SURVEY DESIGN OPTIMIZATION BY ILLUMINATION ANALYSIS IN AN AREA WITH COMPLEX STRUCTURE AND TIGHT ENVIRONMENTAL RESTRICCTIONS

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Abstract

Complex structures, such as foothills thrusts, and restricted areas are commonly coincident in prospective areas. As result, non-uniform illumination is obtained on horizons underneath the structures. In order to find a balance between illumination and environmental impact we propose a methodology to optimize the acquisition geometry, taking into account the three objective functions: illumination of target horizon, environmental impact and cost. Additionally an uncertainty analysis on the structural model was performed. It allows obtaining the optimal illumination for the target formation minimizing the environmental impact.

Introduction

In areas with structural complexity, like foothills thrusts, shadow zones appear mainly due to the contrast of velocities between the hanging wall and the footwall, and to the high fault dips. Adding the environmental related restrictions, like a natural reserve area in the full fold zone (**Figure 1**), seismic illumination optimization becomes a difficult task in the zones surrounding the fault and the horizon of interest. To solve this optimization problem we propose a methodology that integrates the 3D seismic design parameters optimization as a function of environmental impact. We analyze the following parameters: density of shot/receivers, patch size, acquisitions area and uncertainty of the structural model (fault dip angle and target horizon topology –pull up effects), in order to identify the acquisitions geometry with the optimal illumination on a horizon of interest constrained by the environmental restriction of the area.

Method

Our procedure consisted of two phases: (1) Design parameter optimization as a function of illumination and environmental restrictions, (2) Structural model uncertainty analysis of the optimized geometries of phase I.

Phase I: We have considered five parameters: active receiver lines in patch, active area (area of sources and receivers), source density, receiver density and receiver area.

Three objective functions were jointly optimized. First it was to minimize the environmental impact function (EI):

$$EI = \frac{0.7\ (SEA) + 0.2\ (REA) + 0.1\ (S) + 0.05\ (R)}{IABC} \quad (1)$$

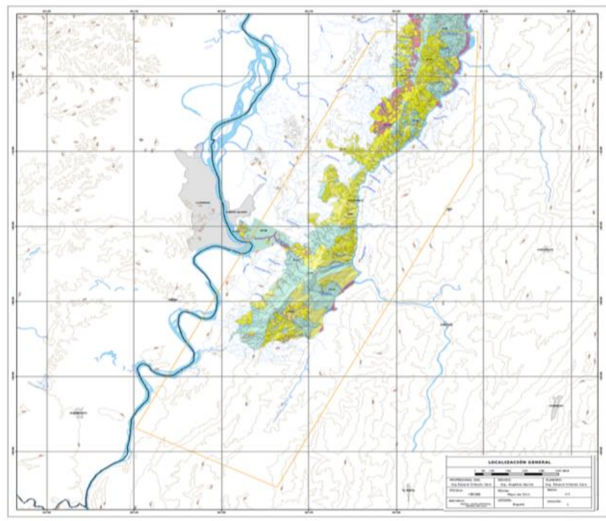

Figure 1. Location of the exclusion zone. Pink, aquamarine and green colors represent a protected area (environmental restriction) Ecopetrol, 2011).

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Where SEA is the number of sources in the exclusion area, REA is the number of receivers in the exclusion area, S is the number of sources outside the exclusion area, R is the number of receivers outside the exclusion area and IABC is the environmental impact of the base case. Coefficients were obtained from our experience in the environmental impact of successful and failed cases. Coefficients of the parameters inside the exclusion area (SEA and REA) punish the placement of sources and receivers in the area. In the same way, the coefficients of the source parameters (SEA and S) also have higher values than the other coefficients because due to government regulations for any seismic survey sources are of explosive type and its environmental impact is much higher than receiver deployment (Ecopetrol, 2011).
Secondly, it was maximized the illumination function:

$$\%IA = \frac{IA}{Ahor} \quad (2)$$

Where %IA is the normalized illumination area, IA is the area whose illumination is greater or equal to the fold of design and Ahor is the total area of the interest horizon. The third objective function is costs. However for this particular case EA and IA had more weight for the selection than costs.

Figure 2 shows how optimization move in the environmental impact (EI) versus illumination percentage (IA) plane. Each possible acquisition parameter set could be represented by a point on this plane. Trajectories are obtained varying the analyzed parameter while keeping constant the others. A series of steps towards the blue zone (good illumination and low environmental impact) is obtained modifying one parameter each time. A possible path is depicted in Figure 2 and will be considered in the Study Case.

