NGU REPORT 2017.025

Refraction seismic modeling and inversion for the detection of fracture zones in bedrock with the use of Rayfract® software

GEOLOGY FOR SOCIETY

SINCE 1858

GEOLOGICAL SURVEY OF NORWAY

· NGU ·

NORGES GEOLOGISKE UNDERSØKELSE
- NGU -

REPORT

Geological Survey of Norway
P.O.Box 6315 Torgard
NO-7491 TRONDHEIM
Tel.: 47 73 90 40 00

Report no.: 2017.025	**ISSN: 0800-3416 (print)** **ISSN: 2387-3515 (online)**	**Grading:** Open

Title: Refraction seismic modeling and inversion for the detection of fracture zones in bedrock with the use of Rayfract® software	
Authors: Georgios Tassis, Jan Steinar Rønning, & Siegfried Rohdewald	**Client:** Norwegian Public Roads Administration (NPRA) / NGU
County:	**Commune:**
Map-sheet name (M=1:250.000)	**Map-sheet no. and -name (M=1:50.000)**
Deposit name and grid-reference:	**Number of pages:** 62 **Price (NOK):** 200,- **Map enclosures:**

Fieldwork carried out:	**Date of report:** 31.08.2017	**Project no.:** 329500	**Person responsible:** Marco Brönner

Summary:
In this report we have investigated the response of several synthetic models of variable complexity to tomographic inversion using the Rayfract® Software. Through this process it has been clearly demonstrated that this is a fairly advanced and complex software which offers many different options and paths when inverting refraction seismic data. Its level of complexity makes it necessary for the user to have a fairly good knowledge of its attributes in order to obtain successful results, or at least to identify possible miscalculations.

When investigating the detection of fracture zones in bedrock, the software's parameters may be roughly grouped in three main categories: the inversion and weighting method used, whether single or multi-run will be employed and the intensity of the smoothing. **We have discerned that multi-run Conjugate Gradient inversion method, with Cosine-Squared weighting and a 2D Plus-Minus starting model can give pretty good results.** However, the task that requires closer attention is choosing the parameters which will result in minimized smoothing. Minimal smoothing is essential for the quantitative characteristics of the detected zones to be calculated accurately, but this is a hyper sensitive procedure which may result in over or underestimations of zone velocity values. Regardless of this, the complexity of Rayfract® guarantees that a successful combination is not unique in each case, which allows us some flexibility when processing and interpreting such data.

Generally, this modeling procedure has deemed it possible to locate and characterize fractured zones in bedrock albeit with some limitations. It has been found that the **imaging of the position and inclination of zones** can be problematic especially when the zones are neighboring bedrock areas with small velocity contrast. The detectable **depth extent** of fracture zones can be followed to a certain depth, but deep zones give the same response as shallow zones due to geological noise. The **width** of the zone is almost always quite close to reality and **overburden layers** can be precisely defined when the interactive picking of branch points prior to inversion is carefully done. The **velocity** of a zone can be accurately calculated with a good combination of inversion parameters. Moreover, as was seen in reprocessing some the Knappe tunnel real data, tomographic inversion can pick up detailed zones that cannot be interpreted traditionally. Finally, it should be noted that denser **shot point spacing** can bring about a noticeable improvement on the inversion results. Therefore, if there is a possibility for more shots when conducting a refraction seismic survey, they should be realized since they make tomographic inversion more reliable.

Keywords:	Geophysics	Fracture zones in bedrock
Detection	Characterization	Refraction seismic
Tomographic inversion	Modelling	Scientific report

CONTENTS

FIGURES

1 INTRODUCTION

The main purpose of this report is to test the efficiency of refraction seismic tomographic inversion for the detection and characterization of fracture zones that could threaten the stability of technical structures such as road tunnels. Such inversion has already been performed by NGU on real data collected at the Knappe tunnel in Bergen Norway using Rayfract® by Intelligent Resources Inc. and this was our software selection for the modeling procedure as well.

Prior to the construction of Knappe tunnel west of the city of Bergen, 1.44 km of refraction seismic data were obtained (see NGU report 2016.048 for more information). NGU has performed tomographic inversion of these data and compared inverted profiles with other available information such as additional geophysical data, traditional seismic interpretations and geological mapping as well as observations inside the tunnel during its construction. This work demonstrated that this type of processing can be a useful tool when fracture zones are surveyed (Rønning et al., 2016). However, little is known about the method's response to various geological structures, hence purposeful modeling has been carried out in regard to this matter with the use of Rayfract® (Rayfract, 2016 a & b).

Rayfract® by Intelligent Resources Inc., is a program for inverting refraction seismic data based on the Wavepath Eikonal Traveltime (WET) formula (Schuster & Quintus-Bosz, 1993). This particular software was utilized to invert the Knappe tunnel data, running inversion with two independent starting models. A smooth gradient structured 1D starting model was automatically determined and directly derived from the seismic traveltime data and a second one was obtained by picking branch points on these traveltimes and using the Hagedoorn's Plus-Minus refraction method to compute a layered pseudo-2D starting model. Two types of resulting tomograms emerged which were either classified as "smooth" (1D) or "robust" (pseudo-2D) in order to distinguish which starting model was used for the inversion process.

Our experience with the Knappe tunnel data has shown that the most accurate and consistent starting models are the ones derived from mapping travel-times to refractors interactively i.e. by using the Plus-Minus method (Hagedoorn, 1959). The effect that the starting model will have on the inversion result is then controlled by several WET inversion parameters such as the wavepath frequency, the wavepath width (percentage of one period) and the velocity smoothing settings selected. In this sense, this modeling effort will be focused on exploring the parameters of WET inversion, including the newest additions to the software namely the multi-run inversion with Cosine-Squared weighting function using the conjugate gradient method. We have tested the inversion options in the Rayfract® software we expect to give the best results.

Rayfract® will also be employed to manufacture the synthetic data for our modeling. Our aim is neither to evaluate the software, nor to use extremely sophisticated inversion schemes in order to precisely recreate the models. Our goal is to apply relatively conservative inversion schemes on modeled refraction seismic data surveying fracture zones in Norwegian conditions (abrupt velocity changes, massive bedrocks, etc.) aiming to characterize the method's overall response.

2 RAYFRACT® SOFTWARE DESCRIPTION AND APPLICATION

The software's tomographic method is based on forward modeling refraction, transmission and diffraction (Lecomte et al., 2000) and back-projecting traveltime residuals along wave paths also known as Fresnel volumes (Watanabe et al., 1999) instead of conventional rays.

Before we are able to run WET inversion on either real or synthetic data, an initial model has to be generated. The program offers a series of means to derive a starting model such as 1D Gradient, Delta-tV, Hagedoorn's Plus-Minus or Wavefront method (see **Figure 2.1**). Another option is to use a custom made 2D starting model. In order to pick a preferable method and save us some time, we had to revisit the results of inverting the Knappe tunnel data. The inversion process set off with the production of two different starting models and was concluded with inversion using two different sets of parameters. Two resulting tomograms were then obtained for each profile measured. One was the product of a single-run *Steepest descent* inversion using the smooth gradient 1D grid as a starting model and a second one was determined with the same inversion scheme, but with significantly less smoothing and utilizing the pseudo-2D initial model obtained with Hagedoorn's Plus-Minus method.

Through the above described process we concluded that the 2D starting model yielded more consistent results and led to tomograms with more detailed structures. However, since some of our models do not contain layered structures, the application of Hagedoorn's Plus-Minus method is limited to the models that include an overburden. When this requirement is met, branch points (crossover points) are interactively picked along the traveltime curves in order to indicate a jump in velocity at that point. This leads to a two-layer model and by modifying the smoothing parameters of the Plus-Minus method (overburden filter and base filter width), we can manufacture a starting model which is close enough to the original model from which the synthetic data were created. Our experience with these parameters indicates that decreasing their value ("2" being the minimum value for each) causes the bottom layer of our two-layer model to display a higher rate of lateral variations in velocity. This feature is extremely useful in our case where vertical fracture zones are the main focus, although some restrain in the use of these parameters is advised in order not to fragment the "bedrock" of our initial model more than needed. When no overlaying layer is present, the automatically generated 1D gradient starting model is the alternative.

For the first tomographic inversion of the Knappe refraction data using tomographic inversion (Rønning et al., 2016), the starting model extraction and ensuing processing was carried out with the program tools available at that time and a partial knowledge of the software's capabilities. Therefore, this modeling work is not only aiming at investigating the particular scenario of weak zones in massive bedrock but also at further exploring the software's capabilities including some important new features that have been added to Rayfract® over the last 2 years. WET inversion is mainly controlled by a set of regularization settings i.e. the central Ricker wavelet (wavepath) frequency which modulates the wavepath misfit gradient amplitude, the wavepath width in percent of one period of the Ricker wavelet central frequency and the number of WET tomography iterations. It is preferable that the frequency is kept constant while the other two parameters are varied in order to find the best functioning combination.

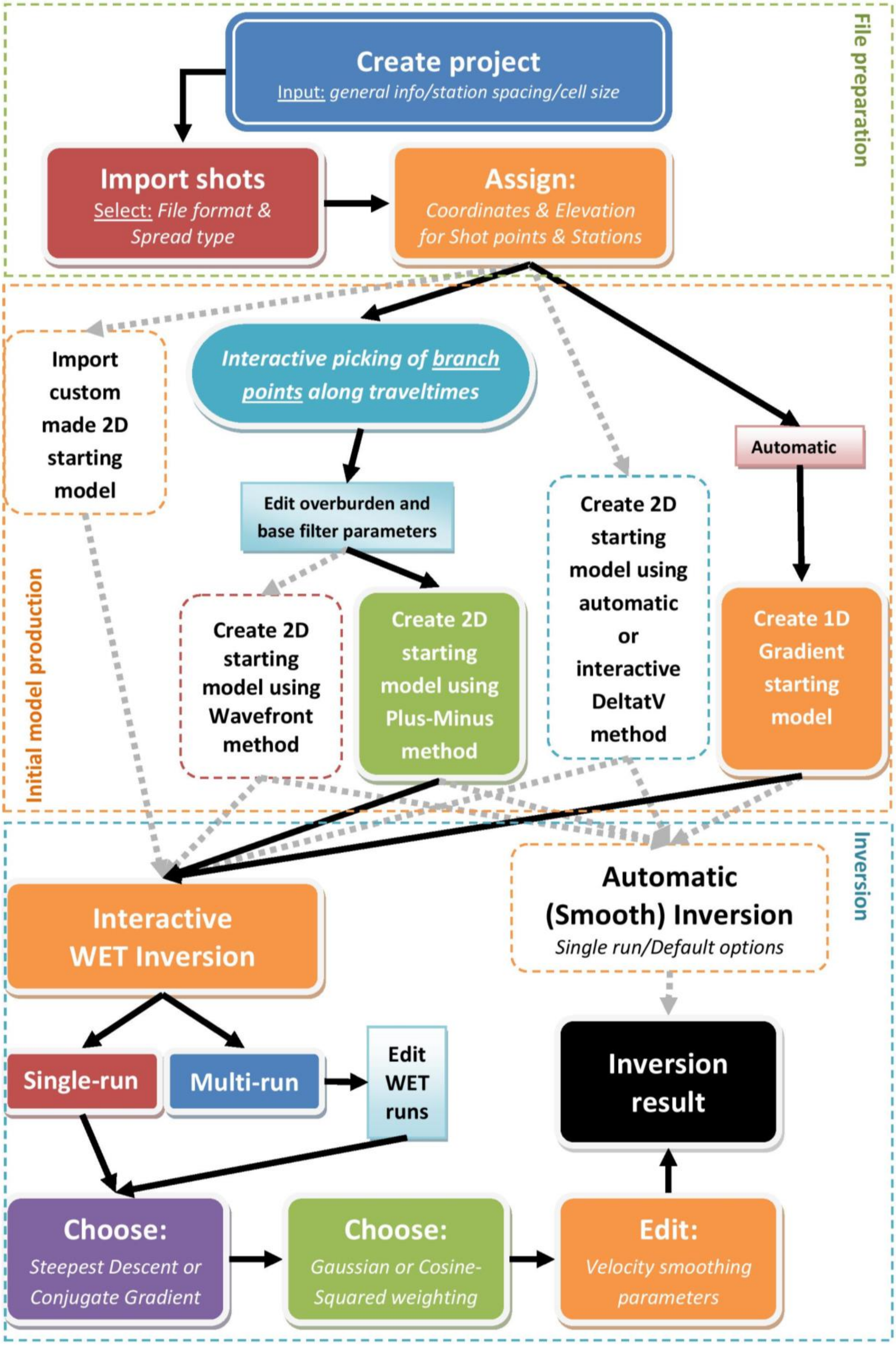

Figure 2.1: Flowchart for Rayfract® software. Black arrows shows procedures we have used, gray dotted arrows other options available with the software.

For the 2016 inversion of the Knappe tunnel data we used a single WET inversion run which predominantly employed 100 iterations, 50Hz frequency and 3.5% wavepath width. However, for this modeling work, we have also put into practice the new **multi-run feature** which essentially performs a number of iterations for a whole package of regularization parameters. When using the multi-run feature, we have kept the frequency and number of WET tomography iterations constant for every run but decreased the wavepath width after each run. This was done in order to induce a decreasing smoothing effect as the number of runs increased. The maximum number of runs available is 10 which essentially means that we are able to run ten different single WET inversions with variable regularization settings. It is essential to clarify the starting model used for each run. The first run employs either the 1D or 2D starting model that we have produced with Rayfract® and each following run uses the inversion result of the previous run as starting model.

Another new feature included with the software while this modeling work was underway, is the option of selecting **Cosine-Squared weighting function as an alternative to Gaussian weighting** that existed in previous Rayfract® versions. This addition has improved our posterior results greatly. By picking a Ricker differentiation of -2 (instead of -1 for Gaussian weighting), we have managed to improve our results especially when more complex models were inverted. Therefore, this feature will only appear in the latter stages of this report and no re-processing of the simpler models will take place. The Conjugate Gradient method has been available since version 3.31 released in June 2014 in addition to the default Steepest Descent method. Both techniques are iterative methods for solving sparse systems of linear equations and eventually calculate velocities in the inverted profiles. The Conjugate Gradient method yields improved imaging of sharp velocity contrasts, a very useful addition considering the structure of our models which is characterized by abrupt changes in seismic velocity.

3 MODELING OUTLINE

Modeling will build up from the simplest case to models which simulate real conditions as good as possible without the addition of any type of noise. In our case, the simplest scenario amounts to a single fracture zone surrounded by homogeneous bedrock without any overburden. The most complex scenarios that we have devised for this study, are profiles based on the traditional seismic interpretations obtained from the Knappe tunnel data and they portray multiple possible weakness zones as well as probable soil layers of various thicknesses covering bedrock and fractures alike. However, it should be noted that the existence of subhorizontal layering within our models is a prerequisite for using Hagedoorn's +/- method in order to construct a 2D starting model. Therefore, models that do not contain overburden layers can only be inverted using a smooth 1D gradient model automatically generated with the software, as described in the previous section.

There is a variety of approaches for reviewing of refraction seismic modeling arrays. What must always be kept in mind is the borderline between the theoretically ideal array settings and what usually takes place in the field, considering the fact that refraction seismic is not the easiest, nor the cheapest geophysical method available. The software specifications require that inversion needs a specific shot density in order to run as effectively as possible. The shot spacing should be two to three times the geophone spacing and not more than six times that. In our case the geophone spacing was set equal to five meters (24 geophones in total per profile) therefore, the ideal shot spacing should be 15 meters. The simplest models will feature the ideal shot spacing in order to investigate the best case scenario. The Knappe tunnel refraction seismic profiles were produced with shots that were placed at distances four times the geophone spacing which is not strictly ideal, but is close enough to the optimal distance. Accordingly, the models based on these data will use the actual field recording settings.

Our modeling efforts will investigate several different inversion aspects as well as a variety of structures that are most likely to occur in Norwegian landscapes. The goal is to be able to discern inversion schemes that could work sufficiently well in cases similar to Knappe. We aspire to achieve this by testing several different parameters of the inversion itself such as the number of iterations, the wavepath frequency and width, the smoothing options and the choice between single or multi-run inversion, between Gaussian or Cosine Squared regularization and between *Steepest Descent* or *Conjugate Gradient* methods. As already mentioned, modeling will begin in simple terms by testing the effect of regularization parameters individually with the inversion scheme being enriched with more sophisticated settings as the modeling procedure moves forward. So the first part of the modeling procedure will present a simplified display of what each parameter generally does, and as the models become more elaborated, so will the inversion scheme advance in complexity. We expect that by the end of this procedure, most of the program's current inversion capabilities will be employed according to the aim of this report.

