Comparison of nonhyperbolic travel-time approximations for multicomponent seismic data

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Abstract

To perform the normal moveout (NMO) correction, it is used the fitting of the curves generated by travel-time approximation to the reflections identified on seismic records. The Dix approximation developed in 1955 is conventionally used, however it is not valid to nonhyperbolic reflection events observed in multicomponent seismic data.

A comparative study was accomplished aiming to evaluate the behavior of several nonhyperbolic multiparametric travel-time approximations used to perform NMO correction of PP and PS (converted wave) seismic data in media with different vertical velocity gradients, of OBN (Ocean Bottom Nodes), PP and PS seismic data with large offsets in layered isotropic media, and analyze the complexity of objective function for those data.

The nonhyperbolic multiparametric approximations evaluated have three variables. For this reason, it was treated as an inverse problem according an optimization criterion.

Due to the results obtained, it were determined the approximations which presented the best fitting for each model with reflection event of PP and PS wave. Finally, the approximation which presented the best fitting for all the models in a general form was determined. Further, it was analyzed the residual function maps, to determinate which approximation is less complex to perform the inversion.

Introduction

The situation which involves processing of converted waves (PS wave) is more complicated than the conventional seismic data processing (PP wave), due to the fact that there is an asymmetric ray tracing generated by the difference of velocity of P wave and S wave.

Not only the wave conversion contributes to nonhyperbolicity of a reflection event. There are some examples of factors which generate a nonhyperbolic reflection event. Two of them are large offsets between source and receptors, and vertical velocity gradients caused by heterogeneous geological media. Other factor is the asymmetric ray tracing generated by datum difference between source and receiver due to the use of OBN technology.

The OBN technology allows the acquisition of multicomponent seismic data in offshore survey, which is not possible when used the conventional technology (Streamer).

Due to the factors which contribute to nonhyperbolicity of a reflection event, is required using nonhyperbolic multiparametric travel-time approximations to perform normal moveout (NMO) correction of seismic data.

Some characteristics of nonhyperbolic behavior of reflection events were studied in last decades (Malovichko, 1978; Blias, 1983 and 2009; Muir and Dellinger, 1985; Castle, 1988 and 1994; Slotboom *et al*., 1990; Tsvankin and Thomsen, 1994; Alkhalifah and Tsvankin, 1995; Li and Yuan, 1999, 2001, 2002 and 2003; Cheret, Bale and Leaney, 2000; Causse, Haugen and Rommel, 2000; Tsvankin and Grechka, 2000a,b; Fomel and Grechka, 2000 and 2001; Tsvankin, 2001; Leiderman *et al*., 2003; Silva *et al*., 2003; Ursin and Stovas, 2006; among others).

This paper aimed to evaluate the behavior of several nonhyperbolic multiparametric travel-time approximations used to perform NMO correction of two sets of data: PP and PS seismic data in media with different vertical velocity gradients; and OBN, PP and PS seismic data with large offsets in layered isotropic media. The complexity of objective function was also analyzed.

There are few works which report comparison of nonhyperbolic approximations in a independent form where there is only approximations not developed by the author, for example Aleixo and Schleicher (2010), and Golikov and Stovas (2012) who performed performance comparison of approximations for qP reflection events on VTI (Vertical Transverse Isotropic) media. However, there are no works about performance comparison of nonhyperbolic approximations for multicomponent seismic data with the characteristics studied in this paper.

Method

Nonhyperbolic multiparametric traveltime approximations were studied to the curve fitting in order to perform a proper NMO correction of nonhyperbolic reflection events.

Equation 1 (Dix, 1955) is the hyperbola equation, used to comparison effect.

$$t = \sqrt{t_0^2 + \frac{x^2}{v^2}} \quad (1)$$

Where t is the travel-time, x is the offsets, t_0 is the time for zero-offset and v is the velocity of reflected wave.

Equation 2 (Malovichko, 1978) is the shifted hyperbola which was strongly studied by Castle (1988 and 1994). This approximation uses the heterogeneity coefficient (S), to media with vertical heterogeneity.

$$t = t_0^2\left(1 - \frac{1}{S}\right) + \frac{1}{S}\sqrt{t_0^2 + \frac{Sx^2}{v^2}} \quad (2)$$

Where,

$$S = \frac{\mu_4}{\mu_2^2} \quad (2.1)$$

and

$$\mu_j = \frac{\sum_{k=1}^{n} t_k v_k^j}{\sum_{k=1}^{n} t_k} \quad (2.2)$$

Equation 3 (Slotboom *et al.*, 1990). This equation was developed aiming the analysis of PS reflection events.

