Subsalt AVO effect of shooting direction in areas of dipping salt: Violation of amplitude reciprocity

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Summary

The well known reciprocity principle in seismic acquisition states that the raypath of seismic energy is unaffected by the switching of source and receiver. Less well known are the amplitude effects of the switching of source and receiver. In this study, raytrace modeling results of subsalt reflectors below dipping salt bodies show a marked AVO difference between a line shot in one direction and the same line shot in the opposite direction. Calculations of Zoeppritz equations confirm the difference in amplitudes caused by partitioning of seismic energy at the salt/sediment interfaces. The effect should be considered when processing and interpreting subsalt reflections and when modeling subsalt areas.

Introduction

A basic tenet of geophysics is reciprocity, which states that seismic source and receiver can be switched without a difference to the raypath traveling down to the reflector and back to the surface (Aki and Richards, 1980). But there can be differences in amplitude dependent on the direction of the energy. The source and receiver arrays can influence the recorded amplitude. Converted wave amplitudes are also dependent on the travel direction (Thompson, 1999). In this paper we report on how dipping salt can influence subsalt amplitude and AVO effects.

This study started with an observation of an asymmetric response of lines shot in opposite directions over a symmetrical model. A first guess at the cause of this phenomenon was an idiosyncrasy in the raytracing program. Further analysis showed that only part of the problem could be assigned to the nature and implementation of the program and that a large portion of the effect is caused by the non-reciprocity of amplitudes in areas of dip and of very high acoustic impedance interfaces.

Methods

A very simple 2-D model of a dipping salt body is designed and the raypaths of several manually calculated rays are derived using Snell's law. An independent program written by the second author calculates the amplitude using the Zoeppritz equation to find the amplitude of these rays. Amplitudes were calculated for a source at the left end and a receiver at the right end of the raypath and for the reverse orientation. These form a basis for comparison with the rays derived using Landmark's QUIKSHOT raytracing program that also uses Snell's law and the Zoeppritz equations. Source and receiver are modeled as point sources in the calculations and in QUIKSHOT so array effects are eliminated.

The same simple model is constructed as a computer model (Figure 1). The salt has a flat bottom, a near-vertical edge on the left, and a top of salt that dips at 20 degrees to the right. Two full offset seismic lines are simulated by raytracing over this model, one line shot from left to right (here called "down-dip") and the other shot right to left (termed "up-dip"). Typical marine geometry is used with a 200 meter offset between the source and 6000 meter hydrophone cable. Shot and group spacing is 100 meters producing 50 meter CMP. For this model, a shallow water layer is included.

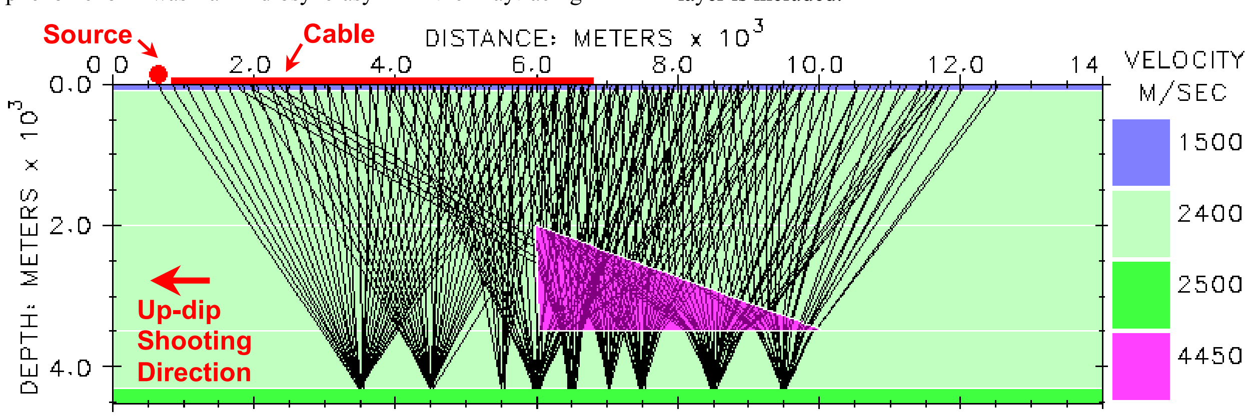


Figure 1: Computer model of simple salt shape with flat bottom and dip on top of salt of 20 degrees. Black lines are raypaths to selected common-reflection-point gathers from the right to left shoot (termed "up-dip" in this paper). For clarity only every fourth ray is plotted. The position of the hydrophone cable is shown for the shot at 600 meters along the model.