Focusing on the structures included in our models, we attempted to vary the properties of each participant layer or zone according to the experience that the NGU had gathered from prior traditional refraction seismic studies and resistivity modeling (Reiser et al., 2010). The cases examined in this report cover various fracture zone velocities (1500 to 4500 m/s), fracture zone widths (5 to 40 m), fracture zone depths (5 to 40 m), fracture zone inclinations (15 to 60^{o}), overburden thicknesses (5 to 20m) and a few combinations between these variations.

4 MODELING RESULTS, INVERSION PARAMETERS

In this chapter we test different inversion parameters on a simple geological model.

The simplest model constructed for this report contains a single vertical fracture zone which is 10 m wide located central in the 240 m long geophone spread, continuous in depth to 100 meters and with a velocity of 3500 m/s. Bedrock is massive, homogeneous and encloses the zone with a velocity equal to 5000 m/s. Since no horizontal layering is present here, the starting model must be the automatically generated 1-D gradient one. In this first simple approach, no multi-run inversion will take place and Steepest Descent will be the selected inversion method. The main focus here is to isolate the main regularization parameters and investigate their effect with single-run WET inversion on the simplest modeled data. In all figures presented from this point onward, red inverted triangles represent shots while gray dots represent geophones. It can be easily seen that the optimal shot spacing for tomographic inversion was employed in all modeling cases (three times the geophone spacing i.e. 15 meters).

In the figures presented in this section the x-axis is the length in m along the profile while the y-axis represents depth in m below the horizontal geophone spread.

4.1 The effect of the number of iterations

Increasing the number of iterations utilized per single-run inversion seems to be positively affecting the result in terms of calculated velocity and depth for the detected weakness zone.

As shown in **figure 4.1** even in this default and premature inversion, 20 smooth iterations are enough to obtain an inversion result which displays an elongated area of low-velocity in the middle i.e. a possible vertical fracture zone. However, the velocity at the core of this presumed weakness zone gradually increases both sideways and in depth from 4370 m/s until it matches the bedrock velocity (5000 m/s). In addition, this low-velocity area, although demonstrating a relatively accurate - if only smaller - width when compared with its modeled width (black dotted line), becomes truncated at ~3 m depth. 50 iterations (interactive WET inversion) result in a ~4370 m/s low-velocity area again. The higher number of iterations increases its extent both laterally and in depth (down to ~5.5 m). Along the lateral direction, the zone acquires dimensions which are even closer to the 10 m wide modeled zone.

The same applies for the 100 iteration result with the exception that the middle part of the detected zone presents a slightly lower velocity (~4295 m/s) while the width of the collective area below 4400 m/s remains equal to about 10 m. The zone is not followed up much farther in depth with the new higher iteration number but only by a few centimeters (down to ~5.8 m). As can be seen in **figure 4.1**, if we use 200 iterations, the inversion result is not much different than with 100 iterations. Therefore, 100 iterations appear to be a number of iterations at which the inversion becomes stable. After this number of iterations there is no significant improvement in the inversion result. However, the increasing amount of iterations also results in a general widening of the weak zone in depth. The maximum depth coverage is about 12 m for 48 geophones with 5 m spacing and shots every 15 m (plus two distant shots at 50 m framing the profile). Still, the zone may be detected but its velocity is estimated at about 800 m/s higher than its modeled value. The depth extent of the low-velocity zone seems to be limited to ca. 10 m despite of being 100 m in the model.

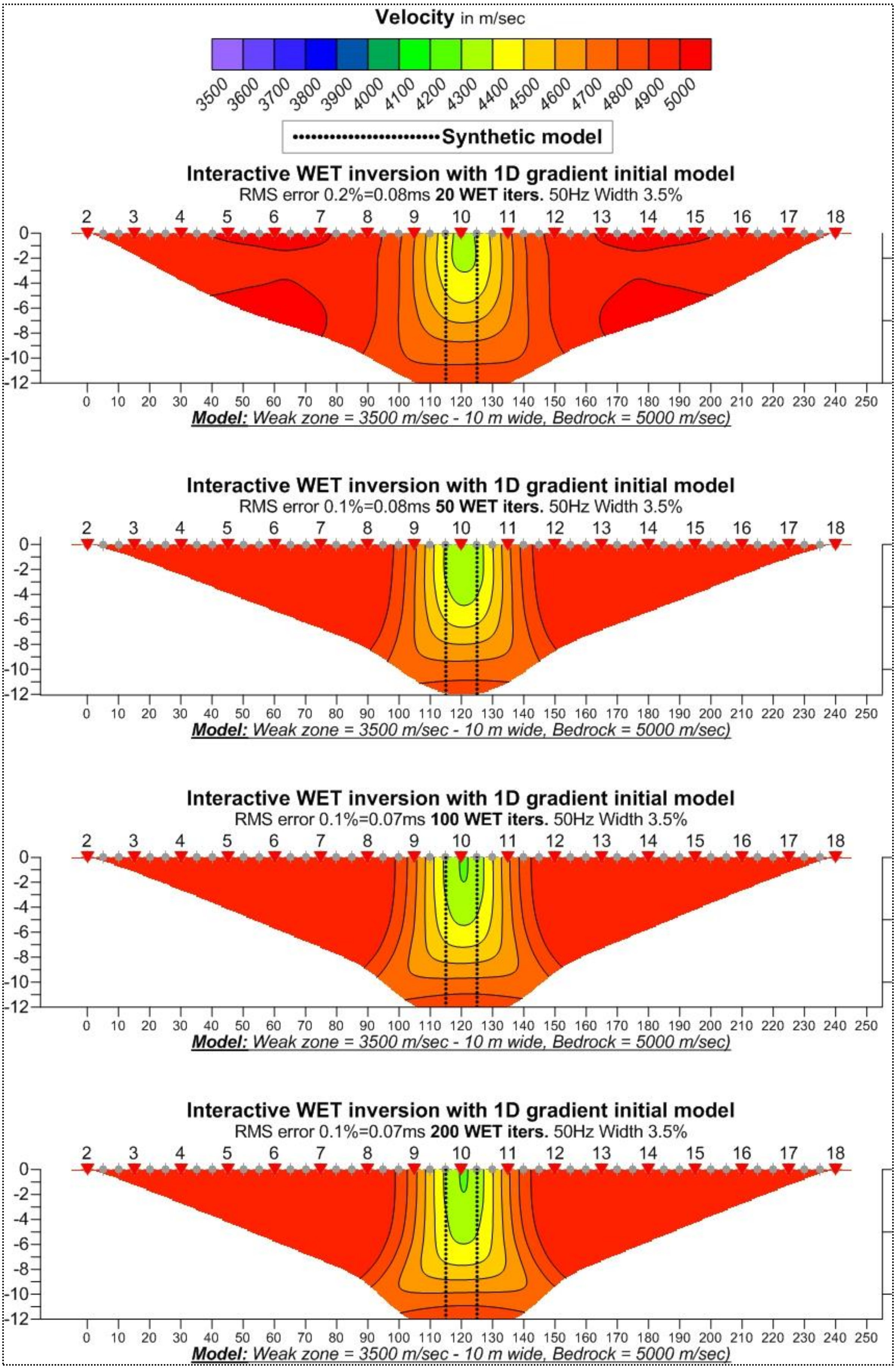

Figure 4.1: Effect of number of iterations in single-run WET inversion (from top 20, 50, 100 and 200 iteration test).

4.2 The effect of decreasing the Wavepath Frequency

We proceed to the next modeling step by establishing a number of iterations equal to 100, as deducted in the previous section. Generally, decreasing wavepath frequency is a means of achieving a more robust inversion i.e. favorable when vertical structures are sought after. Starting from a default frequency of 50 Hz used in our previous scheme, we tested the effect that a decrease would have on the inversion.

Indeed, when decreasing the frequency to 25 Hz we obtain a zone which is not widened at its base and is better followed to depth as seen in **figure 4.2**. The lowest velocity calculated at the core of the zone is still 4295 m/s while the truncation depth is found at around 6 m. Using 10 Hz on the other hand, eliminates the widening effect completely and extends the low-velocity area (~4320 m/s) towards the depth. However, some of the inverted depth penetration is lost and the lower velocity area in the middle of the zone is somewhat increased (~4330 m/s). A wavepath frequency of 5 Hz finally does not seem to be working well, since the zone's velocity is increased after inversion (~4500 m/s) and looks discontinuous. We believe that a wavepath frequency in the range of 10 to 25 Hz with a bigger emphasis on its upper limit should be employed for shaping the fracture as best as possible.

Decreasing wavepath frequency increases the imaged depth extent of the modeled fracture zone, but still we are not able to follow the zone to its entire depth (100m).

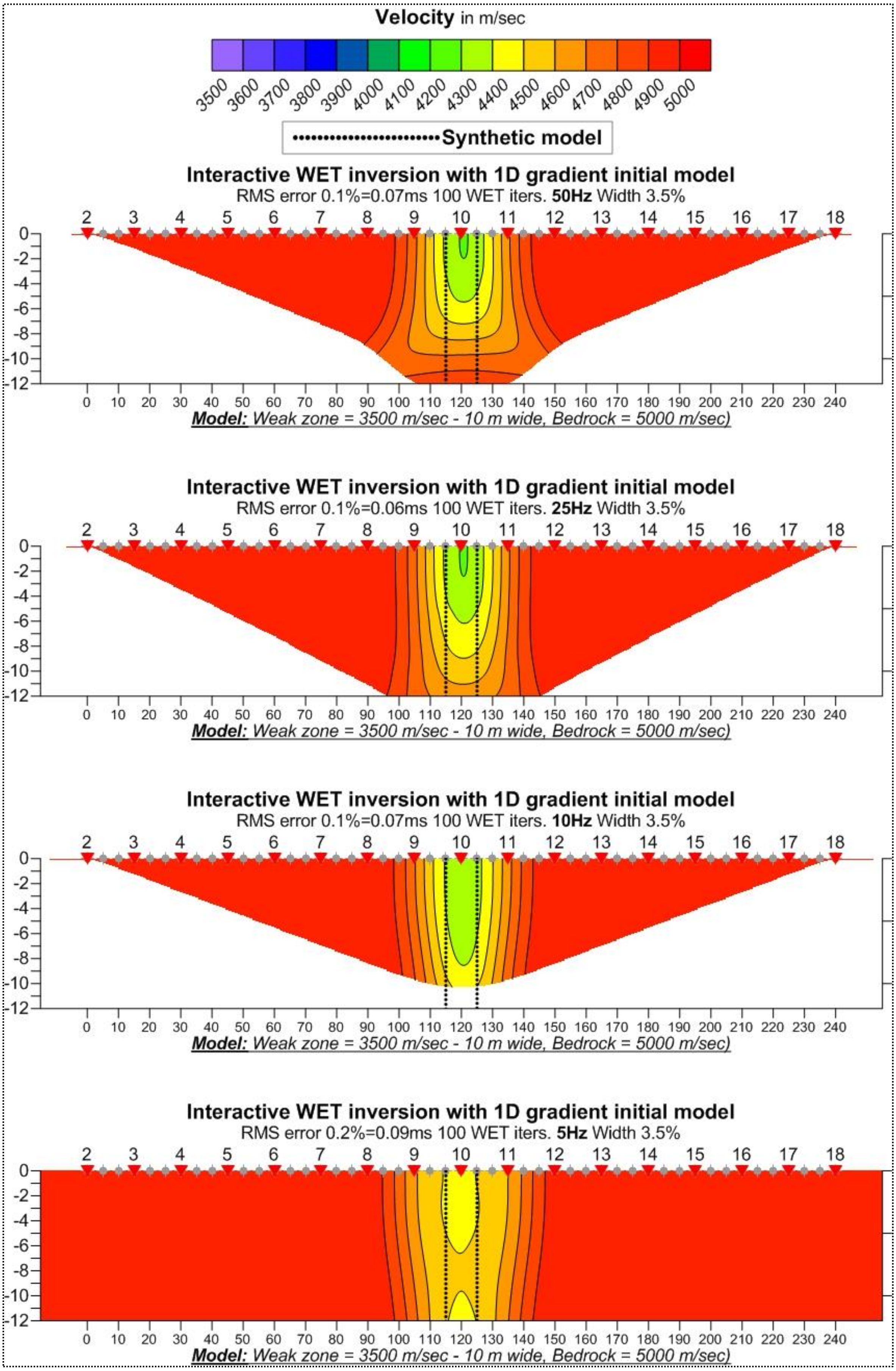

Figure 4.2: Effect of decreasing the Wavepath frequency in single-run WET inversion (from top 50, 25, 10 and 5 Hz).

4.3 The effect of increasing the Wavepath width

The investigations presented in the previous sections for single-run WET inversion, have led us to discern that 100 iterations is the minimum optimal choice while a frequency of 25 Hz shapes up the central low-velocity area better than the default 50 Hz. The third critical regularization parameter is wavepath width and specifies the percentage of one period of the Ricker wavelet central frequency. Generally, an increased value corresponds to wider wavepaths and smoother velocity models. We test a range of values starting from a default 3.5 % up to 10 %. The maximum allowed width is 100% of one period.

The general trend shown in **figure 4.3** is the reduction of the widening of the zone at depth, although it seems that when using intermediate percentages the depth coverage is worsening until it increases again with the maximum value. Using 10 % of wavepath width, we achieve the same effect as using a low wavepath width percentage and a low wavepath frequency (10 Hz) without sacrificing any of the profile coverage. The effect of this parameter should and will be tested in more complex models as well.

Figure 4.3 shows that increasing wavepath width increases the imaged depth of the fractured zone, but it is not possible to follow the zone to its entire depth (100 m) with the modeled geophone spread of 240 m.

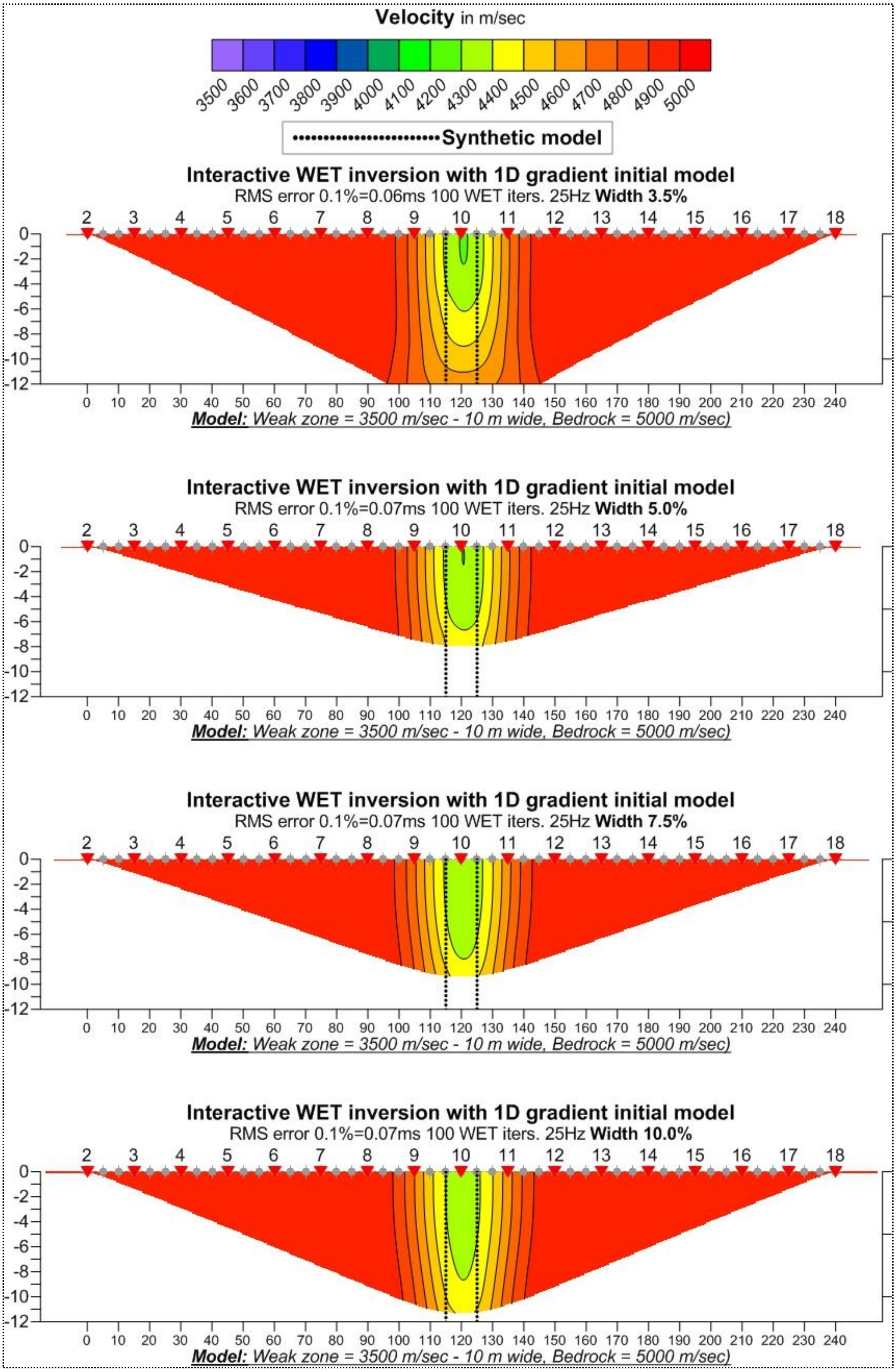

Figure 4.3: Effect of increasing the Wavepath width in single-run WET inversion (from top, 3.5, 5, 7.5 and 10%).