$$t = \frac{t_0}{2} + \sqrt{\frac{t_0^2}{2} + \frac{x^2}{2v^2}} \quad (3)$$

Equation 4 (Alkhalifah and Tsvankin, 1995) was developed to analyze VTI media. Parameter η, which quantify the nonhyperbolicity of an event, represents an anisotropy which is function of anisotropic parameters of Thomsen (1986).

$$t = \sqrt{t_0^2 + \frac{x^2}{v^2} - \frac{2\eta x^4}{v^2\left[t_0^2 v^2 + (1+2\eta)x^2\right]}} \quad (4)$$

$$\eta = \frac{\varepsilon - \delta}{1 + 2\delta} \quad (4.1)$$

Equation 5 (Ursin and Stovas, 2006). This is a fractional approximation with heterogeneity parameter (S), also studied by Fomel and Grechka (2001).

$$t = \sqrt{t_0^2 + \frac{x^2}{v^2} - \frac{(S-1)x^4}{4v^4\left(t_0^2 + \frac{(S-1)}{2}\frac{x^2}{v^2}\right)}} \quad (5)$$

Equation 6 (Blias, 2009) is an expression which uses the same heterogeneity parameter as Equation 2 and 5.

$$t = \frac{1}{2}\sqrt{t_0^2 + \frac{1-\sqrt{S-1}}{v^2}x^2} + \frac{1}{2}\sqrt{t_0^2 + \frac{1+\sqrt{S-1}}{v^2}x^2} \quad (6)$$

For Equation 7 (Muir and Dellinger, 1985) was proposed the use of anelliptical parameter (f). This parameter describes how the wave front differs from the spherical shape. This phenomenon was also studied by Fomel and Grechka (2000).

$$t = \sqrt{t_0^2 + \frac{x^2}{v^2} - \frac{f(1-f)x^4}{v^2\left(v^2 t_0^2 + fx^2\right)}} \quad (7)$$

Equation 8 (Li, 2001) has a third parameter (γ) and aims to obtain better information in a CP (Converted Point).

$$t = \sqrt{t_0^2 + \frac{x^2}{v^2} - \frac{(\gamma-1)}{\gamma v^2}\frac{(\gamma-1)x^4}{4t_0^2 v^2 + (\gamma-1)x^2}} \quad (8)$$

Where γ is the ratio between squared stack velocity of P wave and squared velocity of converted wave, γ_2 is the ratio between stack velocity of P wave and stack velocity of S wave, γ_0 é the ratio between velocity of P wave and velocity of S wave which propagate in normal component, and γ_{eff} is the ratio between squared γ_2 and γ_0.

$$\gamma = \frac{v_{p2}^2}{v_{C2}^2} = \frac{\gamma_{eff}(1+\gamma_0)}{(1+\gamma_{eff})} \quad (8.1)$$

$$\gamma_{eff} = \frac{\gamma_2^2}{\gamma_0} \quad (8.2)$$

In this paper, the inversion of travel-time of PP and PS wave of each model was made according an optimization criterion. The objective function used was the least squares, and the optimization was performed with Nelder-Mead (Nelder and Mead, 1965) method and using Multi-start procedure.

The complexity of each approximation was analyzed to determine which search algorithm should be used. This analysis is conventionally made observing the residual function maps (Larsen, 1999; Kurt, 2007). It is appropriated to analyze problems with two parameters, however problems with more variables do not bring reliable results. To overcome this problem, Bokhonok (2010) proposed to analyze the dispersions obtained with multiples inversions (Multi-start procedure).

Results

An important analysis concerning the complexity of objective functions was accomplished for each multiparametric approximations aiming to demonstrate the complexity each multiparametric approximations presents to reach the global minimum of the objective function.

The performance analysis of the used approximations was accomplished observing the residual error between the observed curve and the curve calculated by approximations with resultant parameters from inversion.

Analysis of strong vertical velocity gradient for PP reflection events. Excepting Equation 3, all equations presented (Figure 1.a) a good fitting to the travel-time curve of PP reflection event of the first model (homogeneous and layered isotropic medium).

The travel-time curve of PP reflection event of second model (layered isotropic medium and vertically heterogeneous with velocity gradient of 0.667) was best fitted by Equation 8 and Equation 7 (Figure 1.b).

For the third model (equal model 2 excepting the velocity gradient of 1.333) was determined Equation 7 and Equation 8 presented the best fitting (Figure 1.c).

Observing the results of the fourth model (equal model 2 and 3 excepting the velocity gradient of 2) was once more determined Equation 7 and Equation 8 presented the best fitting (Figure 1.d).