The results of both surveys are sorted into common-reflection-point (CRP) gathers. The details of all of the rays can be analyzed, including exact raypaths, amplitudes, travel distances and travel times. The last two parameters can be combined to produce the average velocity along the raypath. Additional details of raytracing methods used are contained in Muerdter and Ratcliff (in press).

For confirmation of the program's accuracy, the several independently calculated rays are compared to the computer raytrace modeled rays. Then the response of the down-dip and up-dip CRP gathers are compared to check the amplitude reciprocity at various angles and locations.

Examination of existing 3-D seismic surveys where the shooting direction reverses is in progress. Finite difference modeling of this same model is underway. The results of these additional studies will be shown during the presentation of this paper.

Results

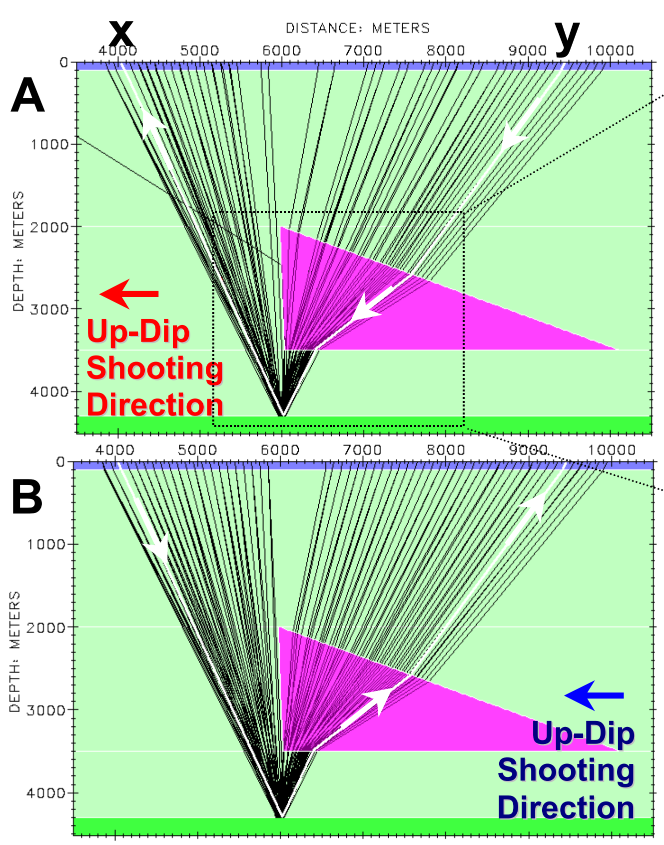
Figure 1 shows the model overlain with raypaths to selected CRP bins for the "up-dip" shoot. The CRP modeling results directly below the near vertical salt edge at 6000m distance along the model (Figure 2) is selected for comparison to manual calculations.

Table 1: Transmission coefficients and product for selected raypath through salt

	Transmission Coefficient		Transmission
	16.4 31.6°	51.6 25.0°	Product
Down-dip	0.75	0.99	**0.74**
Up-dip	0.83	1.17	**0.97**

The independent calculations are made for raypaths with a reflection angle of 25 degrees and offset of 5400m as shown in white lines in Figure 2. The enlargement of Figure 2A shows the angles calculated for the ray using Snell's law. Table 1 shows the p-wave transmission coefficients at the salt-sediment interface calculated for the ray with source at position y (marked on Figure 2A) and receiver at x (down-dip) and the source at x and receiver at y (up-dip). The partitioning of the amplitude is different depending on the direction through the salt as seen in the transmission product in Table 1.

The amplitude difference for the rays traveling in different directions on this raypath is approximately proportional to the transmission product difference using the following