4.4 The effect of editing velocity smoothing prior to inversion

Employing a single-run interactive WET tomography inversion using an automatically generated 1D gradient model as a starting point with 100 iterations, 25 Hz wavepath frequency and 10% wavepath width, we explore further improvement in our inversion result by editing more velocity smoothing options prior to inversion. The main focus here is to gradually take away smoothing factors one by one in order to make the inversion output to better match the modeled low-velocity central area.

In the previous sections, the only fundamental problem persisting was the fact that the low-velocity calculated was not low enough compared with the modeled value. The last step towards rectifying this issue includes tuning a set of parameters which is described here. The first attempt includes the use of minimal smoothing instead of full smoothing after each iteration. This generally results in more detailed tomograms and the improvement regarding the fracture zone's calculated velocity is vast, dropping to 4150 from 4350 m/s which was the previous inversion scheme's result as seen in **figure 4.4**. Next tomography portrays the result after using a smooth n-th iteration equal to 10 instead of 1. This further improves the detected zone velocity since an area of 4050 m/s is formed at the position of the modeled fracture zone. The final edit in velocity smoothing is done by using a Gaussian smoothing filter weighing of 3.0 sigma. This represents the best result we can achieve with the inversion, with a small area of 3950 m/s appearing at the lower part of the detected zone. In the end, a zone of 3500 m/s which is 10 m wide is detectable using tomography inversion but its calculated velocity is just below 4000 m/s i.e. ~500 m/s above the modeled value. The bedrock velocity on the other hand is accurately depicted. These options will be revisited when more complex inversion runs are tested. In general, the aforementioned settings represent one relatively successful approach but not the only one when trying to push the imaged fracture zone closer to its modeled value.

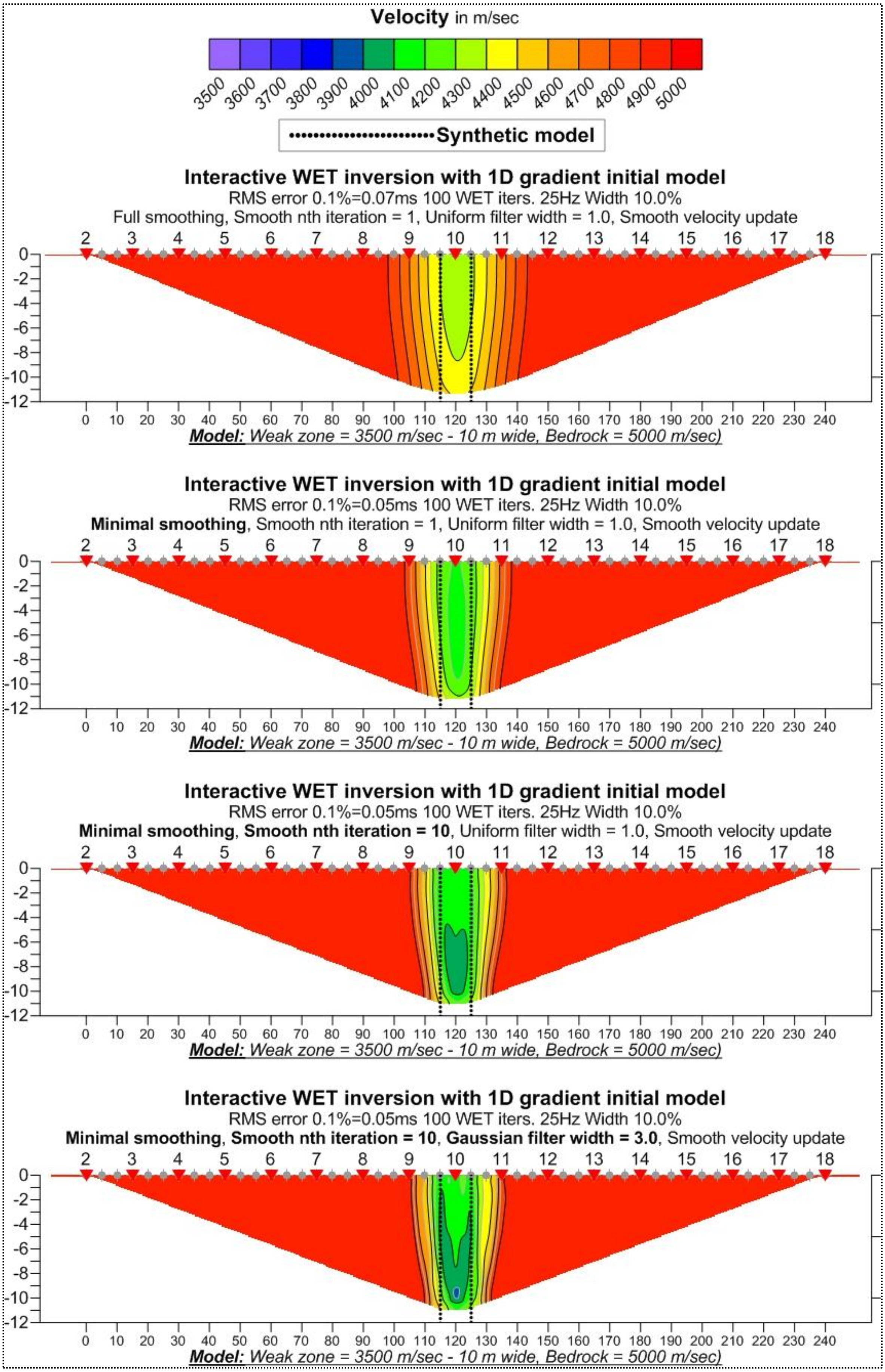

Figure 4.4: Effect of editing velocity smoothing prior to single-run WET inversion. Different smoothing parameters are given in the figures headline.

4.5 Multi-run/Steepest descent/Gaussian weighting

Rayfract® is a software that is constantly updated with new and more powerful tools for inverting refraction seismic data. While this modeling process was in progress, new versions of the program were released with features that couldn't be ignored in the scope of this investigation. In this section we present one of these tools, i.e. the **possibility of running multiple single inversions with varied regularization parameters** for each run. We will be referring to this type of inversion as multi-run inversion. The results presented in the previous section represent single inversions with 100 iterations. However, the multi-run option enables us to perform a number of separate single inversions (maximum of 10) with variable iterations, wavepath frequencies and widths per run. The starting model for this inversion process is the automatically generated 1D gradient model or the layered refraction Plus-Minus model but this is only valid for the first run. After that first run, the inversion product obtained from each run is used as a starting model for the following run. When using multi-run inversion, it is recommended that wavepath frequency and number of iterations remains constant while wavepath width decreases.

Figure 4.5 presents the process of applying multi-run WET inversion on our simple fracture zone model and is focused on displaying the effect of reduced smoothing. The regularization parameters used for this task were a frequency of 50 Hz, a number of iterations equal to 50 per run and a decreasing wavepath width from 30 to 6 % distributed over 7 runs. It can be clearly seen that smoothing removal is pushing the value of the low-velocity area to drop down until it reaches a minimum of 3520 m/s which is almost identical to the modeled velocity for the fracture zone. In the beginning, we have discerned that a rather crude smoothing filter which is manually specified results in a huge drop in velocity for the weakness zone. Furthermore, un-checking the adaption of the shape of the rectangular filter matrix option, the zone becomes better shaped although truncated after around 10 meters in depth. Finally, increasing the number of smooth n-th iteration to 100 and the Gaussian smoothing filter weighting width to 5.0 sigma, we achieve the lowest velocity possible for this data set. A higher Gaussian filter width results in a more noisy distribution of velocity which can be seen as a high-frequency distortion on the contours of the bottom profile in **figure 4.5**. Nonetheless, the application of such a filter causes the velocity within the potential fracture zone to drop from ~3600 m/s to 3520 m/s.

It is evident that the use of the multi-run tool has resulted in a much better and far more accurate inversion result than what we have achieved with the single WET inversion. It has also been proven that there is no single path to a good result parameter-wise. When single-run was employed, a 25 Hz frequency was deemed the best option but multi-run inversion yielded far better results with the use of 50 Hz. The final product of this decreasing of smoothing used for multi-run WET inversion indicates a clear fracture zone which presents quite good quantitative and qualitative characteristics in relation to the modeled zone. Therefore, it is highly recommended that multi-run inversion is essential in the modeling to follow. However, since this tool was added to the software after this procedure had already yielded several single-run WET inversion results, we will continue presenting them along with the multi-run outcomes for comparative reasons.

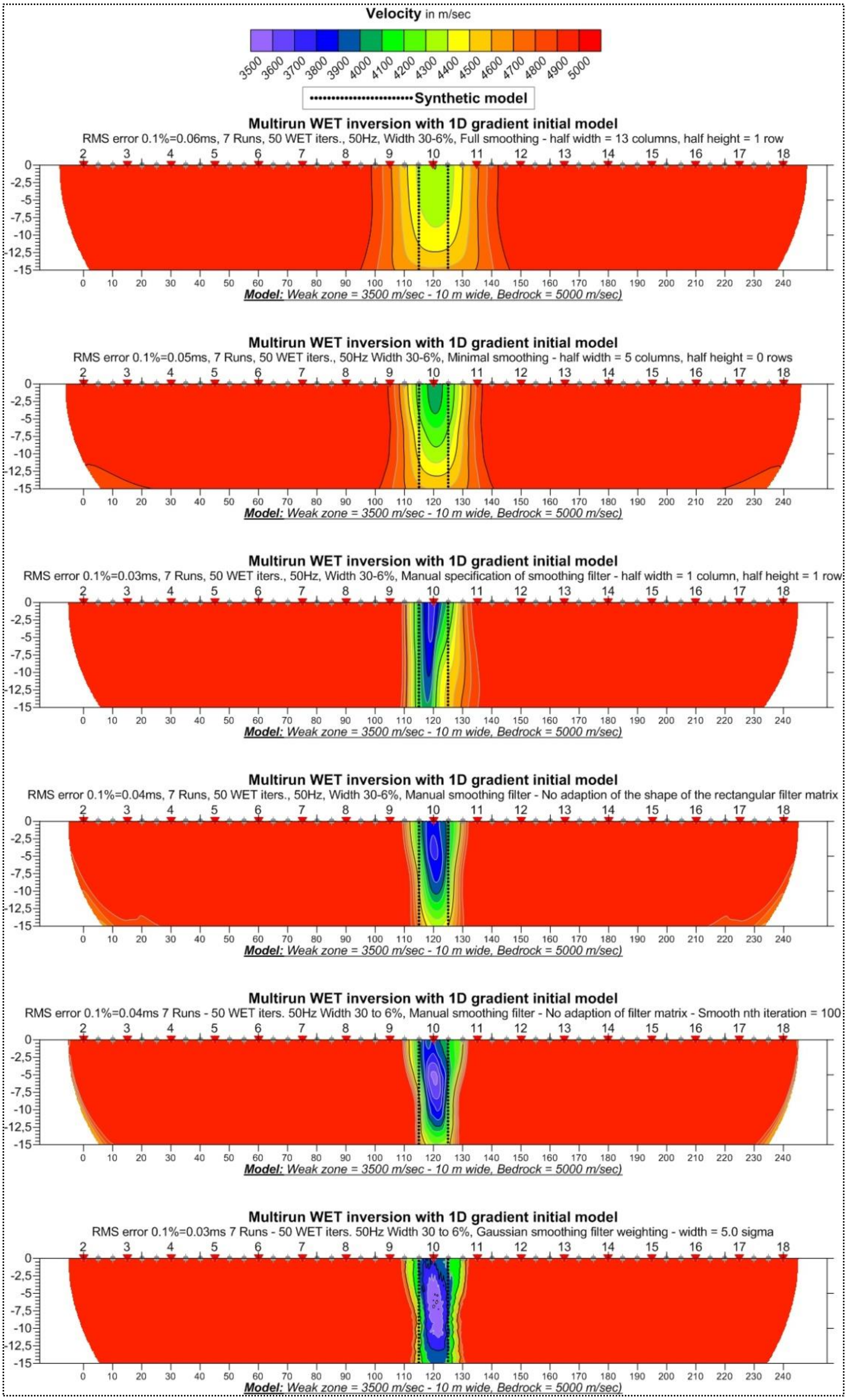

Figure 4.5: Simple fracture zone in bedrock: 7 step multi-run WET inversion using variable wavepath width 30 – 6 % and decreasing smoothing.

4.6 Summary, inversion parameters and procedures

This introductory modeling effort was focused on forcing the calculated zone velocity value down in order to match the modeled one. Testing single-run inversion parameters on the synthetic data forward-modeled over the simple fracture zone model described above, has primarily indicated that velocity smoothing must be minimized in order to succeed in the aforementioned task. However, as soon as multi-run inversion became available to us, its superiority over single-run was proven to be undoubtable. Essentially, we have discerned that if minimal velocity smoothing is combined with a default 50 Hz frequency, a decreasing wavepath width percentage (starting from 30%) and 50 iterations per run, multi-run inversion with 7 runs can yield very successful results.

5 MODELING RESULTS, MODEL PARAMETERS

In this section we test the effect of varying modeled fracture zone velocity, width, depth extent, dip (inclination) and soil cover.

5.1 Simple fracture zone with varying velocity in massive bedrock

The modeling is performed both with the traditional single-run and with multi-run inversion. The fracture model is a 10 m wide vertical fracture zone, continuous to a depth of 100 m. Bedrock velocity is 5000 m/s while fracture zone velocity is 4500, 3500, 2500 and 1500 m/s.

5.1.1 Single-run/Steepest descent/Gaussian weighting

In this section we investigate how single WET inversion is influenced by the velocity contrast between weak zone and bedrock. For this purpose, we have tested three more velocity variants for our modeled fracture zone in addition to the simple model described in previous sections. Bedrock velocity was kept constant at 5000 m/s while fracture zone acquired velocities of 4500, 3500, 2500 and 1500 m/s. As in other geophysical prospecting (e.g. ERT), a higher velocity contrast is expected to "aid" inversion and enable it to calculate the velocity of the fracture zone more accurately and better delineate its dimensions. We should note that the inversion scheme used in all cases presented here is the one using 100 WET iterations, 25 Hz wavepath frequency and 10 % wavepath width together with the optimal smoothing settings. The initial model is the automatically compiled 1D gradient model and all color scales are adjusted to the spectrum of modeled velocities for each case.

As can be seen in **figure 5.1.1**, in the extreme scenario of a very small velocity contrast between bedrock and fracture (4500 m/s), the zone is detected with a velocity equal to 4770 m/s which is not that far away from the modeled value. As the contrast increases (3500, 2500 and 1500 m/s), so does the quality of the inversion results with increasingly good results both in qualitative and quantitative terms. The zone remains detectable in all cases, even though with overestimated velocity for the most part. This part of the modeling procedure indicates that when fracture zones are present in massive bedrock and single WET inversion is run, they will be detected but with an overestimation of their velocity which becomes more severe as the velocity contrast between fracture and bedrock becomes smaller.