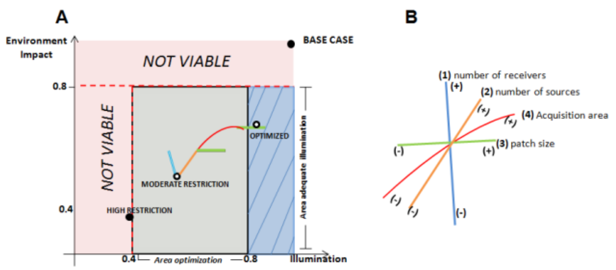

Figure 2. Phase I A) Illumination Area vs. Enviromental impact plane depicting the objective and forbiden areas. B) trajectories described by varying (positive or negative) the analyzed parameter while keeping constant the others: (1) receivers density: blue trajectory, (2) source density: orange trajectory, (3) patch size: green trajectory and (4) acquisition area: red trajectory. The optimization searches a series of steps to arrive to the blue area.

Let's say a few words about the trajectories. Illumination percentage (IA) is different from fold as we measure the proportion of the area in the target horizon with fold greater or equal to the design fold. That could help to explain why trajectory 1 (blue at Figure 2B) goes with negative slope. For a constant patch, increase the receiver density would increase the fold, but reduce the covered area (Cordsen, 2000). Other interesting trajectory is the patch variation (trajectory 3, in green at figure 2B) which would not affect the receiver or source quantities, so it would have a constant Environmental Impact (obviously it is not the case for costs). Area increase (at constant receiver and source density) is a very efficient way (trajectory 4, in red at Figure 2B) to increase Illumination, thus is a "low" slope trajectory. Each trajectory has lower and upper limits. For example patch cannot be greater than a no roll-on/off template or lower than a single receiver line.

Phase II: In this phase, due to uncertainty of the time to depth conversion of the structural model, we proposed three scenarios and evaluated its influence in the illumination: (1) fault dip less than 30° (2) fault dip greater than 30°, (3) flat target horizon that simulates a hypothetical pull up effect in the foot wall that is removed.

Examples: Middle Magdalena Valley (Colombia)

The studied area is a monocline structure in the hanging wall of a fault, dipping 30° W. The geological target is the Formation 1, which is discordant in relation with the fault 1 (Figure 3). The initial design area consists of 269km². It has an exclusion subarea of 76km². The receiver and source spacing are the same for each geometry. We vary the source density, receiver density, patch size and area. Evaluation of each geometry was performed using simulated illumination maps in the structural model for interest horizon. The illumination maps were generated with the wavefront construction technique (Vinje, et al.,1999).

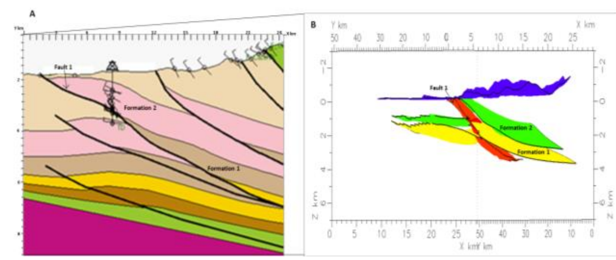

Figure 3. Geology in the studied area. A) Structural interpretation (González, 2011) b) Geophysical model.

Phase I: Our trajectory consists of eight points (geometries): Point 1 is the base case (Figures 4A, 5A and 12) with sources and receivers located over all the acquisition area. Point 2 has a moderate environmental restriction (Figures 2A, 4B, 5B and 12) where the sources inside the exclusion area were eliminated. Point 3 has a low environmental impact, but also low illumination (Figure 2A, 4C, 5C and 12) where sources and receivers were eliminated of the exclusion area. Points 1 and 3 determine the end points of the objective functions of illumination and environmental impact. The optimized geometry we are looking for is between these two ends. Point 3 is not very promising (go away from the blue zone, Figures 2A and 12) so it is discarded.