Analysis of strong vertical velocity gradient for PS reflection events. For the PS reflection event of the first model (Figure 2.a), Equation 2 and Equation 6 followed by Equation 8, Equation 5, and Equation 7 presented the best fitting.

Equation 6 and Equation 8 presented the best fitting for the PS reflection event of the second model (Figure 2.b).

Equation 6 and Equation 8 appeared again as the approximations which presented the best fitting, but now for the PS reflection event of the third model (Figure 2.c).

Concerning the PS reflection event of the fourth model Equation 8 presented the best fitting (Figure 2.d).

Analysis of OBN data for PP and PS reflection events. It was observed Equation 8 presented the best fitting to both travel-time curves of PP (Figure 3.a) and PS (Figure 3.b) reflection events for the fifth model (multilayered medium, with large offsets and using OBN tehnology).

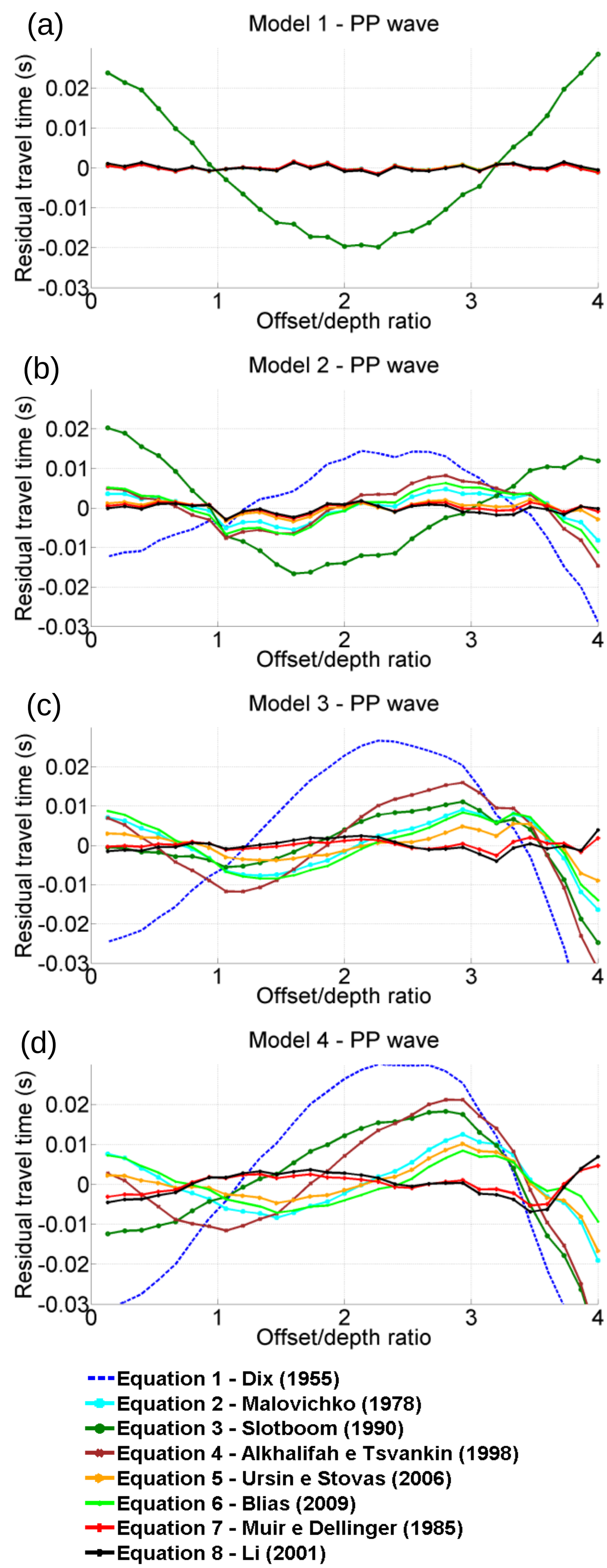

Figure 1: Difference between exact and calculated (from the inversion) travel-times of PP reflection event of (a) Model 1, (b) Model 2, (c) Model 3and (d) Model 4.