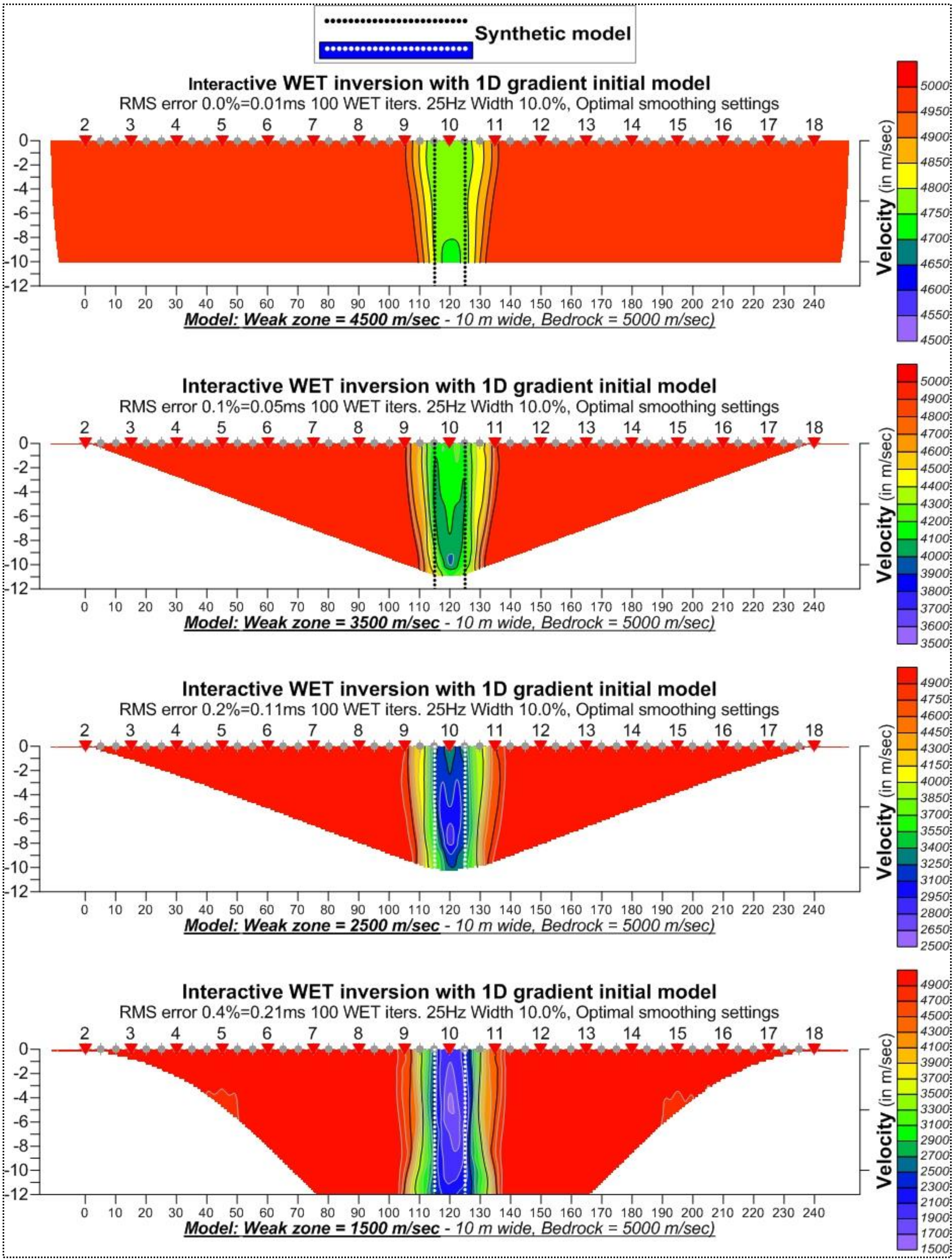

Figure 5.1.1: Effect of velocity contrast between fracture zone and bedrock in **single-run WET inversion** (weak zone: from top 4500, 3500, 2500 and 1500 m/s).

5.1.2 Multi-run/Steepest descent/Gaussian weighting

Multi-run WET inversion with parameters similar to the previous model (10 runs, 50 Hz, width descending from 30 to 6 %, 50 iterations per run and minimal manual smoothing) was also applied on the variable fracture zone velocity case.

Its results shown in **figure 5.1.2** present once more far more successful overall outcomes than with single-run WET inversion. Even in the extreme scenario of a hardly distinguishable 4500 m/s zone when the velocity contrast is very small (500 m/s), the calculated low-velocity area presents values with a local minimum of 4530 m/s which is a negligible overestimation of only 30 m/s. Same applies for a velocity contrast of 1500 m/s but from this point on and for increasing contrasts, the zone is no longer overestimated but underestimated instead. The larger the contrast is, the larger the underestimation (200 m/s for a contrast of 2500 m/s and 300 m/s for contrast of 3500 m/s). This implies that one should be cautious when using the parameters described above since they are more or less designed to push the estimated low-velocity down in order to fit a modeled value which is known beforehand. It could also be said that a set of parameters such as these are more fit for a contrast of 2000 m/s or more and whenever lower velocities are calculated, the possibility of underestimation should be considered.

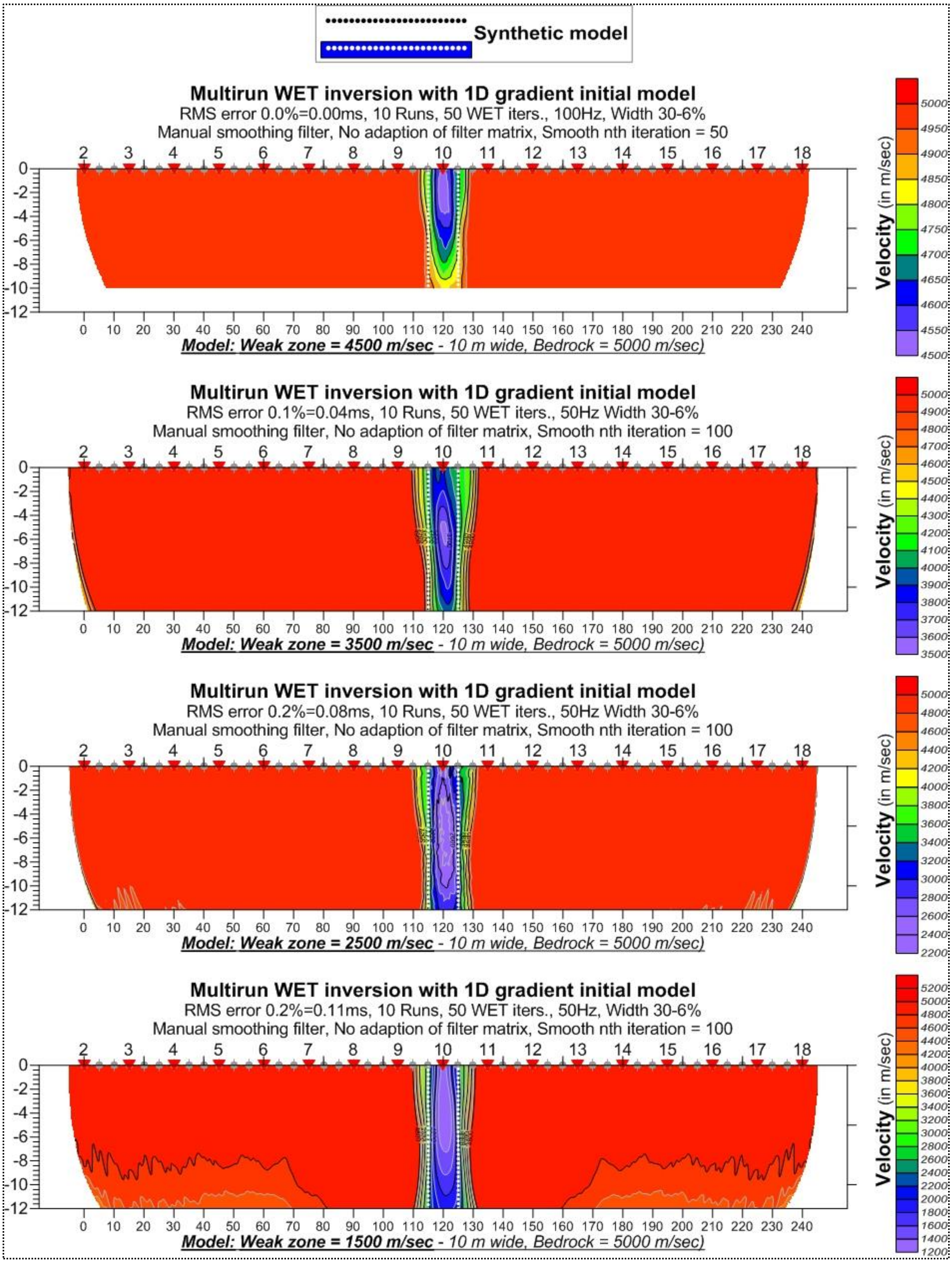

Figure 5.1.2: Effect of velocity contrast between fracture zone and bedrock in **multi-run WET inversion** (weak zone: from top 1500, 2500, 3500 and 4500 m/s).

5.2 Simple fracture zone of varying width in massive bedrock

The model in this section is a vertical fractured zone with velocity 3500 m/s to a depth of 100 m. Width is 5, 10, 20 and 40 m.

5.2.1 Single-run/Steepest descent/Gaussian weighting

This modeling scheme is aimed at determining the effect that the width of a fracture zone can have on the inversion process and how successful such an inversion can be. We have already seen that with single-run WET inversion, a 10 m wide zone is detectable but its velocity is overestimated compared to the modeled value.

Figure 5.2.1 presents the results of inverting synthetic data originating from zones of fixed velocity (3500 m/s) and varying width. A narrow zone whose width is equal to the geophone spacing (5 m) is still detectable but with a width and velocity that are not accurate after single-run inversion. It appears that if we consider the central low-velocity area (around 4500 m/s) as indicative of a fracture zone, its width could be mistakenly estimated equal to 20 m. However, when the modeled zone is 20 m wide, the inversion result is very accurate both in terms of calculated velocity and width. Same applies for a 40 m wide fracture. One more observation that can be made independent of zone width is that after inversion there can be a 10 m wide area framing the detected fracture zone on both sides which represents a rapid increase in velocity until 5000 m/s is reached which represents the true bedrock velocity. This variation should not be taken into account since this gradual transition is the only way in which inversion can illustrate the modeled immediate jump in velocity from 3500 to 5000 m/s between fracture and bedrock. The general rule remains "the wider the zone, the more accurate the inversion of refraction seismic data becomes". The true width of the zone is shown with the white dotted line in all profiles.

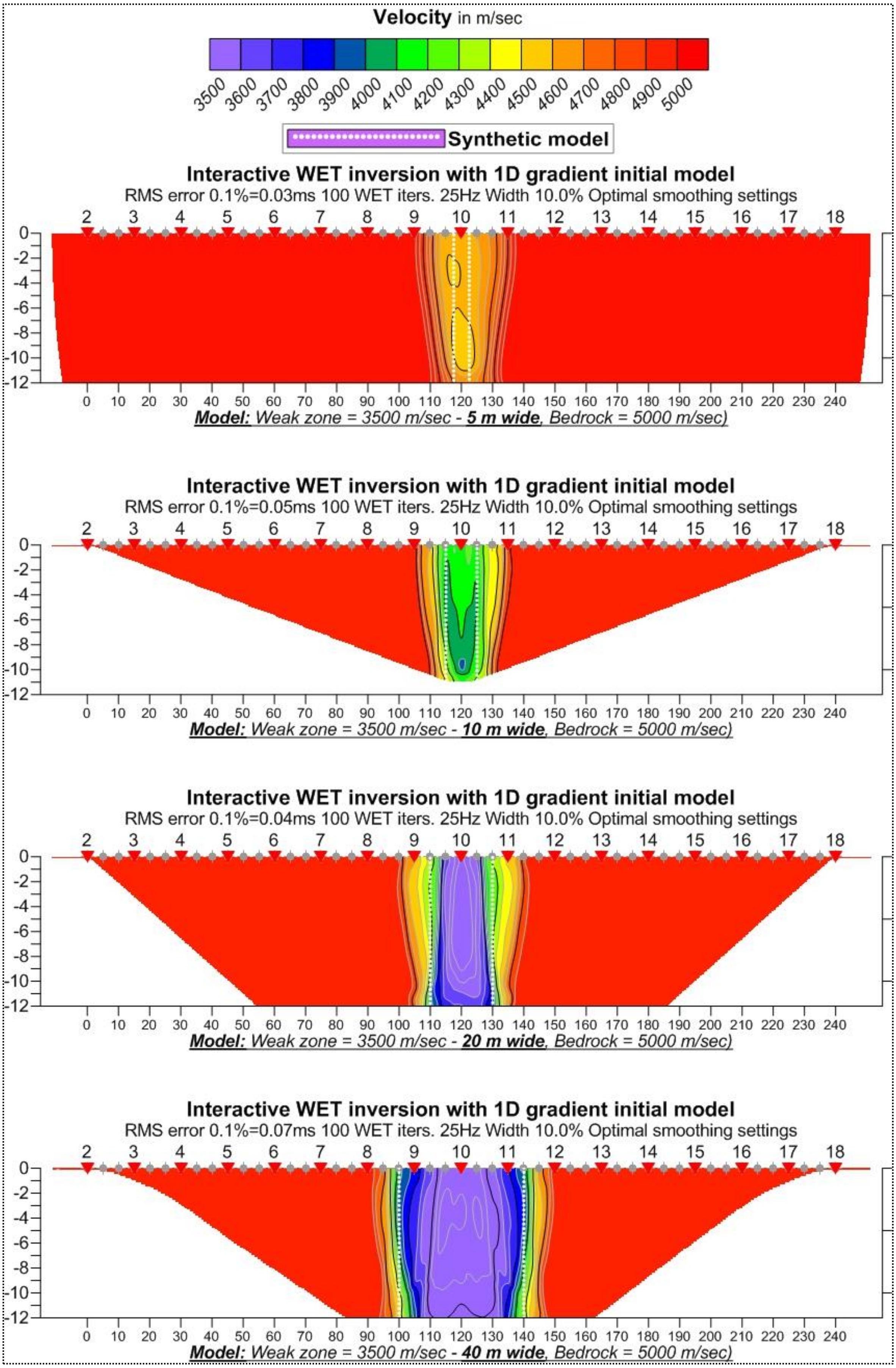

Figure 5.2.1: Effect of fracture zone width in **single-run WET inversion** (from top 5, 10, 20 and 40 m).

5.2.2 Multi-run/Steepest descent/Gaussian weighting

It is once again expected that the application of the same multi-run inversion scheme as before will yield better results compared to the single-run results. **Figure 5.2.2** validates this claim although some remarks need to be made in order to fully describe the effect of such an inversion on our synthetic data. Starting off with the 5 m wide zone, it can be easily seen that the dimensions of the zone are better delineated while the calculated velocity is closer to the modeled one, but still overestimated (4090 m/s). On the other hand, the result for a 10 m zone is very good but in the case of a 20 m wide zone, the result is almost impeccable from all aspects although the zone velocity is still a bit underestimated. When a 40 m zone is surveyed, the multi-run WET inversion product is also great, with an estimated velocity of 3320 m/s and a width that could be interpreted equal to 35 m or more. Additionally, we may also deduce that as the modeled zone becomes wider, the effect of zone truncation with depth is diminishing and the low-velocity areas seem more continuous with depth. Finally, as in some of the previous cases, some high-frequency artefacts can be seen at the edges of the bedrock formation, but they do not affect the interpretation whatsoever. The depth coverage remains relatively shallow (about 12 m).