Point 2 was chosen as the next starting optimization point because it has moderate environmental impact and has acceptable illumination (Figure 12 and 5B). The optimization path followed the next steps. First, intermediate receiver lines parallel to the original ones were added in the area near the exclusion zone (point 4, Figure 6A, 7A and 12). That means we are moving in the blue trajectory of Figure 2B. Second, because the increase in illumination was meager in point 4 (Figure 7A and 12), point 5 was designed keeping the receiver lines as in point 2 but adding intermediate parallel source lines around the exclusion polygon (Figure 6B, 7B and 12). That is increasing the source density, the orange trajectory of figure 2B.

Third, in order to recover the long offsets lost during the elimination of sources inside the exclusion area, the point 5 were modified by adding to it an extra 38Km² area located northeast of the original acquisition area (Figure 6C, 7C and 12). This moves us to the point 7 (Figure 12) along the red trajectory of figure 2B.

Fourth, the patch size in points 5 and 7 was incremented from 12 to 16 receiver lines, moving to points 6 and 8 (Figure 8, 12) along the green trajectory of Figure 2B with the aim to obtain a more homogeneous illumination.

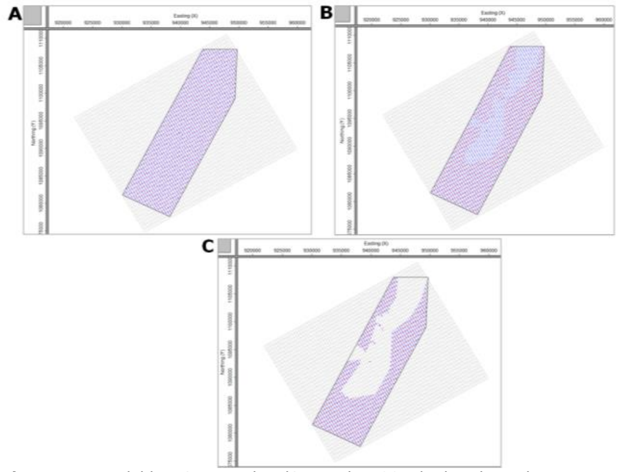

Figure 4. Acquisition Geometries (Saavedra, 2011) A) Point 1: base case. B) Point 2: moderate restriction. C). Point 3: high restriction.

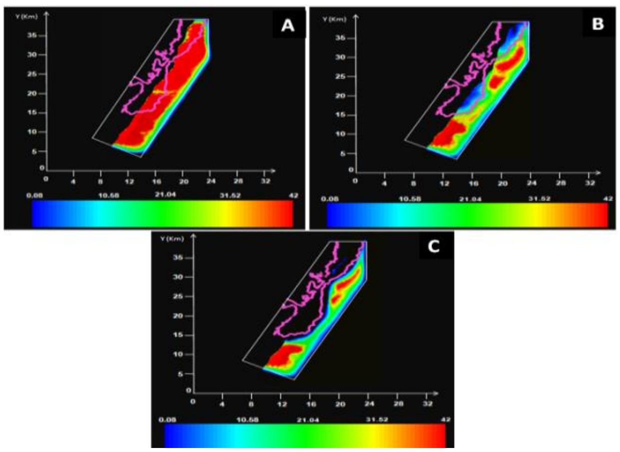

Figure 5. Illumination map simulated in the target horizon- hanging wall: A) Illumination map simulated in the target horizon hanging wall: A) Point 1: base case B) Point 2: moderate restriction C). Point 3: high restriction.

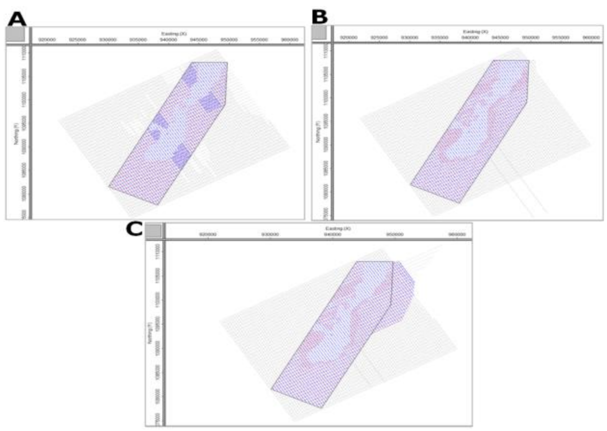

Figure 6. Acquisition Geometries, (2011) **A**) Point 4: increase number receiver B) Point 5: increase number sources **C**). Point 6: increase number source and area acquisition

Phase II: Points 6 and 8 were tested in three different structural variations of the interest horizon: (1) the fault dip was modified to be less than 30° (Figures 9A and 10A). (2) Now the fault dip is modified to measure more than 30° (Figures 9B and 10B). (3) The pull-up effect was eliminated in the footwall (Figure 11).

