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Ray-trace modelling: Innovative approach to image anticlinal structures
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Summary
Seismic acquisition in geologically complex and logistically difficult areas like fold-belts is quite challenging and requires meticulous planning during geometry designing phase. It could be demonstrated from ray trace modelling studies, that conventional symmetric split spread (SSS) shooting techniques do not provide desired results in steeply dipping fold belt areas even though they are quite successful in imaging flat reflectors. For imaging steeply dipping limbs of anticlinal structures, unconventional shooting techniques like Up dip flipflop asymmetric split spread (ASS) will be useful. Hence, it is imperative to carry out modelling studies, to design a hybrid geometry, utilizing the advantages of both symmetric and asymmetric shooting techniques to get the best subsurface illumination.

In this paper, subsurface illumination maps have been generated using a fixed subsurface model with varying orthogonal geometry configurations like Symmetric Split Spread (SSS), End on, Up-dip and Down-dip variants of flip-flop Asymmetric Split Spread (ASS). The subsurface illumination maps, thus generated, have been compared to arrive at a suitable geometry for fold-belt areas. A detailed illumination-ray analysis has also been carried out to understand the reasons behind the poor illumination of anticlinal flanks. Shot and receiver domain illumination maps have also been generated to understand the contribution of various shot and receiver pairs in illuminating predefined target areas.

Introduction
Seismic imaging is mostly dependent upon two variables viz. subsurface geology (a function of structural disposition, velocity, lithology, etc.) and the geometry adopted for acquiring the data. The geometry designer has no control over the subsurface geology. The only control a designer has, is to modify the acquisition geometry. Hence, it becomes very essential that before finalizing any geometry, rigorous modelling studies are carried out using an approximate subsurface model, since limited subsurface information is available in most of the cases.

In complex geological setups like fold-belt areas which has a complex velocity distribution, survey designing with a simplistic flat earth model is prone to errors because it does not incorporate ray bending and attenuation phenomenon. Here, the role of subsurface model in geometry designing becomes even more significant. Efforts must be made to use all available geological & geophysical data to create a reasonable model.

Modelling studies can provide valuable insights about subsurface illumination that could be achieved using an acquisition geometry. It can also help in identifying the shot and receiver pairs that contribute the most to the sub-surface illumination. This information provides the designer with a flexibility to tweak the survey geometry to illuminate areas which were poorly illuminated by conventional geometries.

In this paper, one such type of shooting technique (flip-flop asymmetric split spread) is discussed which could be useful in fold belt areas. Flip-flop is a shooting technique where unit template flips by 180 degree while switching from one flank to the other. This kind of shooting technique has been earlier utilized to acquire 2D seismic data in fold-belt areas (Hazra et.al, 2017) with encouraging results.

Validity of Ray trace modelling results
Before carrying out any ray-trace modelling study and utilizing its results, it is necessary to understand the accuracy and pitfalls associated with its results. To have a better understanding of the accuracy of modelling results, a study was carried out using 3D seismic dataset acquired in an earlier campaign, interpreted horizons on this dataset, well log data and survey geometry (SPS).
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Figure-1 shows velocity and density models used to create a subsurface Acoustic Impedance (AI) model on which ray trace modelling studies were carried out.

Keeping the same acquisition geometry as that used to acquire the 3D dataset, illumination maps were generated incorporating only primary reflections from three horizons of interest (H1, H2 and H3). For this study, phenomena such as attenuation, anisotropy, dispersion, mode conversion, etc. were ignored. The illumination maps were then compared with the actual seismic sections (figure 2), obtained after processing the data.

Using this simplified subsurface model, different shooting techniques have been tested for their suitability in fold belt areas. To ensure that the comparison is not affected by variations in survey parameters, the various shooting techniques have been designed keeping fixed survey parameters as shown in Table 1. Also, all the geometries have been designed such that receivers are laid out perpendicular to the geological strike of the anticlinal structure. Illumination results of various shooting techniques have then been compared to decide a suitable geometry that could be used in fold belt areas.

| No. of receivers/line | 272 |
| No. of receiver lines (NRL) | 14 |
| Receiver Interval (m) (RI) | 40 |
| Shot Interval (m) (SI) | 40 |
| Shot Line Interval (SLI) | 320 |
| Receiver Line Interval (RLI) | 320 |
| Crossline rollover | 7*RLI |

Table 1. Common acquisition parameters
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Figure 4 depicts the depth structure map of a shallow anticlinal structure overlain by a symmetric split spread (SSS) geometry. For the sake of consistency, this reflector would be used throughout this study.