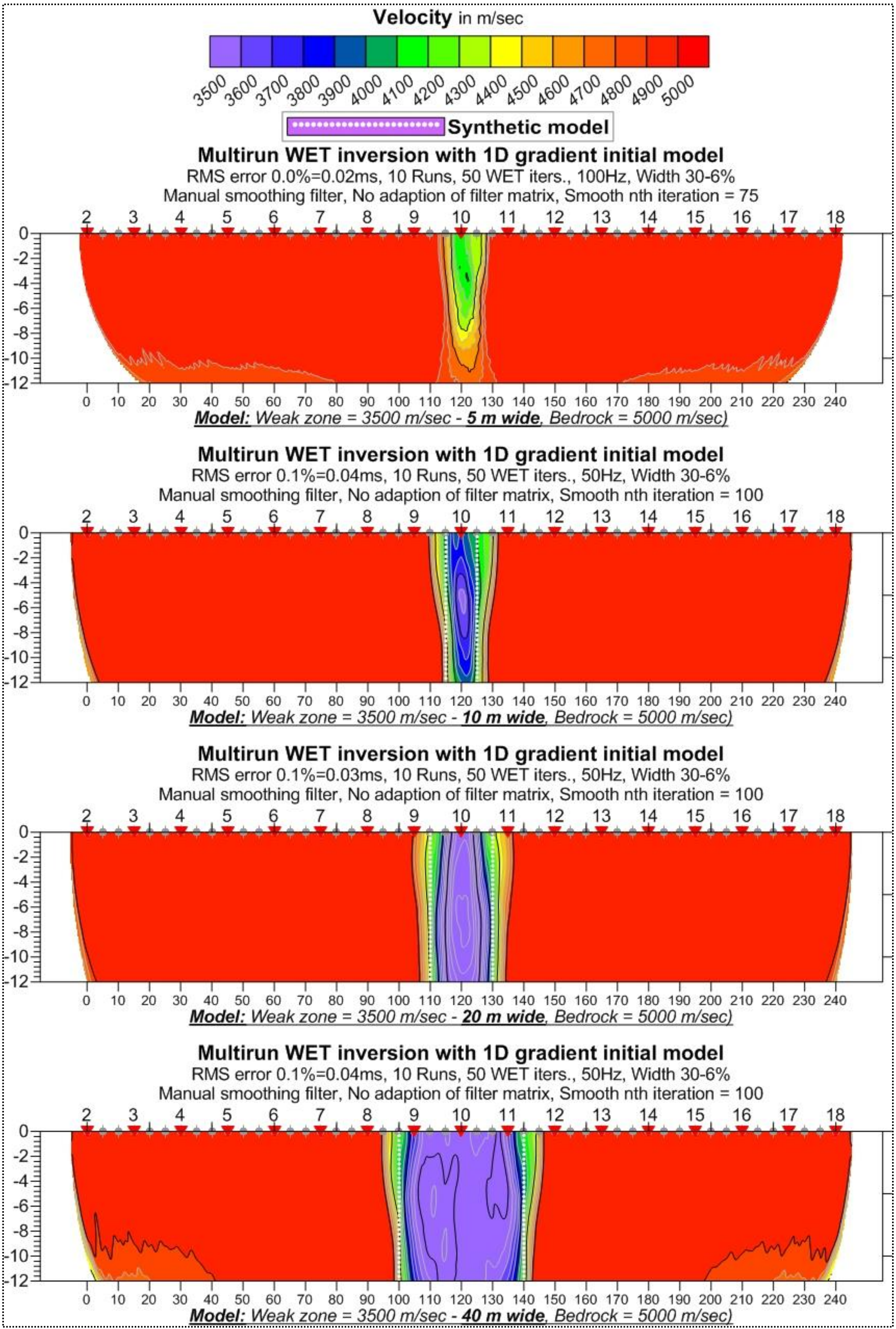

Figure 5.2.2: Effect of fracture zone width in **multi-run WET inversion** (from top 5, 10, 20 and 40 m).

5.3 Simple fracture zone of varying depth in massive bedrock

In this section the model represents a 10 m wide vertical fractured zone with velocity 3500 m/s in a 5000 m/s environment and increasing depth extent.

Up to this point, it is obvious enough that multi-run WET inversion returns far better results than its single-run counterpart. In all aforementioned cases, when robust multiscale tomography WET inversion is implemented, the modeled fracture zones are imaged much better both in qualitative and quantitative terms. Therefore, from now on we will not be investigating single-run inversion anymore and will stick to multi-run for more robust results. It is also reasonable to assume that this is valid not only for synthetic data but also for real datasets.

One aspect revealed so far is the truncation of the detected fracture zone at some specific depth although its modeled counterpart is continuous with depth to 100 m. In this section we investigate this particular scenario by modeling weakness zones which become truncated at various depths. The inversion scheme for this case is somewhat differentiated compared to the previous sections. We are still employing a total number of 10 runs with 50 iterations per run and Wavepath width decreasing from 30 to 6 % however, we increase frequency to 100 Hz. Smoothing parameters remain constant except for smooth nth iteration which is reduced to 20. We once again acknowledge the fact that different data sets require different approaches and Rayfract® is a software which is offering a variety of options and combinations of parameters to obtain good results.

Figure 5.3.1 shows the results of the application of the aforementioned inversion scheme on three different variations of a truncated zone and a continuous one. It must be noted that all profiles are presented with custom depths for presentation purposes although some of them reach higher depths than the ones exhibited. Starting off with a **5 m** deep zone we may conclude that its depiction is quite accurate since the lowest velocity contour area reaches down to 4.2 m with a width of ~8 m. However, when the modeled zone acquires a depth of **10 m**, the interpretation of the inversion result becomes somewhat tricky. If we again isolate the lowest velocity contour area, the depicted zone depth is 7.5 m with a width of ~10 m. Still, it is quite easy to define that we are dealing with a truncated zone and not a continuous one. If we use the whole interpreted low-velocity area, the imaged zone depth better matches the modeled depth but the width is overestimated to twice its original value. In the case of **20 m** zone depth, the interpretation's success is once more dependent on our point of view. If we estimate the depth using the whole set of low-velocity contours the result is more accurate while the width must be based upon the lowest calculated velocities.

The bottom profile in **figure 5.3.1**, where the fracture zone reaches a depth of **40 m,** shows the effect that we have experienced so far i.e. the truncation of the detected zone beneath a specific depth. We may now establish a quantitative estimation of this effect, but this has to be in direct connection with the applied geophone spacing (5 m), the modeled zone width and the current multi-run WET inversion scheme. The overall result we obtained is identical to the 20 m deep zone which denotes that the maximum detectable depth for a fracture zone is exactly that for this geophone spread and shooting point spacing. For zones continuing farther than 20 m in depth, the inversion scheme fails to delineate their deepest part.

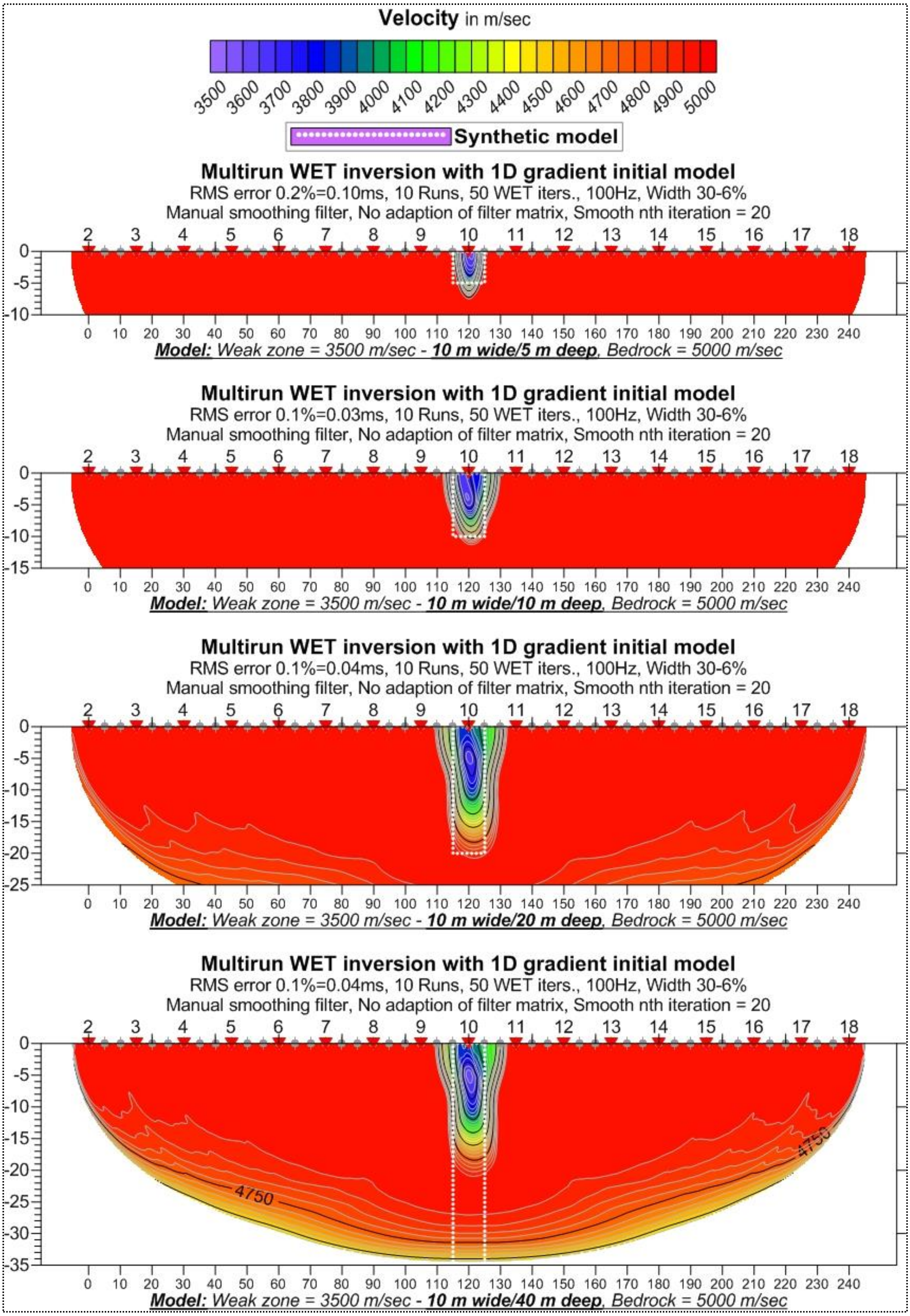

Figure 5.3.1: Effect of fracture zone depth in multi-run WET inversion (from top 5, 10, 20 and 40 m).

5.4 Simple fracture zone of various inclinations in massive bedrock

Although it is known that the dip of fault zones is difficult to image with traveltime tomography, we have constructed a series of models containing inclining fracture zones in order to complete the modeling process by covering as many theoretical cases as possible. Test inversions using *Steepest Descent* as a gradient search method, gave inadequate results with no evidence about whether the detected weak zone was dipping or not. This led us towards testing the other such available method with Rayfract®, the Conjugate Gradient method. Regardless of that, while the inclined zone models were investigated, another new powerful feature was added to the software, the Cosine-Squared weighting method. Combining this tool with the Conjugate Gradient method, we managed to obtain better results than what we had received thus far with Gaussian weighting, therefore these results are included in this report.

The model here is a 10 m wide fractured zone with velocity 3500 m/s in a 5000 m/s environment. The depth extent is 100 m and the inclination (dip) varies from 0º to 60º from vertical.

5.4.1 <u>Multi-run/Conjugate Gradient/Gaussian weighting</u>

The inversion scheme consists of 10 runs with 50 iterations and 50 Hz frequency and more slowly decreasing wavepath width i.e. gradually reducing from 30 to 12 %. The Conjugate Gradient method was used with default settings except no smoothing and a wide Gaussian for update weighting set to 30 sigma.

Figure 5.4.1 displays an interesting set of results for various inclining zones. It is obvious that the zone appears truncated and almost vertical in all cases while the minimum velocity area widens with depth and acquires a shape which can be indicative of the zone's true inclination. However, no actual quantitative assessment can be done on these results, except maybe for the case when the inclination of the zone is high enough (30 degrees or more from vertical). Generally, the detected zone appears to be consisting of two parts, a top one which displays the zone down to 8.5 m as a vertical zone with accurate velocity and lateral dimensions and a bottom part which is vague and presents a clearly overestimated velocity distributed over a wide area (~4500 m/s). In the case of a **60º dipping** zone (from vertical), the lower part appears more clearly formulated and the top one more limited in the space it occupies than any other scenario. By connecting these two low-velocity bodies, we may acquire a somewhat accurate inclination value although the possible addition of noise could make this whole bottom area too vague to interpret.

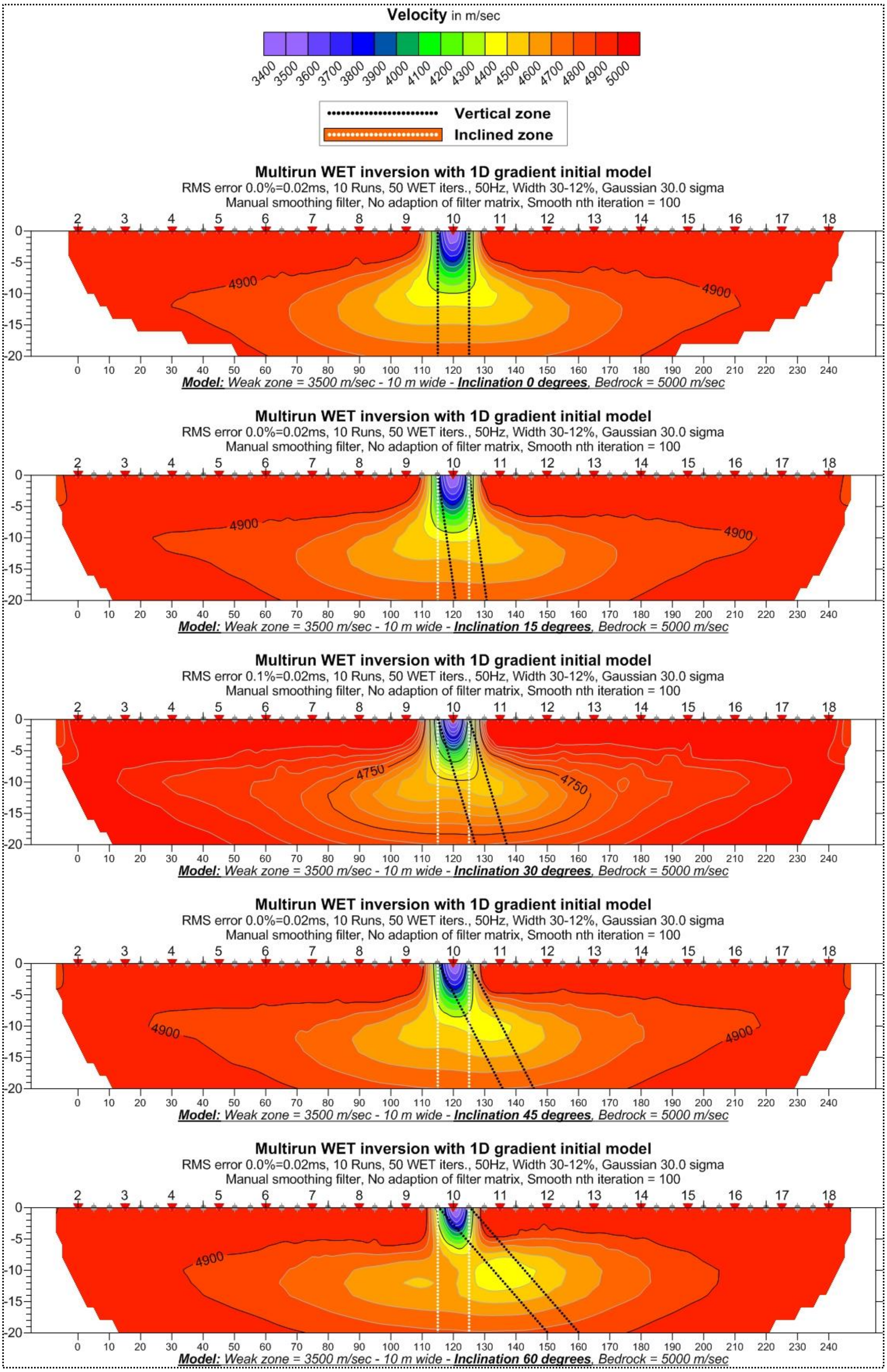

Figure 5.4.1: Effect of fracture zone inclination in **multi-run WET inversion** using Conjugate Gradient method and **Gaussian weighting** (from top 0º, 15º, 30º, 45º and 60º from vertical).

