semblance greater than this threshold. The error in the strike is determined using a search for the strike angle with a semblance above the threshold that differs most from the strike of the maximum calculated semblance. Initially two possible angles are found: one by a search from the strike of the maximum over higher values up to 180° above the maximum; the other by a search of lower values up to 180° below the strike of the maximum. The final output error corresponds to the greatest difference in angle of these two possibilities from the strike of the maximum calculated semblance. When the seismic line is linear, the angles representing dip and strike cannot be separated, as noted above, resulting in large errors in both dip and strike estimates. Along a crooked seismic profile, however, the distribution of source-receiver azimuths within a CDP gather varies, allowing the dip and strike to be well determined if a sufficiently large range of azimuths is present, for example where there is a large change in the direction of a seismic line (Bellefleur et al., 1997). In practice, most single CDP gathers on a crooked seismic line contain an insufficient number of traces, but this limitation can be overcome by combining multiple CDP gathers into a much larger supergather that can be used for the estimation process. The estimation method assumes that reflections within the supergather originate from a planar interface; as more CDP gathers are combined, this assumption can break down, especially where the geology is complex, for example where folded reflectors are present. For the crooked lines tested, supergathers of 40–80 CDPs appear to provide an adequate range of source receiver azimuths in the non-linear sections of the profile for the estimation of dip and strike, and this analysis can be carried out every few CDPs to generate a continuous characterization of reflector geometry along a seismic line.

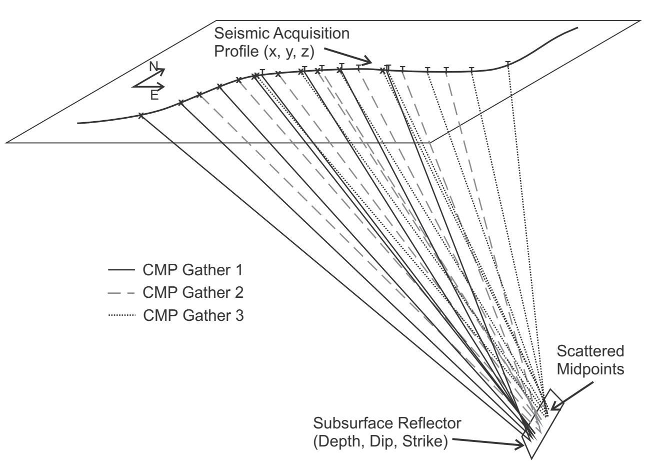

Fig. 1. Ray paths for three adjacent low fold CMP along a crooked seismic line over a constant velocity subsurface. The reflection points are scattered over a planar reflector, allowing its orientation to be determined from the best fitting travel time curves.

3. Synthetic data example

To evaluate the orientation estimation method in a realistic, but challenging setting, I have selected part of vibroseis line 10GA-YU1, which was shot by Geoscience Australia and the Geological Survey of Western Australia in 2010 along a fairly straight road in the Youanmi terrane in the northern Yilgarn craton. A source array of three Hemi-60 vibrators was deployed in a varisweep configuration of three 12 s sweeps with a 20 s listen time (Costelloe and Jones, 2013). The vibration point interval was 80 m, and data were recorded by a 300-channel symmetric split spread with 40 m group interval, implying a maximum

Please cite this article as: Calvert, A.J., Continuous estimation of 3-D reflector orientations along 2-D deep seismic reflection profiles, Tectonophysics (2016), http://dx.doi.org/10.1016/j.tecto.2016.11.002