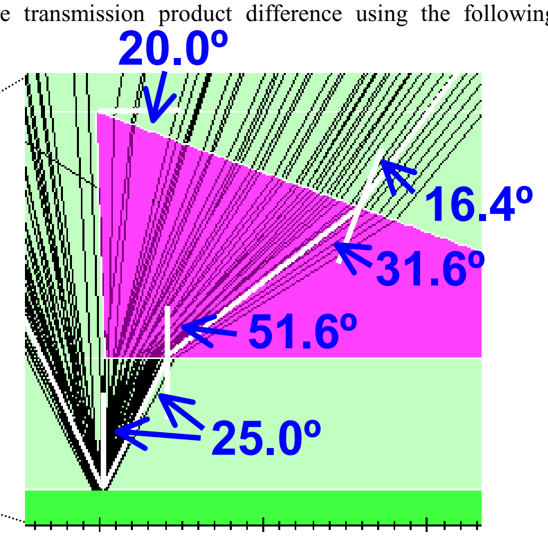


Figure 2 A) Plot of all rays in CRP bin centered at 6000m for a 2-D line shot from left to right. An enlargement of the salt body is shown to the right with angles of the ray to the interfaces marked. **B**) Plot of all rays in CRP bin at 6000m for a 2-D line shot from right to left with exact same shot locations as A. The rays with 5400m offset for which the amplitudes were manually calculated in the text are marked as white lines in 2A and 2B. Note that the down-dip shooting direction has fewer near offset rays captured.

logic. The amplitude for a given raypath (disregarding spreading and array effects) is the product of the transmission coefficients (T_{nn}) down to the reflection layer multiplied by the target reflection coefficient (R_t) multiplied by the product of the transmission coefficients (T_{nn}) from the upward path:

$$Amp_{out} = Amp_{in} * T_{12} * T_{23} * \ldots * R_t * \ldots * T_{32} * T_{21}$$

In this simple model the only transmission effects are at the water-bottom and at the salt-sediment interfaces. If the input amplitude is constant, the output amplitude is proportional to the salt and water-bottom transmission product. All other interfaces traversed have a constant 2400m/sec velocity and have no rock property contrast. The reflection coefficient (R_t) is constant for a 25-degree angle and thus does not differ for the two rays going in different directions. Table 2 shows the transmission product difference caused by the water bottom is considerably smaller than caused by salt.

Table 2: Transmission coefficients and product for raypath through the water bottom

	Transmission Coefficient		Transmission
	15.3 25.0°	36.4 21.8°	Product
Down-dip	1.47	0.47	**0.70**
Up-dip	0.46	1.39	**0.64**

Figure 3 shows the amplitudes for all the rays in the 100m wide CRP gather centered at 6000 meters distance along the model. Note the AVO is different for the two directions with the amplitude difference between the down-dip and up-dip increasing as the offset increases. The zero offset rays should be the same because the source and receiver are

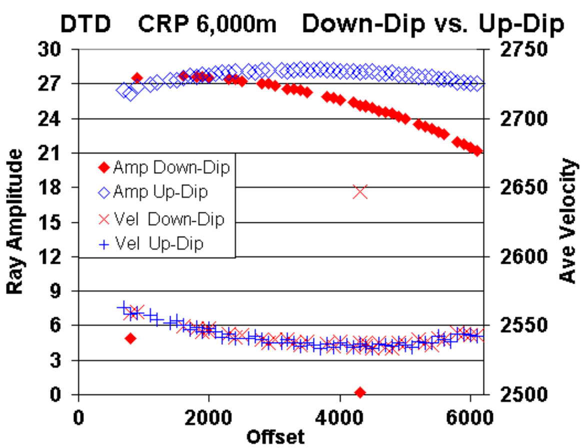


Figure 3: Amplitudes and average velocities for raypaths in CRP centered at 6000 meters along the dipping salt model. The amplitudes for the line shot left to right (down-dip) are marked as red diamonds, the up-dip line in blue. Note the amplitudes diverge as offset increases.

coincident and the down-going and up-going raypaths are the same.

The velocity plotted in Figure 3 confirms that the down-dip and up-dip paths are the same. If the path length or travel time differ the velocity will not be the same. All the travel paths are the same except for a down-dip ray with 4200m offset. This ray goes through the near vertical edge of salt at a highly oblique angle (Figure 2A). The transmitted amplitude should be very small because most of the energy would be reflected or converted to shear energy at this very high angle.

When both the up-going and down-going rays penetrate the dipping salt the asymmetric AVO effect is greater. Figure 4 shows a comparison of the down-dip and up-dip results for the CRP centered at 8500 meters along the line. For the far offsets the up-dip amplitudes are twice those of the down-dip amplitudes.