5.4.2 *Multi-run/Conjugate Gradient/Cosine-Squared weighting*

Figure 5.4.2 presents the results for the same inversion scheme described above except this time we used Cosine-Squared weighting instead of Gaussian update weighting. The improvement is vast in all aspects. The zone can still be thought of as split in two parts like before but the results now are slightly more informative even for small inclinations i.e. deviation from vertical. The calculated velocity in the bottom part is distributed in a smaller area and its value is even closer to the modeled one (4300 m/s). It can be said that by using the Cosine-Squared weighting, the possibility of inclination becomes easier to interpret although still not accurately enough. However, even the hint of an inclined weak zone can prove useful on several occasions.

For all dip variations, there is an artificial effect where the low-velocity zone is spread out on both sides of the fracture zone. For shallower dip, 30^o to 60^o, there is an asymmetry indicating the dip of the fractured zone. However, we believe it is difficult to give accurate quantitative interpretations with real data.

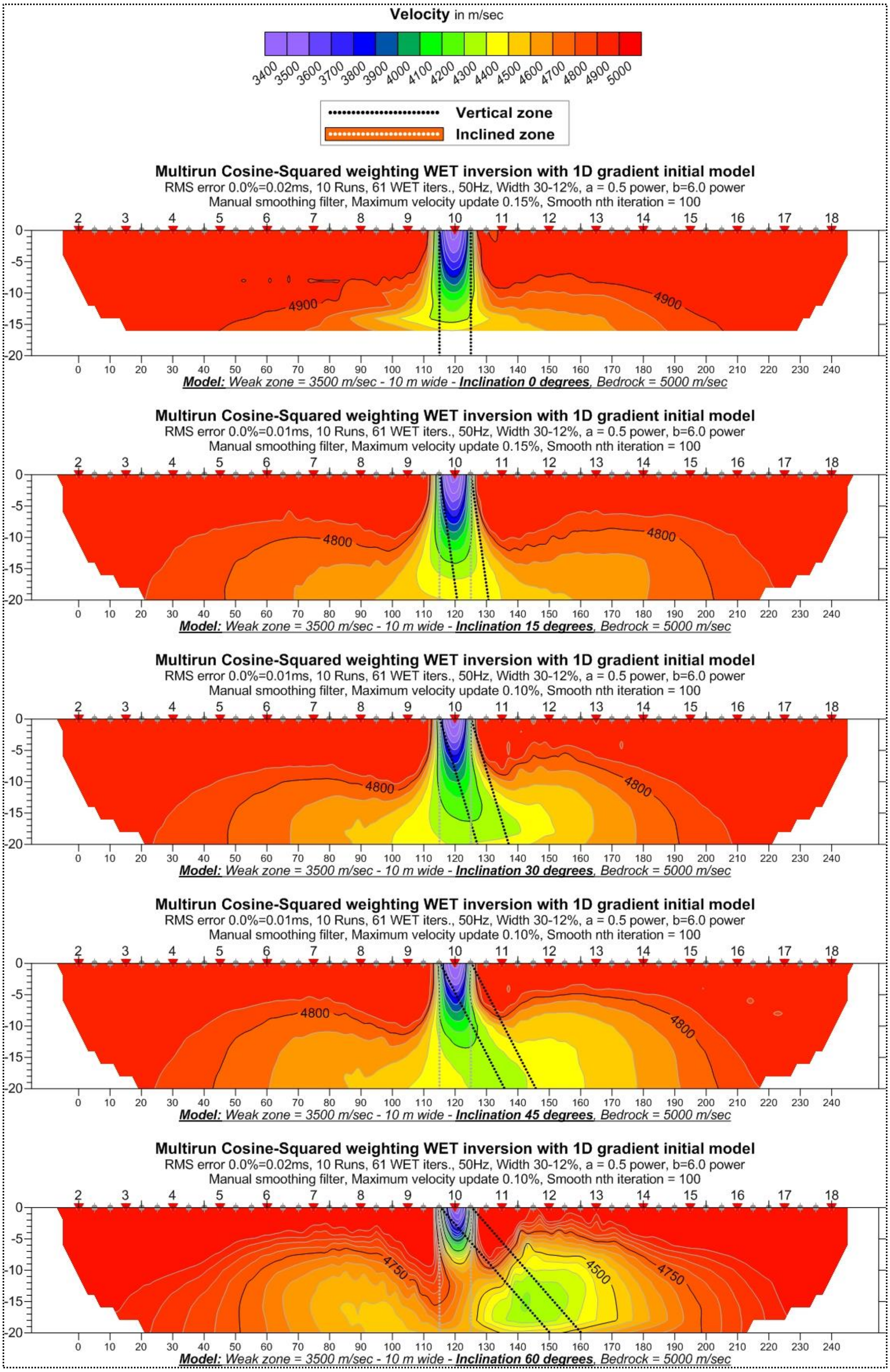

Figure 5.4.2: Effect of fracture zone inclination in **multi-run WET inversion** using Conjugate Gradient method and **Cosine-Squared weighting** (from top 0º, 15º, 30º, 45º and 60º from vertical).

5.5 Simple fracture zone in massive bedrock covered by overburden

The presence of an overburden layer means that this is the first time we can use Hagedoorn's Plus-Minus method to produce a starting model for the inversion. This is accomplished by picking branch points (crossover points) along the traveltimes of the synthetic data which are then used by the Plus-Minus method within Rayfract®. Considering the fact that no additional noise has been added to the synthetic models, the produced refraction seismic traveltimes are quite "clean" therefore the branch points i.e. the points where the dip of the traveltime curve changes, are easy to pick. This leads to quite accurate starting models which can be manipulated even further by changing the smoothing factors so that the resulting model fits the synthetic one as closely as possible. The Plus-Minus models were created by using the lowest values allowed for overburden and base filter width which is 2. With these settings, the program allowed more lateral variations to become apparent within the lowest layer of the model (bedrock) and thus gave us the possibility to better image the fracture zone.

5.5.1 <u>Fracture zone of fixed velocity beneath overburden of various thickness</u>

In this section we are investigating the effect of overburdens of various thickness on the detection of an underlying vertical fracture zone of fixed velocity 3500 m/s and 10 m wide going down to 100 m. For this purpose we have constructed 3 models which contain overburden layers that are 5, 10 and 20 m thick (maximum thickness for current geophone spacing) and allow the seismic waves to travel within them at 1500 m/s (simulating clay, silt or water-saturated sand/gravel). We are using the same multi-run WET inversion mode with Cosine-Squared weighting and Conjugate Gradient search method. Inversion consists of 9 runs with 42 iterations per run (50 by default but the minimum error is reached after 42 iterations) and a frequency of 50 Hz. All other parameters vary according to the case at hand.

Figure 5.5.1 presents the calculated 2D Plus-Minus models (top for each pair of profiles) along with the inversion result using the 2D Plus-Minus model as starting model (bottom). The Plus-Minus method let us calculate models which are quite accurate in all aspects except for the zone's velocity and width. As the thickness of the overburden increases, the overall quality of the Plus-Minus model decreases regarding these two characteristics. At 5 m overburden thickness the zone velocity and width values were 4000 m/s and 15 m respectively, at 10 m thickness they were 4050 m/s and 15 m while at 20 m thickness they were 4450 m/s and 30 m. However, these models are much closer to the synthetic model than any 1D gradient model, regardless of the inaccuracies described above and therefore represent the best possible starting point for our WET inversion process.

When inverting these data, we have found that inputting the minimum and maximum velocity that any formation can acquire during inversion prior to running the inversion, is essential to the success of the procedure. Since we already know the spectrum of velocities apparent in our synthetic models, we have safely limited the inverted velocity to vary between 1500 and 5000 m/s. Maximum velocity update per iteration had to be minimized in most cases (below 1%) and damping was varied according to the case examined. All specific parameters used for this inversion can be seen at the top of each inverted profile in **figure 5.5.1**.

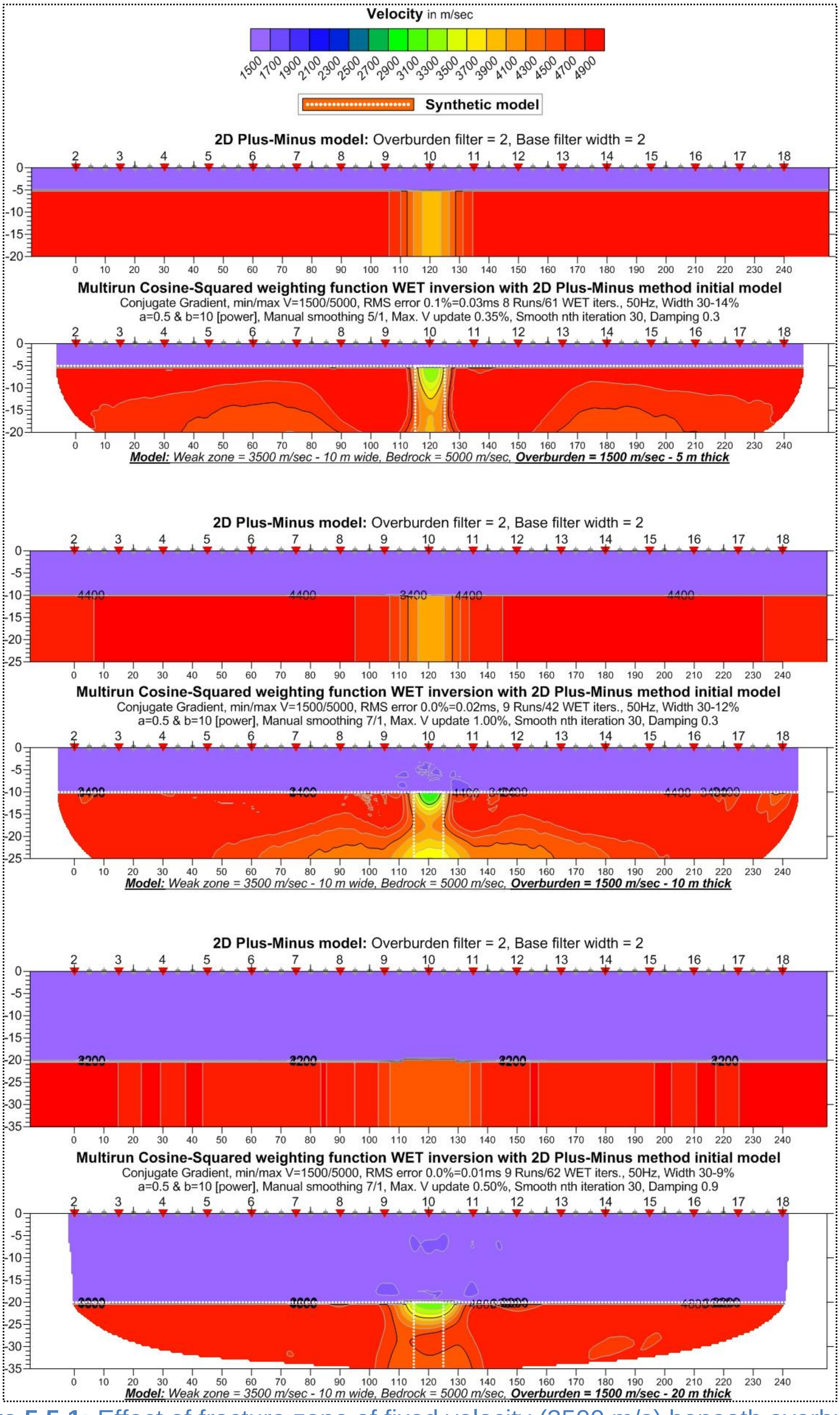

Figure 5.5.1: Effect of fracture zone of fixed velocity (3500 m/s) beneath overburden of 1500 m/s. Upper figure is the 2D starting model using Hagedoorn's +/-, lower figure is the multi-run WET inversion using Conjugate Gradient method and Cosine-Squared weighting (from top 5, 10 and 20 m soil thickness).

Evidently, the modeled zone is detectable in all cases, the overburden thickness and velocity are calculated correctly and the bedrock velocity is as accurate as it can be with a few minor artefacts outside the fracture's influence area. However, as can be seen in all cases depicted in **figure 5.5.1,** only the top part of the zone is adequately calculated while the bottom part is either overestimated, unrealistically widened or nonexistent due to truncation. We also have to keep in mind that with the presence of an overburden, not only does the resolution become reduced but we are also trying to locate vertical structures near this particular geophone setting's maximum depth range and/or near the area where zones become truncated as shown in previous sections. Regardless of the limitations inherent in the process due to presence of an overburden layer, we may deduce that fracture zones are detectable even when 20 meters of sediments lay above them, while information about their dimensions and velocity should be sought within the top part of the resulting low-velocity area.

5.5.2 <u>Fracture zone of various velocity beneath overburden of fixed thickness</u>

In this section we investigate the case where the overburden acquires a relatively higher velocity (2200 m/s simulating moraine) while the 10 m wide fracture zone's velocity varies between 3000 and 4000 m/s. As opposed to the previous section, this time we have maintained a fixed inversion scheme in order to test how different models react to a standardized approach, instead of modifying parameters to achieve the best result in relation to the synthetic model. We should always keep in mind that when real data are processed, the luxury of knowing the underground structure is not available as in modeling. Therefore, compiling fixed inversion schemes that could work well when fracture zones are investigated is the main focus here. The inversion scheme applied is described below.

Again we have utilized 9 runs with no blanking, a frequency of 50 Hz, 61 iterations per run, wavepath width reducing from 30 to 9 %, and a maximum velocity update of 0.35 %. However, some modifications were made in order to achieve certain goals. For example, we reduced the cosine-squared power from 10 to 3 which seems to be a better fit for the combinations of parameters used in these models, we used no damping at all, we dropped the smooth nth iteration number from 30 to 10 in order to reduce the generation of high-frequency artefacts and we limited the manual smoothing to 2/1 to achieve better velocity agreement regardless of the zone widening that it causes at depth.

The results shown in **figure 5.5.2,** present quite good agreement with the synthetic models. Zones are detected with quite accurate widths and only slightly overestimated velocities, the overburden is flawlessly depicted while bedrock velocity is successfully calculated in its majority. The only inaccuracy found in these results is a widening of the fracture zone at depth, which is expected as described above. We may conclude that a fixed inversion scheme could yield satisfactory results without prior knowledge of the geology and structure of the profile. Even the 2D Plus-Minus starting model for the inversion shows a good fit with the model.

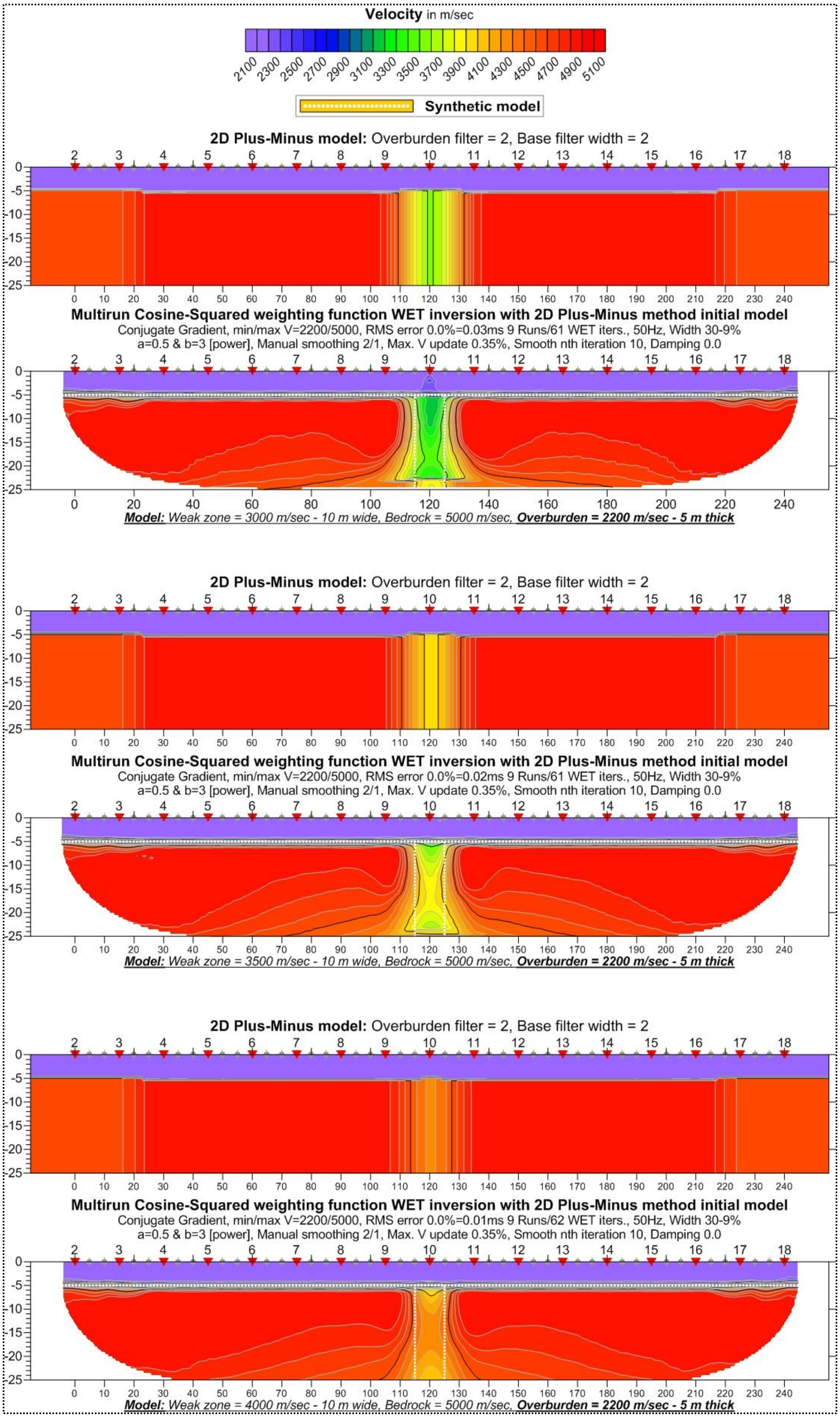

Figure 5.5.2: Effect of 10 m wide fracture zone of various velocity beneath overburden of fixed thickness and velocity (5 m and 2200 m/s) in multi-run WET inversion using Conjugate Gradient method and Cosine-Squared weighting (from top zone velocity: 3000, 3500 and 4000 m/s).