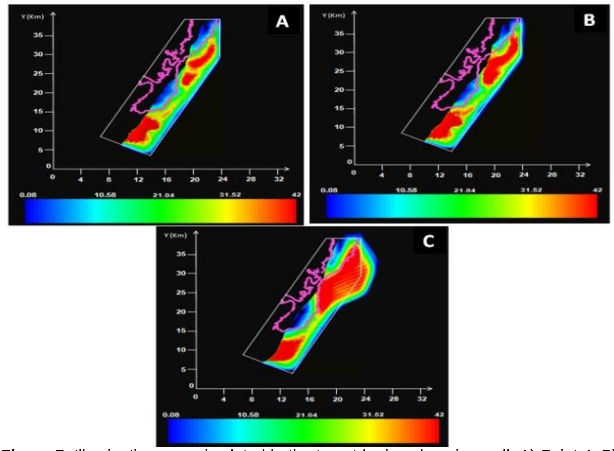

Figure 7. Illumination map simulated in the target horizon hanging wall: A) Point 4, B) Point 5, C) Point 7.

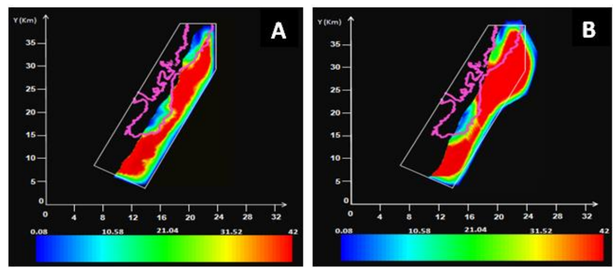

Figure 8. Illumination map simulated in the target horizon hanging wall: increase size patch A) Point 6 B) Point 8

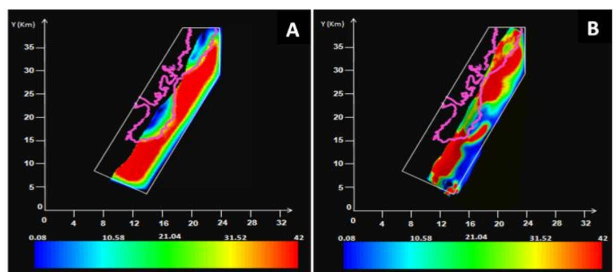

Figure 9. Illumination map simulated in the target horizonhanging wall: point 7. A) Fault dipping less than 30° B) fault dipping higher than 30°.

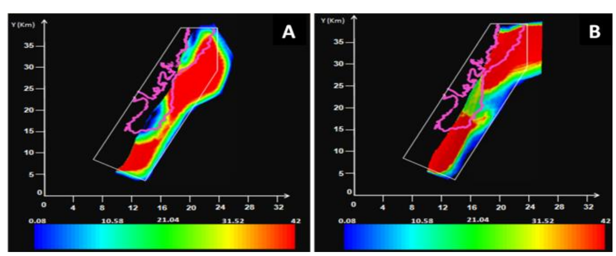

Figure 10. Illumination map simulated in the target horizon hanging wall: point 8. A) Fault dipping less than 30° B) fault dipping higher than 30°.

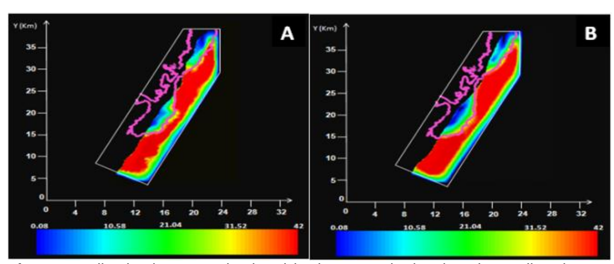

Figure 11. Illumination map simulated in the target horizonhanging wall: point 7: **A**) Pull up effect, **B**) flat horizon simulating no Pull Up in the target horizon- hanging wall.