Symmetric Split Spread (SSS) Geometry

It could be seen from Figure 5 that a symmetric split spread shooting technique is unable to illuminate the steeply dipping eastern flank of the anticline. Moreover, the western flank also suffers from poorly illuminated patches having east-west trend.

End-On Geometry

Next, End-on geometry is analyzed for its efficacy (figure 6) in fold-belt areas. It is observed that an end-on survey would only be effective to image the axis and one of the limbs viz. eastern limb in this case.

Intuition for an ideal geometry for fold belt areas

An ideal acquisition geometry for fold belt areas is one which properly illuminates both the anticlinal flanks as well as the axis. Conventional techniques like End-on and Symmetric split spread fail in this regard (figure 5 and 6). To understand the reason behind poor illumination of steeply dipping flanks by SSS and End-on, illumination rays from the flanks of anticlines were examined. Figure 7 show a cross section with illumination rays from a shallower reflector (figure 4).

The present analysis focuses on illumination of a fixed target point P on the steeply dipping flank. A1, A2, A3, A4, A5, B1, B2, B3, B4 and B5 are positions on the surface where shots and receivers could be placed. The significance of illumination rays could be understood in the following way: ‘If a shot is placed at position A3, then after reflection from a point (P) on the reflector, the reflected rays would be recorded.
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at positions B3 and vice versa.

For proper illumination of eastern flank, shots placed at locations A4 and A5 would require a spread with receivers placed downdip at very large offsets (B4 and B5) to record the reflected energy. This downdip setup with very large offsets is difficult to implement in the field. Moreover, as the travel path increases, energy of reflected rays would also become feeble. So, shots positioned at A4 and A5 would not be important for illuminating target point P. Shots positioned at A3 would require a downdip receiver setup with reasonable offsets which could be achieved in the field. Shots placed at A1, A2, B1 and B2 do not pose much challenge as the rays from these positions fall on the reflector at small incidence angles. They require a normal receiver spread which could be easily made available.

The prime focus is on shots positioned at B3 because they constitute the largest number of shots and these shots would require an extended receiver spread (ASS) in up-dip direction. It would also be beneficial to increase the receiver density in the location A3 while acquiring the data in shots placed at B3.

Shots placed at B4 and B5 would require receivers placed up-dip at very large offsets which is also difficult to implement in the field. In-line with the above analysis for eastern limb, it could be concluded that for illuminating the western limb, a similar setup would be required at the other end of the anticline.

**Shot and Receiver domain illumination maps**

It could be observed from figure 7, that the shot and receiver pairs which contribute the most to illuminate flanks are positioned at A1, A2, B1 and B2 viz. at surface locations from where rays are incident at small angles. To validate this point, illumination maps were generated in shot and receiver domains (figure 8), which highlight the shots and receivers contributing the most towards illuminating a predefined target area.

Figure 8. Shot and receiver domain illumination maps

It could also be seen that there is negligible contribution of the shots and receivers placed on the western side of the anticline to illuminate polygon A. Moreover, depending upon the target area to be illuminated, shot and receiver density could be modified to achieve better illumination. It could be seen that by introducing five shot lines in areas suggested by figure 8, illumination has significantly improved in the eastern flank of anticline (Figure 9).

Figure 9. Improved illumination in polygon A due to increased shot density

**Deeper Reflectors**

Next, we will analyze illumination rays (figure 10) from two target points P1 and P2 on a deeper reflector.
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For illuminating point P1, positions A5 to B5 would move eastwards which suggests that, for illuminating deeper anticlinal structures, shot density needs to be increased further away from the axis. For illuminating P1, only shots positioned at A2, A1, B1 and B2 would be useful since shots placed at other positions would require invariably large offset receiver spreads.