The CRP gather results (both total amplitude and hits per bin) for the entire seismic line are plotted in Figure 5. The plot shows that the amplitude decreases under salt because much energy is reflected and converted to shear energy at the salt-sediment interfaces. The roll-on and roll-off at the edges of the model are apparent from 2000 to 3000m and from 11,000 to 12,000m along the model. Full fold amplitude away from salt is seen from 3000 to 4000m. The 1500m high, near-vertical edge of salt at 6000m causes a shadowing of the subsalt reflector. Away from this point the amplitudes increase with the exception of a fold and amplitude increase directly below the salt edge at 6000m where the edge is undershot (compare CRPs in Figure 1).

The difference between amplitudes in the down-dip and up-dip lines is colored orange. As expected from the above

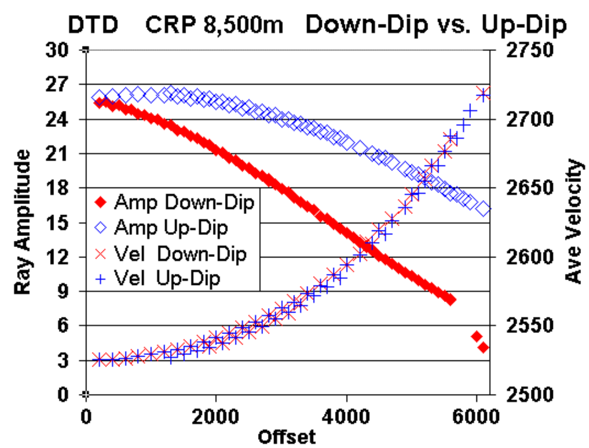


Figure 4: Amplitudes and average velocities for raypaths in CRP centered at 8500 meters along the dipping salt model.

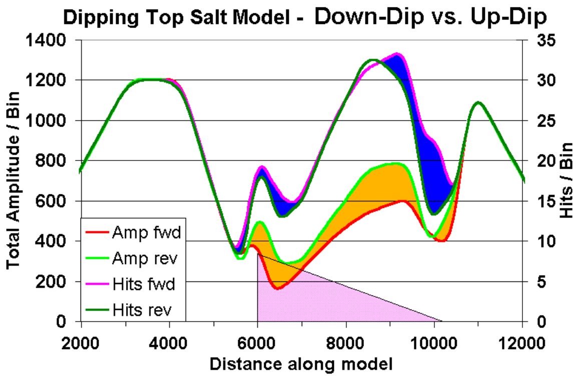


Figure 5: Comparison of CMP amplitude and fold along the model. The differences between the up-dip and down-dip results are color filled. The pink triangle shows the lateral position and shape of the salt body.

reciprocity discussion, the up-dip line always has higher amplitude under salt except for a small area at about 10,000m.
A part of the variation in amplitude differences is caused by hits per bin differences color-coded in blue in Figure 5. Raypaths should be reciprocal but are not, as shown in Figures 2, 3 and 4. This fold difference appears to be an idiosyncrasy of the ray capture algorithm in the QUIKSHOT program.

In the QUIKSHOT program, raytracing is a two-step process: 1) shooting working rays, and 2) capturing final rays. First, working rays are shot out from the source location at regular spacing. In 2-D models there may be 100 rays shot in a fan from a ray straight down to rays nearly horizontal. In 3-D models a cone of 4000 rays is more typical. Second, at each receiver location the working rays are examined for rays that surround the receiver within certain limits. If surrounding rays are identified, additional working rays are shot at a finer interval to fill in between the identified working rays. If one of these rays falls within the user specified “capture radius” of the receiver, that ray is “captured” and saved as part of the raytracing results.

When a strong refracting interface with a bend or curvature is encountered nearer to the source when rays are close together, many working rays will be affected by the curvature. Such bends occur at the edges of salt bodies or in more complex curved salt bodies. But if the curving interface is encountered later when the rays have spread out, the effect of the curvature may be missed and insufficient working rays will be found to make ray captures. This is what we believe is happening to cause the fold asymmetry. As yet, no procedure has been formulated to correct this problem. Fortunately it is a relatively small effect in most models. Other raytracing programs are being investigated that may have overcome this problem.

Conclusions

- A dipping, high acoustic contrast interface, such as occurs with salt bodies in the Gulf of Mexico, can produce large differences in seismic amplitude and AVO for energy traveling in opposite directions along the same ray path.
- Seismic lines shot up-dip of a sloping, high acoustic contrast interface will produce higher amplitudes than those shot in the down-dip direction.
- To obtain accurate amplitude modeling results, replicate the shooting geometry that was used to collect the actual seismic data.
- Simple models can help to identify and clarify idiosyncrasies in modeling programs.

References

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