Discussion

This work focused its analysis in how to create an acquisition geometry that can obtain an illumination similar to the point 1 and that have lower environmental impact. In order to reach that goal, five parameters were varied with the aim of simulating a geometry close to the illumination range of 80%-90% (blue area) vs. geometry 1 (Figure 2A and 12). The parameter variation order was constrained by the environmental restrictions. Point 3 allowed a 40% decrease in the environmental impact but the illumination area also decreased in 40%. Point 2 (Only receiver stations in the exclusion area) was taken as the new starting point for optimization. The optimization consisted in the variation of five acquisition parameters that represented trajectories in the EI-IA plane. The redistribution of the sources of the exclusion area allowed to recovery the 73% of the illumination (point 5) vs. 55% obtained by increasing the receiver density (point 4) with a very similar environmental impact. Due to the increasing of the sources and receivers density it was necessary to augment the patch size with the aim of not degrading the seismic illumination, obtaining a significant increase in the illumination for the points 5 and 7 (70%).

Other important graphic are costs for each point (Figure 13), from Ecopetrol tables. Evaluating the increase in costs of the points 6-8 vs. the design point 1, it is important to emphasize that although the design points 6 and 8 are more expensive, they present less environmental impact than point 1. The design points 2 to 5 are less expensive than the point 1 but they do not significantly increase the illumination of the target horizon.

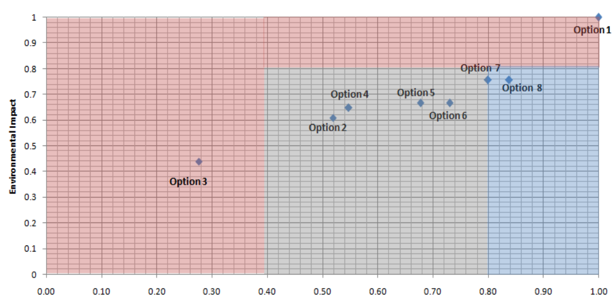

Figure 12. Environmental Impact vs. Illumination for eight geometries. Geometries in red areas are not viable, geometries in gray should be optimized and geometries in blue are the best option.

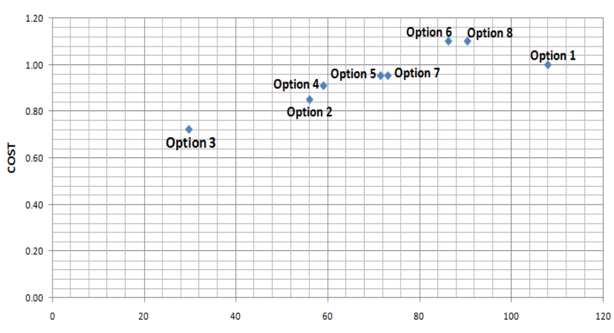

Figure 13. Cost vs illuminated area of target horizon (km2) for eight geometries.

Design point 3 is the less expensive option and has the lower environmental impact but it correspond to the more critical scenario with only a modest 29% of illumination.

Point 8 allows illuminating a bigger area with respect to points 2 to 7. Adding extra intermediate source lines to the design causes a better fold recovery for the target horizon 1 that adding extra intermediate receiver lines.

Conclusions

We follow an optimization path in the Illumination Percentage vs Enviromental Impact plane: First, we deploy receivers inside the exclusion area (point 2). Second, relocating the shot points of the exclusion area in extra intermediate lines (point 5). Third, increasing the patch size (point 6). And fourth, adding an extra area of 38Km² adjacent to the original area. When it is not possible to locate receiver stations inside the exclusion area, the design point 3 is the more critical and risky scenario (illumination decreases 50% with respect to design point 8). If the target horizons of the hanging wall do not have pull-up effect, the design point 7 would illuminate the target horizons of the footwall. If the dip of Fault 1 is less than 30°, the exclusion area directly affects the target horizon with the design point 7. Due to this, it is necessary the addition of an extra area. Thus, point 8 is our preferred solution that guarantees optimal illumination at acceptable environmental impact.

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References

Ecopetrol, 2011. Plan de Manejo ambiental programa de exploración sísmica VMM32. Informe interno.

Cordsen, A., Galbraith, M. y Peirse J., 2000. “Planning Land 3-D Seismic Surveys” Geophysical Developments Series No. 9. Society of Explorations Geophysicists. USA

González, R.E. (2011) Interpretación modelo estructural VMM32. Informe Interno de Ecopetrol.

Vinje, V., Astebol, K., Iversen, E., GjØystdal, H. (1999). 3-D ray modeling by wavefront construction in open models. Geophysics, vol. 64, No. 6.