5.6 Model parameters, summary

The above described modeling section has surveyed the software's performance on simpler and more complex models together with the addition of a new inversion feature added to Rayfract® while this work was still ongoing. The most important outcome is that we validated that there is no single approach to success and that the complexity of the software offers more than one approach to obtain good results for each case. However, it is apparent that Cosine-squared weighting can yield better results especially when paired up with Conjugate Gradient multi-run inversion method. Moreover, some cases required fixing of minimum and maximum velocity before inversion, others called for higher nth-iteration values and some for lower percentages of velocity update. Regardless, the fact that velocity smoothing has to be minimized was once again validated as a prerequisite for tomographic inversion trying to detect vertical or inclined fracture zones.

Modifying and combining the above mentioned inversion parameters, we have verified that the dimensions, geometry and velocity of a modeled fracture zone can be unveiled but with some limitations. Generally, we can make pretty good qualitative assessments about virtually every case investigated, but the quantitative part is a bit more complicated. The velocity of a zone can be accurately calculated regardless of the contrast with bedrock, but there is a possibility that its value is underestimated thus deeming it more dangerous. The width of the zone is always close to the modeled value as long as it is at least equal to the geophone spacing and so is its depth extent until a certain depth. From that point downwards, continuous zones are not followed and appear truncated at ca. 20 meter depth according to our models. Moreover, the inclination of a zone cannot be accurately defined, even though less inclined zones (below 45º deviation from vertical) give a different image than those which are dipping more (above 45º). Finally, the thickness and velocity of any given overburden layer can be accurately calculated only when the picking of branch points along traveltime curves is done carefully. It should also be noted that no overburden with velocity between 1500 and 2200 m/s masked an underlying fracture zone, as long as overburden thickness is less than ca. 20 meters.

6 MODELING RESULTS, COMPLEX MODELS

In this section we will do some modeling of complicated models derived from traditional interpretation (Hagedoorn's Plus-Minus) of real data from the Knappe tunnel in Bergen (Wåle 2009), using the experience achieved in the previous sections. These data has been inverted with the Rayfract software before (Rønning et al. 2016). We will also study the effect of shot-point distance in a complicated model.

6.1 Modeling based on traditional interpretation of real data from Knappe

By inverting relatively simple synthetic models, we have managed to investigate a satisfying number of the parameters included in Rayfract®, different model parameter settings and experiment with combining them in order to improve our results. Moving on to the next phase of this modeling procedure, we will try applying the knowledge acquired on more complex models. However, instead of creating such models based on our imagination, we have revisited the traditional interpretations done by Wåle (2009) shown in Rønning et al. (2016) on refraction seismic profiles collected prior to the construction of Knappe tunnel in Bergen. Thus, we have constructed complex synthetic models based on those interpretations, with the geophone array and the geophone/shot-distances employed at the time. In this way, we may test tomographic inversion on models that contain larger number of velocity "blocks" in the ideal situation when no noise has corrupted our data.

We have based our models on two different traditional interpretation profiles from Knappe, profiles P1_1 and P1_6-7 (Rønning et al. 2016). We chose profile P1_1 because that interpretation contains a thin low-velocity top soil layer and a variety of possible fracture zones of various thicknesses below that overburden. Profile P1_6-7 on the other hand, contains a relatively thick low-velocity soil layer which overlays a relatively wide fracture zone that is segmented into two areas with different velocities. Profile P1_6-7 is double the length of profile P1_1 and both of them were modeled using the existing topography at the site where measurements were registered.

We have applied two distinct inversion schemes on these models. Both of these schemes use combinations of parameters that were successful in inverting the simpler models presented in the previous sections. The first scheme applies ***Steepest Descent inversion with Gaussian weighting**,* a crude velocity fixing between 500 and 5500 m/s and a symmetrical manual smoothing filter of 5/5. The second inversion scheme uses the ***Conjugate Gradient method with Cosine-Squared weighting*** and the same velocity fixing but a more irregular manual smoothing (7/1). Both schemes use **9 (multi)runs** of 50 Hz frequency and 50 WET inversions per run plus a wavepath width decreasing from 30 to 9 %. In the sense of utilizing validated schemes i.e. combinations of parameters which already yielded adequately successful results in modeling, we have employed a higher velocity update percentage (25 %), a minimal smoothing with smooth nth iteration number set to 20 or 30 and high damping (0.9). For the second scheme we used a cosine-squared power equal to 10, as used in most overburden model cases. Synthetic models derived from traditional interpretation made by Wåle (2009), 2017 Plus-Minus interpretation and WET inversion results for these profiles are shown in **figures 6.1.1**, **6.1.2** and **6.1.3**.

6.1.1 *Model based on Profile P1_6-7 from Knappe*

For the model based on profile P1_6-7 from Knappe and the construction of the 2D Plus-Minus model using Rayfract®, we employed a wide base filter in order to avoid fragmenting caused by lower values of this parameter. As can be seen in the second profile shown in **figure 6.1.1**, the calculated model is again generally close to the synthetic model. Some discrepancies may be seen in regard with the top profile which represents the original model. First of all, Hagedoorn's method as applied in Rayfract®, cannot differentiate the two zones seen in the synthetic model, and attributes a single but thinner fracture zone to the whole low-velocity interpreted fractured zone with a velocity value closer to its left modeled counterpart (3400 m/s). The other significant discrepancy has to do with the thickness of the low-velocity overburden at the area where the soil layer is observed. The shot spacing used does not allow us to calculate a realistic three layer model with the Plus-Minus method, therefore the resulting basin is thinner than its modeled value and has a velocity which is more representative for the top layer of the synthetic model. Still, this approximation is quite good as a starting model to our inversion, and even as a final model for location of a fracture zone but not for its characterization. A three layer model can be determined with the Plus-Minus method if first breaks are mapped to refractors in Refractors/Midpoint breaks display offered by Rayfract®, but this requires a denser receiver spacing.

We follow the same procedure as in the previous sections i.e. multi-run WET inversion using 2D Plus-Minus model from Rayfract® as starting model and applying two different inversion schemes and compare the results they yield. As seen in the relevant modeling section, zones overlain by **overburden of various thicknesses** are detectable although sometimes truncated or of irregular shape. This can be validated in the third and fourth profile presented in **figure 6.1.1**. When **Steepest Descent/Gaussian inversion** is employed, the zone appears singular and truncated at greater than 15 m depth. Same applies for **Conjugate Gradient/Cosine-Squared** although there is a better overall continuation with depth. Of course, the differentiation of the low-velocity area below the basin was not achieved and the calculated velocity is underestimated in relation to the 2D Plus-Minus model but also in good agreement with the right (lowest velocity) part of the fracture zone seen in the synthetic model.

The width of the resulting zone is a bit tricky for both cases since the velocity contouring is extending the zone to the sides and it is not clear which contour one should use to frame the zone. If we consider the area enclosed by the lowest calculated velocities as the limit, the first inversion scheme returns a less wide zone than the modeled value while the second is more accurate. The thickness and the velocity of the overburden layer on the other hand, are fixed equal to the thickness and velocity obtained when Hagedoorn's Plus-Minus method was applied. **Some artefacts** that could be interpreted as fracture zones are also apparent in our results. Both inversion schemes locate a rather low-velocity area at the beginning of the profile while the second locates another rounded low-velocity to the right of the modeled basin. Both schemes also agree on some differentiation in bedrock around the area of the 13th shot point. However, no zones have been modeled in these locations and we may formulate a new rule which says that areas close to the limits of local and relatively thick overburden, are prone to artefacts. Selecting WET blanking options such as "Blank below envelope after last iteration" could help remedy similar artefacts.

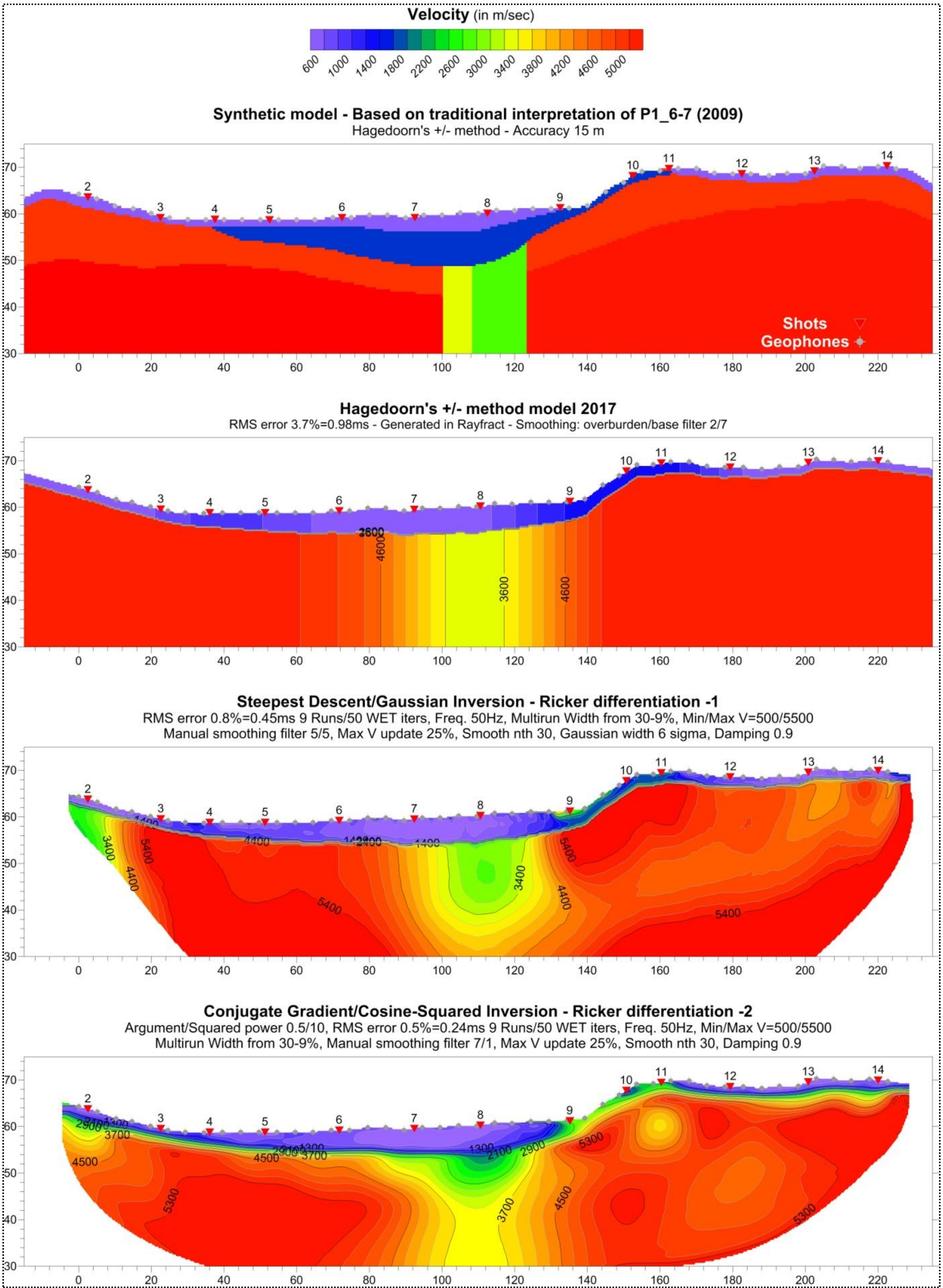

Figure 6.1.1: Inversion of synthetic data from a complex model. From top to bottom: synthetic model based on Profile P1_6-7 from Knappe - 2D Plus-Minus method model as constructed in Rayfract® - Inversion result using the Steepest Descent/Gaussian inversion scheme - Inversion result using the Conjugate Gradient/Cosine-Squared inversion scheme.

6.1.2 Model based on Profile P1_1 from Knappe

The second model result presented in **figure 6.1.2** displays the 2D Plus-Minus model created in Rayfract® with the use of branch points picked along traveltime curves (crossover points). It can be clearly seen that with the use of a smoothing overburden and base filter of 2/2, the depiction of fracture zones is very good, although overestimated in velocity value as expected. All fracture zones contained in this model are easily detectable with this basic approach. However, the use of such filter values causes the bottom layer to be fragmented into many pieces, especially adjacent to the modeled fracture zones. Regardless, this is a fairly good starting model for any inversion process and much better than the automatically generated 1D gradient one as shown in Rønning et al. (2016). This 2D Plus-Minus model created in Rayfract® can also be used as the final interpretation product.

The third model result shown in **figure 6.1.2** presents the inversion results after the multi-run WET inversion using the Steepest Descent/Gaussian scheme, the fourth one the results after applying the Conjugate Gradient/Cosine-Squared inversion and the fifth the first inversion scheme with default full smoothing and too strong, non-default damping of 0.9. Default damping for Steepest Descent is 0.0. All three inversions used the Plus-Minus model generated with Rayfract® shown in the second place as starting model. It can be clearly seen that the two first inversions return profiles with several possible zone localities, represented by low-velocity concentrations. However, there are differences in how the two inversion schemes affect the resulting profiles. The effect of zone truncation is evident in some cases whereas the effect of zone widening with depth can be registered in others. The bottom profile displays the importance of the decreasing of smoothing and how wrong things can go for us if the inversion parameters are unwillingly forced too much in the wrong direction.

All fracture zones presented in the synthetic model are detected although with some positioning problems, especially for the zone in the middle. The fracture to the far left of the profile on the other hand is a special case. The first scheme positions it wrongly and interprets the zone combined with the relatively low bedrock velocity area to its left as two separate zones with lower velocities than the modeled ones. The second scheme locates the right limit of the zone fairly well, while as opposed to the previous scheme, it returns the whole area in question as one possible fracture zone although there is a relatively accurate differentiation marked by the 3900 m/s contour line. The zone in the middle, although vertical in the original modeling, is shown inclined after using the first inversion scheme, but as seen in the respective modeling section, an inclined zone would have a different appearance after inversion. Utilizing the second inversion scheme though returns a far better imaging of the zone's verticality, although slightly widening at depth. The third zone is the one most accurately detected of all, although the second scheme is accompanied by an artificial effect that could be interpreted as the formation of the top horizontal bedrock sub-layer found in the synthetic model past that zone. Again, all zone velocities are underestimated and sometimes this deviation below the modeled value can reach a value of 800 m/s (zones detected at the edges of the profile). However, this underestimation in velocity value is limited superficially with the Conjugate Gradient/Cosine-Squared inversion scheme while in medium and higher depths, the zones acquire quite accurate velocity values.

