Sub-basalt depth imaging using stacking attributes
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Summary

In basalt-covered areas, most seismic reflection imaging methods are confronted with the difficulties of accurate knowledge of interval velocities. To eliminate this, we develop a special prestack depth migration technique which avoids the necessity of constructing a macro-velocity model. It is based upon the weighted Kirchhoff-type downward continuation and migration formulae expressed in terms of stacking attributes. These formulae are applied to both synthetic and real data. Results show that the method can be used to successfully image underneath basalts. The final model provides a consistent geological interpretation.

Introduction

Most depth imaging or image transformation techniques require the interval macro-velocity input information. Conventionally, this information is provided by velocity analysis algorithms which estimate standard NMO-DMO velocity, prestack NMO attributes (de Bazelaire 1999), instantaneous dip (Whiting 1998), common-shot (CS), common-receiver (CR) and common-reflection-point (CRP) stacking attributes (Keydar et al. 1996; Perroud et al. 1999).

Instead, our approach incorporates attributes into the above transformations in a way that they avoid the necessity to input the subsurface model. In this regard, mention may be made of the migration-to-zero offset (MZO) correction (Perroud et al. 1999) which attempts to simulate a particular zero-offset (ZO) reflection using the near-surface velocity only.

In this paper, we present the weighted space-time Kirchhoff-type downward continuation and depth migration operators (Tygel et al. 1994) expressed in terms of the stacking attributes by analogy with the MZO. Firstly, the field is extrapolated from the acquisition surface into the medium. Secondly, we operate on the extrapolated field to obtain a migrated image of the target.

We show the application of the method to a real data set from the Rockall Continental Margin. Previous studies reveal a very complicated sub-basalt structure in this area due to the wide spread occurrence of Early Tertiary basalt lavas. Our purpose is to image underneath the basalt by migrating the P-wave energy reflected from below, without any other attempt to build an interval macro-velocity model.

Method

Let \( u(S, R, t) \) be the wavefield recorded on the acquisition surface \( \Sigma_0 \) in which the source-receiver pairs \( \{S, R\} \) are specified. The first step is the downward wavefield continuation for the new acquisition surface \( \Sigma \) with arbitrary source-receiver pairs \( \{S^+, R^+\} \). Only the ZO rays \( SR^+ \) and \( RS^+ \) are traced for the CS and CR gather, respectively. The ZO ray tracing equations can be represented via the stacking attributes (Koren and Gelchinsky 1989; Whiting 1998). By introducing a paraxial approximation of the Green’s function in the vicinity of the ZO ray \( SR^+ \), the resulting CS space-time downward continuation operator in a 3-D laterally inhomogeneous medium can be given as

\[
u(S, R^+, t) = C \int_{\Sigma_0} FD(t) \ast u(S, R, t + \tau) d\sigma_R, \quad (1)\]

where \( C = A(S, R^+) n(S), \ F = A(R, R^*) \cos \psi_R, \ \tau = \tau(R^*), \ \psi_R \) denotes the acute angle between the straight auxiliary ray \( RR^* \) and the normal to \( \Sigma_0 \) at \( R \), \( n \) is the slowness, \( A \) and \( \tau \) are, respectively, the amplitude and phase parts of the Green’s function, and \( D(t) \ast i\omega \) is the convolution operator. In the above equation, the point \( R^* \) is the centre of curvature of the emerging wavefront at \( S \) (de Bazelaire 1999). It can also be regarded as the centre of curvature of a hypothetical auxiliary wavefront originating at \( R^* \) in the auxiliary medium with the constant apparent velocity \( n = n(S) \) (Perroud et al. 1999).

Hence, \( \tau(S, R^*) \) is the radius of curvature of the emerging wavefront and \( \tau(R, R^*) = n \cdot A(R, R^*) = \frac{[r(S, R^*)/r(R, R^*)]}{r} \) with \( r \) being the distance. The hypothetical source \( R^* \) explodes at the non-zero time \( \tau(R^*) = \tau(S, R^*) + \tau(R = S, R^*) \) in which \( \tau(S, R^*) \) is the one-way travelt ime along the ZO ray \( SR^+ \). By constructing the ZO ray \( SS^+ \) and operating with the CR gather, the CR downward continuation operator can be written in the form similar to equation (1). A joint usage of the CS and CR operators allows us to bring both sources and receivers from \( \Sigma_0 \) to \( \Sigma \).

Next, we operate directly on the extrapolated wavefield \( u(S^+, R^+, t) \) employing the CS weighted imaging formula (Tygel et al. 1994) for each termination point \( Q \) of the ZO ray \( S^+Q \). By analogy with equation (1), this formula may be written as

\[ u(Q,t) = C^+ \int_{\Sigma} F^+ D(t) \ast u(S^+, R^+, t + \tau^+) d\sigma^+ \quad (2)\]

where \( C^+ \) is the constant of proportionality.
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where \( C^+ = n(S^+), \quad F^+ = G(R^+, S^+) \cos \psi_{R^+}, \quad \tau^+ = 2\tau(S^+, Q) - \tau(S^+, S^+) + \tau(S^+, R^+) \), \( \psi_{R^+} \) is the acute angle between the straight auxiliary ray \( S^+ S^* \) and the normal to \( \Sigma \) at \( R^+ \), and \( S^* \) is the centre of curvature of the emerging wavefront at \( S^+ \). The same considerations apply to the CR, ZO and CMP gathers. To account for the effect of rapidly varying near-surface velocity, several ZO rays must be traced for each specific gather.