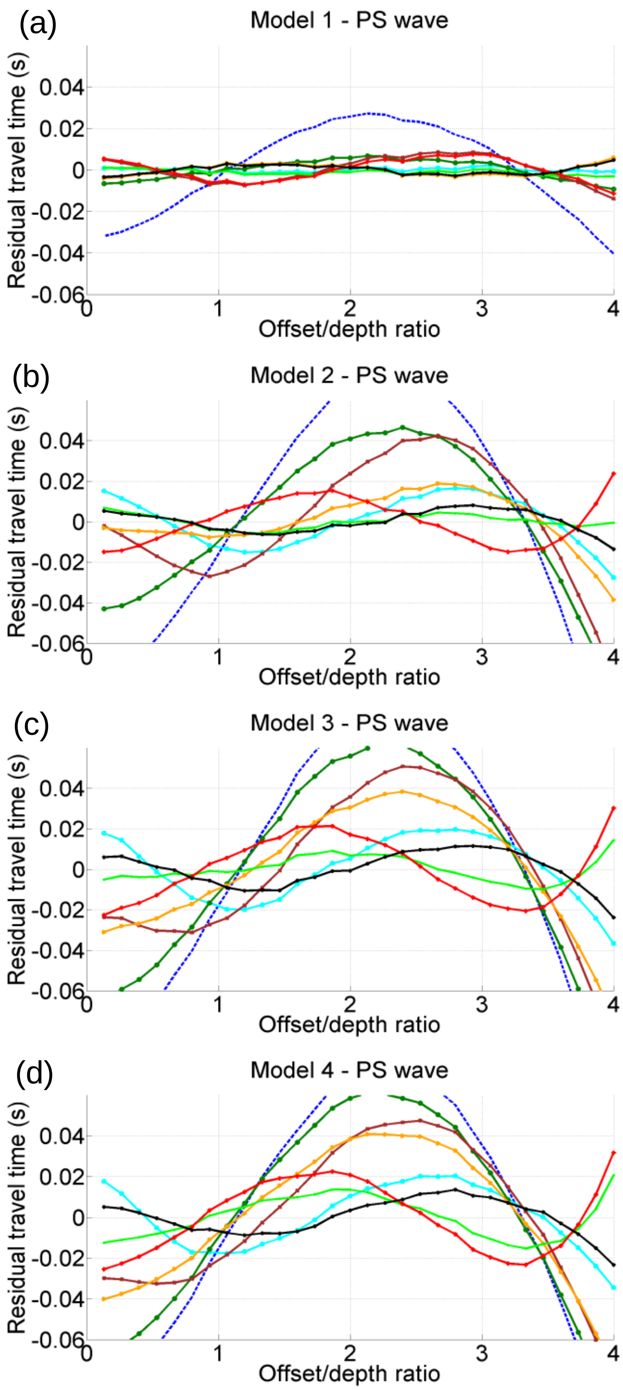

Figure 2: Difference between exact and calculated (from the inversion) travel-times of PS reflection event of (a) Model 1, (b) Model 2, (c) Model 3 and (d) Model 4. Line colors correspond to the same approximations as in Figure 1.

Conclusions

Between the equations presented, Equation 8 produced, in a general form, the best fitting to travel-time curves to perform nonhyperbolic NMO correction of reflection events of PP wave and PS wave calculated for the five models. Equation 8 demonstrated to be the most stable one, and brought good results for each reflection event of each model.

Concerning the complexity of the objective functions, Equation 2 and Equation 4 demonstrated to be less complex than the others (excepting Equation 1 and 3). With only one minimum region, these equations are categorized as unimodal. However, the other equations used in this paper demonstrated to be multimodal ones, for being more complex and present both global minimum region and local minimum region (Figure 4).

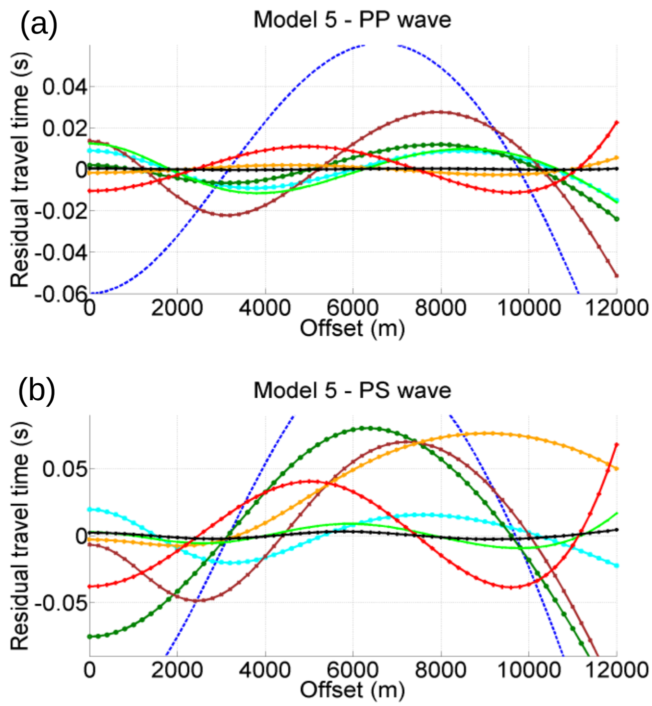

Figure 3: Difference between exact and calculated (from the inversion) travel-times of (a) PP reflection event of Model 5, and (b) PS reflection event of Model 5. Line colors correspond to the same approximations as in Figure 1.