Shot Classification scheme:

From the above discussion, it could be concluded that based on shots’ position and required receiver templates, shots could be segregated into five classes.
1. Shots (A5 & A4) that require unreasonably large-offset down-dip ASS receiver spread.
2. Shots (A3) that require a reasonable offset down-dip asymmetric split spread receiver spread.
4. Shots (B3) that require a receiver spread with up-dip ASS configuration having reasonable offsets.
5. Shots (B4 & beyond) that require unreasonably large-offset down-dip ASS receiver spread.

Experimental Design

To test the effectiveness of flipflop shooting techniques in fold belt areas, modelling studies were carried out using the same subsurface model (figure 3). Six variants of flip flop shooting techniques were tested, and for brevity, only the last two variants are displayed in figure 11.

Figure 11. Overview of Up-dip (Variant 5) and Down-dip (Variant 6) flipflop ASS shooting technique

In figure 11, white shot lines (17-30) represent overlapping shot lines which use both templates A and B. Shot lines (31-46) at the western end use template A in variant 5 while they use template B in variant 6. On the eastern end, Shot lines (1-16) use template B in variant 5 and template A in variant 6.

The six variants used in the study are described below and table 2 presents an overview of the unit templates used by various shot lines in the six variants of flip-flop shooting technique.

Variant-1: Up-dip shooting with 2 overlapping shot lines
Variant-2: Down-dip shooting with 2 overlapping shot lines
Variant-3: Up-dip shooting with 8 overlapping shot lines
Variant-4: Down-dip shooting with 8 overlapping shot line
Variant-5: Up-dip shooting with 14 overlapping shot lines
Variant-6: Down-dip shooting with 14 overlapping shot lines
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<table>
<thead>
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<th>Templates</th>
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<td>17-30</td>
</tr>
<tr>
<td>Variant-6</td>
<td>1-16</td>
<td>31-46</td>
<td>17-30</td>
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</tbody>
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Table 2. Unit templates among A and B used by various shot lines in the 6 variants

Results

Figures 12 shows illumination maps generated using the six variants described above. It could be observed that to achieve better illumination, the number of overlapping shot-lines has to be increased, thereby increasing the production cost. This study highlights the areas where the shot density needs to be increased to achieve better data quality. It also demonstrates the benefits of asymmetric flip-flop technique in fold belt areas. It could be seen that up-dip shooting is preferred over down-dip flip-flop shooting to illuminate the axis and flanks. In Up-dip asymmetric split spread (ASS) flip flop shooting, majority of the rays are focused towards illuminating the axis and the limbs of the anticlines. The up-dip setup ensures that shots falling in classes 3 and 4 are properly utilized while the down-dip setup does the same with shots falling in classes 2 and 3. The increased overlapping of shot lines provides us with the benefit of both the up-dip and down-dip variants thus improving the illumination.

![Illumination maps generated using six variants of flip-flop asymmetric split spread (ASS). The upper three variants correspond to up-dip shooting with 2, 8, and 14 overlapping shot lines while the bottom three corresponding to down-dip shooting.](image)

Conclusion

- Conventional shooting techniques like End-on and Symmetric split spread fail to properly illuminate the anticlinal structures.
- Based on shot classification scheme described above, shots falling in classes 2, 3 and 4 with an appropriate receiver spread would be best suited to illuminate steeply dipping anticlinal flanks.

- Ideal geometry for fold belt areas would be a hybrid geometry utilizing the benefit of various shooting techniques to achieve the objective. A carefully planned combination of SSS and flip-flop asymmetric split spread shooting techniques could be a viable technique in fold belt areas.
- Among flip-flop shooting techniques, Up-dip is
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- Depending upon the target area to be illuminated, shot and receiver density could be modified to achieve better illumination. Increasing shot and receiver density in areas from where rays fall normal or close to normal, to the dip of anticlinal structure would significantly improve its imaging.

References

Hazra Anupam et.al., 2017, Exemplary seismic data acquisition in Tripura fold belt using flip-flop up-dip asymmetrical split spread shooting geometry;

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