Results from real data

We consider a 2-D test line acquired in 1993. The 6 km cable length and CMP range of more than 10 km enables the use of wide-angle PP reflections. Fig.1 is the result of standard 120-fold CMP processing. It is possible to identify some of the uppermost dipping reflectors on this time section such as the sea and sludge beds and the top of the basalt structure. However, the CMP image below the top of basalt is not satisfactory.

To overcome this, equation (1) is applied to original offset data to move the acquisition level down to the sea floor. Despite the obvious aperture limitation, it allows to achieve a better illumination of the target. Next, the extrapolated field is transformed into the depth image in accordance to equation (2). Thus the two images can be directly compared and show a good correlation of migrated primary events (Fig.2). Their discrepancy is mainly due to unremoved free-surface multiples in Fig.2b.

The final velocity-depth model in Fig.3 was constructed by interpreting migrated data in Fig.2. This model is consistent with prior geological information (Bergman 1997).

Synthetic tests

The ray-Kirchhoff modelling technique (Tygel et al. 1994) was utilized to compute a forward acoustic re-
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response for the model in Fig.3. Fig.4 portrays the ZO synthetic sections.

![Primary response](image1)

![Multiples](image2)

![Total response](image3)

Figure 4: ZO synthetic sections.

Fig.5 compares the CRP depth imaging against the simple constant-velocity migration with input synthetic data representing primaries and primaries with free-surface multiples. Obviously, incorrect velocity information produces severe errors in the constant-velocity migration output. On the other hand, the CRP image is consistent with the model geometry in Fig.3 within the depth range h = 1-6 km being considered. It is seen that multiples do not affect the details of the sub-basalt structure (h = 5-6 km). However, many additional false migrated events due to multiples are predicted by equation (2).

![Figure 5: Depth imaging with synthetic data: standard prestack migration (a) versus CRP depth migration (b).](image4)

Demigration

For a further verification of the model in Fig.3, we compared the ZO sections produced by the ZO transformation of the raw data, prior datuming, with the result of the ZO Kirchhoff-type demigration (Santos et al. 1998). The latter requires a ray tracing from each receiver to the target interface. A fast and reliable algorithm makes use of the CRP parameters (Koren and Gelchinsky 1989). It was applied to the depth-migrated image in Fig.2b. Apart from a difference in the frequency band and sampling/aperture effects, the two sections were virtually identical.
Sensitivity analysis

Even though the ZO ray amplitudes and traveltimes are only approximately known due to errors in the effective parameter input, the accuracy of the numerical integration in equations (1) and (2) is not influenced by their errors. Moreover, these equations can be utilized in such a way that output errors associated with uncertainties in the input parameters will be minimized. In doing so, the traveltime derivatives (sensitivities) with respect to effective parameters as functions of spatial and angle variables are involved. Analysis of such functions reveals the advantage of operating with the near-offset extrapolated field prior to migration.

Multiples

The above numerical examples show that the free-surface multiples are a major source of noise. Other multiples such as peg-leg multiples associated with the sea floor and the top of basalt structure are relatively weak. Our tests show that the low-pass wavelet transform (D10 filter) may be useful in removing part of multiply scattered waves associated with shallow heterogeneities. The image can also be improved by inclusion of the multiples in the imaging process (Reiter et al. 1991). This may still be formulated via the stacking attributes (Keydar et al. 1998).

Geological interpretation

According to Fig.3, the model is subdivided into the blocks A, B and C laterally and into the complexes I, II and III in vertical direction. The uppermost part I is made up of unconsolidated silt or mud, and of siltstones or mudstones ($v_p = 1.6 - 2.2$ km/s). The complex II is believed to be the injection gneiss or migmatite interfingered with slabs of host rocks. The basalt lava ($v_p = 4.8 - 6.3$ km/s) gushing from the macro-fault in the zone C ($x > 11$ km), formed the two planar, but locally irregular top and base of the complex II. The block A is the left margin of the migmatite. Both complexes II and III are composed of volcanogenic sedimentary deposits and of metamorphic rocks ($v_p = 2 - 4$ km/s) related to the igneous contacts.

Conclusions

We have developed a special processing scheme for sub-basalt depth imaging which does not require the knowledge of a macro-velocity model. The key point is the weighted downward continuation and migration of reflection data collected in the CS, CR or CMP gathers. Both transformations make use of stacking attributes without the need of interval velocities. The method has been tested on both real and synthetic data. Results show that it can potentially produce a better image than the conventional CMP processing.

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References