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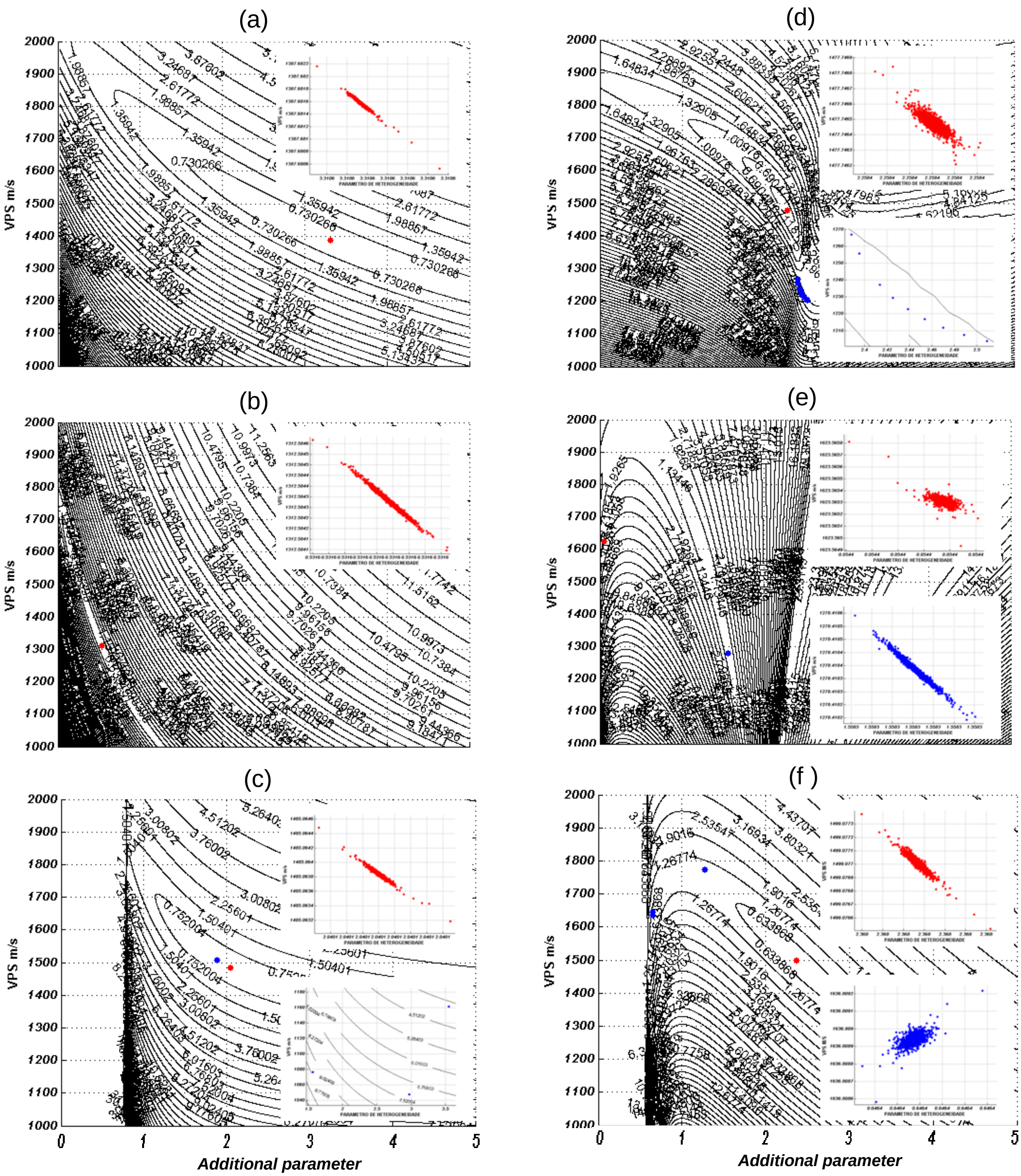

Figure 4: Dispersion maps superimposed over residual function maps demonstrating the complexity of (a) Equation 2, (b) Equation 4, (c) Equation 5, (d) Equation 6, (e) Equation 7 and (f) Equation 8 (PS wave reflection event of Model 5). Red dispersions represent the global minimum region and blue dispersions represents local minimum region.