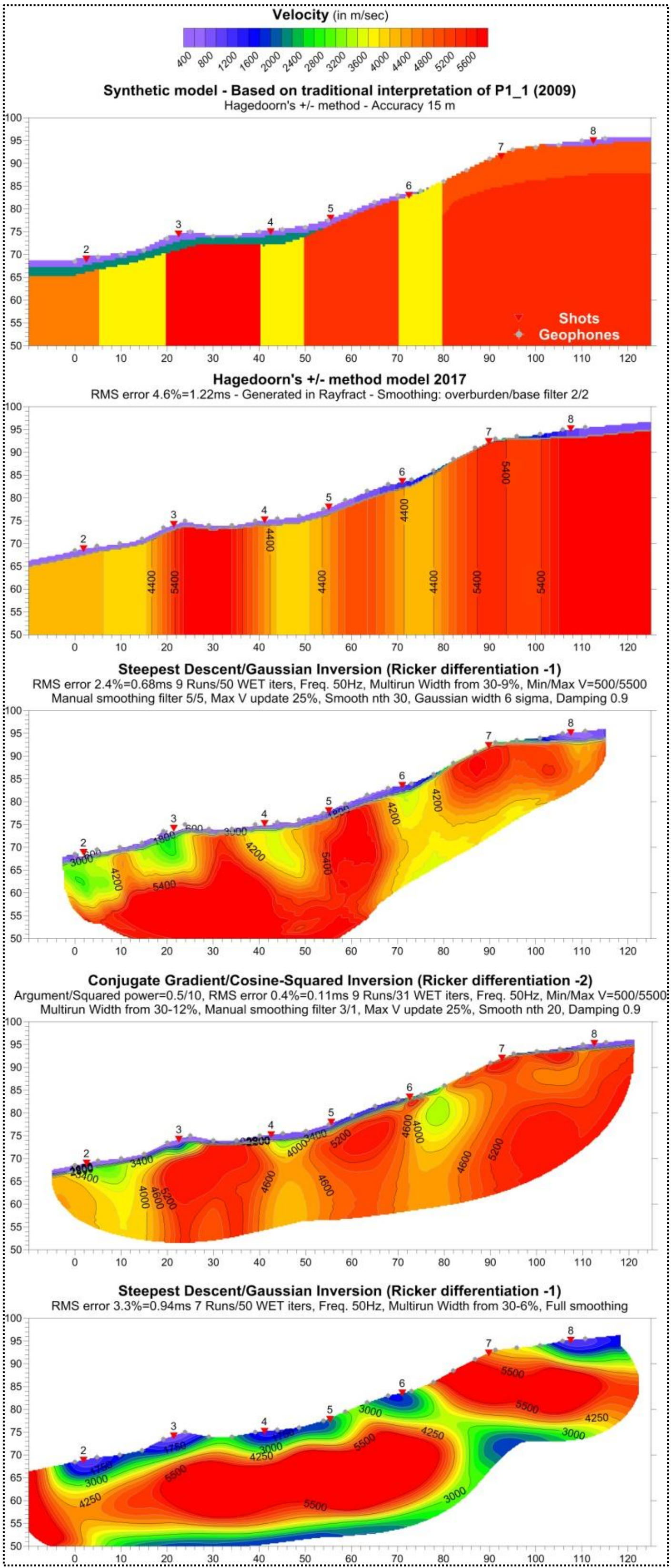

Figure 6.1.2: Inversion of synthetic data from a complex model. From top to bottom: synthetic model based on traditional interpretation of Profile P1_1 from Knappe - 2D Plus-Minus method model as constructed in Rayfract® and used as starting model in the tomographic inversion - Inversion result using the Steepest Descent/Gaussian scheme - Inversion result using the Conjugate Gradient/Cosine-Squared scheme - Inversion result using the Steepest Descent/Gaussian scheme with full smoothing and no blanking.

When it comes to attributing width to the detected zones, both schemes seem to return relatively accurate results. Bedrock is of course affected by the shape of the detected zones but appears solid enough in both cases, although the second inversion scheme is more successful in detecting the top horizontal bedrock sub-layer found at the end of the profile. The overburden layer on the other hand is completely controlled by the picking of branch points during the application of the Plus-Minus method, and is precisely calculated.

From this second complex model inversion, we may deduce that our inversion schemes are not as ‘conservative’ as we initially believed, in a sense that all calculated zone velocities are shown with lower values than modeled. It is also reasonable that we should treat overall positioning and zones appearing at the edges of the profiles with skepticism when the first inversion scheme is applied. Regardless, the detectability of zones by tomographic inversion is unquestionable although we would prefer the second inversion scheme when a series of vertical zones is expected in a survey.

6.2 The effect of number of shots on Profile P1_1

The Knappe data was not collected with the ideal shot spacing although within the acceptable limits for applying inversion. This adds another dimension to the complex modeling presented in this section i.e. if shot spacing such as the one utilized in the Knappe survey can affect the inversion process. Considering the fact that increased shot number also means increased survey cost, we have not tried to create synthetic models with more shots in order to sustain a veritable modeling scenario that also includes a financial aspect. As for the models described above with an overburden layer, it was possible to pick one branch point per traveltime curve only. This means that we managed to create models with two layers in which only the lower one presents lateral variations. Models with three layers can be created for these Knappe data when mapping first breaks to refractors in Refractor/Midpoint breaks display.

It is interesting to investigate a scenario of varying shot spacing for a more complex model such as the one based on Profile P1_1 from the Knappe tunnel. The synthetic model presented in the previous section was created using the same shot-distance as the one utilized when the actual measurements were carried out. This shot-distance was 4 times the geophone spacing i.e. slightly larger than the ideal spacing for the application of tomographic inversion which is 2-3 times that. For this purpose, we have constructed two additional models, one with 3 times the geophone spacing (15 m) and one with 6 times that distance (30 m), which is the least acceptable shot-distance for inversion (Rayfract 2016a).

We once again ran Plus-Minus method to construct the starting model for the following inversion and used the same lowest allowed overburden and base filter values (2/2). This gave initial models which were not much different from each other, regardless of the shot-distance used. Therefore, in **figure 6.2.1** we are only presenting one of these similar Plus-Minus models for comparative reasons. All inversions were performed using the same inversion scheme i.e. the Conjugate Gradient/Cosine-Squared weighting one described in the previous section.

The third profile shown in **figure 6.2.1** presents the worst case scenario i.e. when 30 m shot-distance is used. As expected, the resulting image is oversimplified although the three zones are somewhat detectable with dubious dimensions and shape. The fourth profile is the one which is identical to the field measurements and has already been presented in the previous section. The profile at the bottom of **figure 6.2.1** displays what would have happened if we took that small extra step to match the ideal shot spacing for tomographic inversion. At first glance, the overall result seems to be improved in terms of zone formation and diminished areas of zone velocity underestimation. However, this particular inversion scheme has caused some miscalculations, too, especially at the edges of the profile. The leftmost zone appears with a homogeneous velocity which is about 150 m/s lower than the modeled value and almost merged with the low bedrock area to its left. The upper horizontal bedrock sub-layer on the right end on the other hand, appears more attached to its neighboring fracture zone and with a lower velocity.

We must clarify that these last described effects are due to the inversion scheme used and not to the closer shot-distance. The fact that a denser shot spacing provides an improved image, both in terms of zone detection but also in terms of their calculated velocity, dimensions and continuity with depth, does not change.

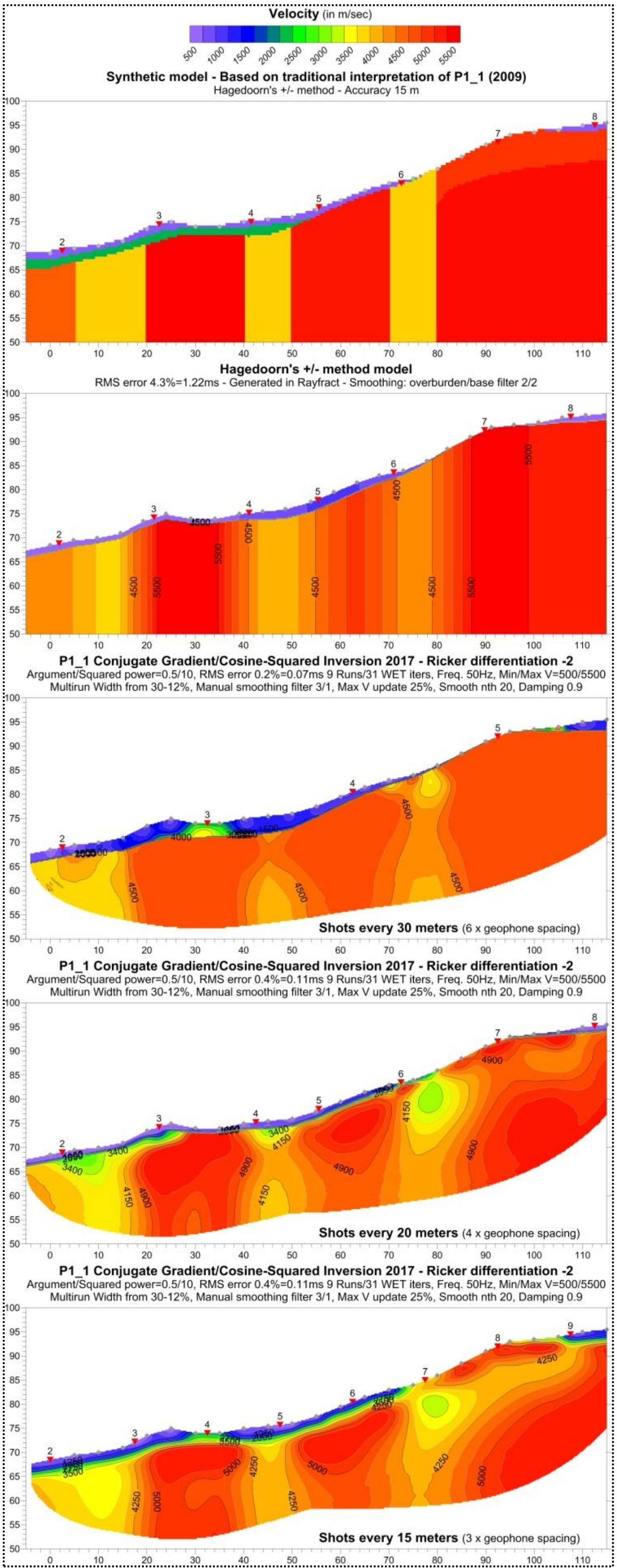

Figure 6.2.1: Inversion of synthetic data, **effect of shot-distance**. From top to bottom: synthetic model based on traditional interpretation of Profile P1_1 from Knappe - 2D Plus-Minus method model as constructed in Rayfract® and used as starting model in the tomographic inversion- Inversion result using the Conjugate Gradient/Cosine-Squared inversion scheme for 30, 20 and 15 meters of shot-distance (6, 4 and 3 times the geophone spacing respectively).

Roughly, the denser the shot spacing is, the higher the resolution of the inversion result is going to be. Yet, the inversion scheme implemented is always of utmost importance and should be investigated in detail with lots of different variations and tests. Nonetheless, the Plus-Minus model calculated within Rayfract®, appears to be more successful than any of the inversion outcomes. We should always keep in mind though that the synthetic model is an oversimplification of the actual conditions at Knappe and therefore, it is only natural for the Plus-Minus model to be able to depict such block-like models accurately. Inversion on the other hand is more sophisticated and aims at producing results with the lowest possible mathematical error i.e. recreate traveltime curves as identical to the field data as possible. Therefore, in this oversimplified case, Plus-Minus results appear superior, but in real conditions, this method cannot achieve the level of detail inversion can. We recommend recording far-offset shots positioned e.g. 10 geophone spacings to left of first geophone and 10 spacings to right of last geophone. These offset shots will be used for determination of the Plus-Minus starting model but not for the 2D WET inversion. We also recommend using overlapping receiver spreads for deeper imaging. Profile-internal far-offset shots positioned inside an overlapping geophone spread can be used for WET inversion. See http://rayfract.com/help/overlap.pdf.

7 COMPARISON, OLD AND NEW INVERSION OF DATA, KNAPPE TUNNEL

The final stage of this report deals with the application of a more educated inversion scheme on the real data, from which the traditional interpretations used as a modeling basis for the previous section were extracted. In this way, we will try to produce more knowledge-based and targeted results than the ones presented in Rønning et al. (2016). We have decided that, since the original processing was done using Steepest Descent and Gaussian weighting although using single-run inversion (instead of multi-run WET inversion which was added to the software in version 3.33 released in August 2015), it would be more useful to apply the Conjugate Gradient/Cosine-Squared multi-run scheme on profiles P1_1 and P1_6-7. The final step is to compare new inversion results with results from the tunnel excavation.

7.1 Reprocessing of profile P1_1

Figure 7.1.1 offers a summarization of all available seismic interpretation results (traditional interpretation and inversion likewise) plus the actual bedrock quality found after the construction of the Knappe tunnel (Rønning et al. 2016, and references herein).

The top of the figure presents the traditional interpretation by Våle (2009). This interpretation suggests three weakness zones with velocities equal to 3800 m/s and at least 10 m wide. It has been shown in the respective modeling section that fracture zones such as these are easily picked up by Hagedoorn's Plus-Minus method, applied within Rayfract® when accurate branch points (crossover points) are interactively picked along the measured traveltime curves. For the production of this profile we had employed the lowest overburden and base smoothing allowed (i.e. 2/2) to allow the algorithm to create as many vertical structures as possible. As seen in the second profile shown in **figure 7.1.1**, possible fracture zones are calculated but they are located in slightly different positions, with smaller widths and higher velocities compared to the traditional interpretation.

The third profile presented here, contains the first attempt at tomographic inversion of real refraction seismic data from Knappe with Rayfract® (Rønning et al., 2016). When tomographic inversion for profile P1_1 first took place in 2016, the multi-run tool was not available to us. Therefore, the only approach available to us was using **single-run Steepest descent method with Gaussian weighting**. The resulting profile indicates three separate areas of low-velocity concentration which appear to be truncated and with fairly low-velocity, especially the first two. The zones detected here are somewhat correlated with the 2D Plus-Minus model but their calculated velocity is much lower than expected (around 3200 m/s) and their positioning is difficult to interpret. The respective zones calculated automatically with Hagedoorn's Plus-Minus method are almost 1000 m/s higher in velocity than the manual interpretation and considering the fact that such increase in velocity was never observed in modeling after inversion, we can deduce that the zones depicted here are unrealistic.

With the **multi-run Conjugate Gradient/Cosine-Squared scheme** which was described earlier with small modifications, we obtain a result which is more consistent with what we've learned from modeling so far (lower profile in **figure 7.1.1**). The detected zones are better correlated with the 2D Plus-Minus model and their velocity is lowered with inversion as expected until settled slightly below 4000 m/s. If we would interpret this new result considering what modeling has shown us, we would say that this is bedrock of moderate quality with two weak zones which are around 10 meters wide and present a velocity which is somewhat higher than calculated with the specific inversion scheme i.e. somewhere between 4000 and 4200 m/s.

The bottom part of **figure 7.1.1** represents the evaluation of the bedrock quality done inside the Knappe tunnel by geologists after its completion (see Rønning et al. 2016). For easier comparison, we have tried to convert these evaluations into a form that fits the color scale used in all of our inversion figures. We tried to assign a quantitative factor that links our interpretations to the descriptive evaluations done by the geologists. In this sense, we have assigned a velocity of 2500 m/s to characterize "class G: Exceptionally bad quality" and 6000 m/s to "class A: Very good quality" (Barton, 2007) and then we picked the colors corresponding to these values in order to fill in the intermediate steps of the scale.

Comparing these evaluations for each tunnel lane with the Conjugate Gradient/Cosine-Squared inversion result and considering the fact that the actual tunnels are outside the result's penetration depth, we may see that there is good correlation in general terms. The whole first half seems to be of moderate to bad bedrock quality, which is validated by the inversion result, although our interpretation would position an individual fracture zone just after the 3rd shot point. The second fracture zone detected after inversion is somewhat validated in the Eastern tunnel, but the overall improvement of bedrock quality in the second half of the profile is also evident in the inversion result. The extremely low-velocity found at the end of the profile (position 110) is definitely an artefact possibly due to wrong shot station specified for offset shot no. 9. A small zone of very bad rock quality at position 44 to 47 is not seen on any of the velocity sections.

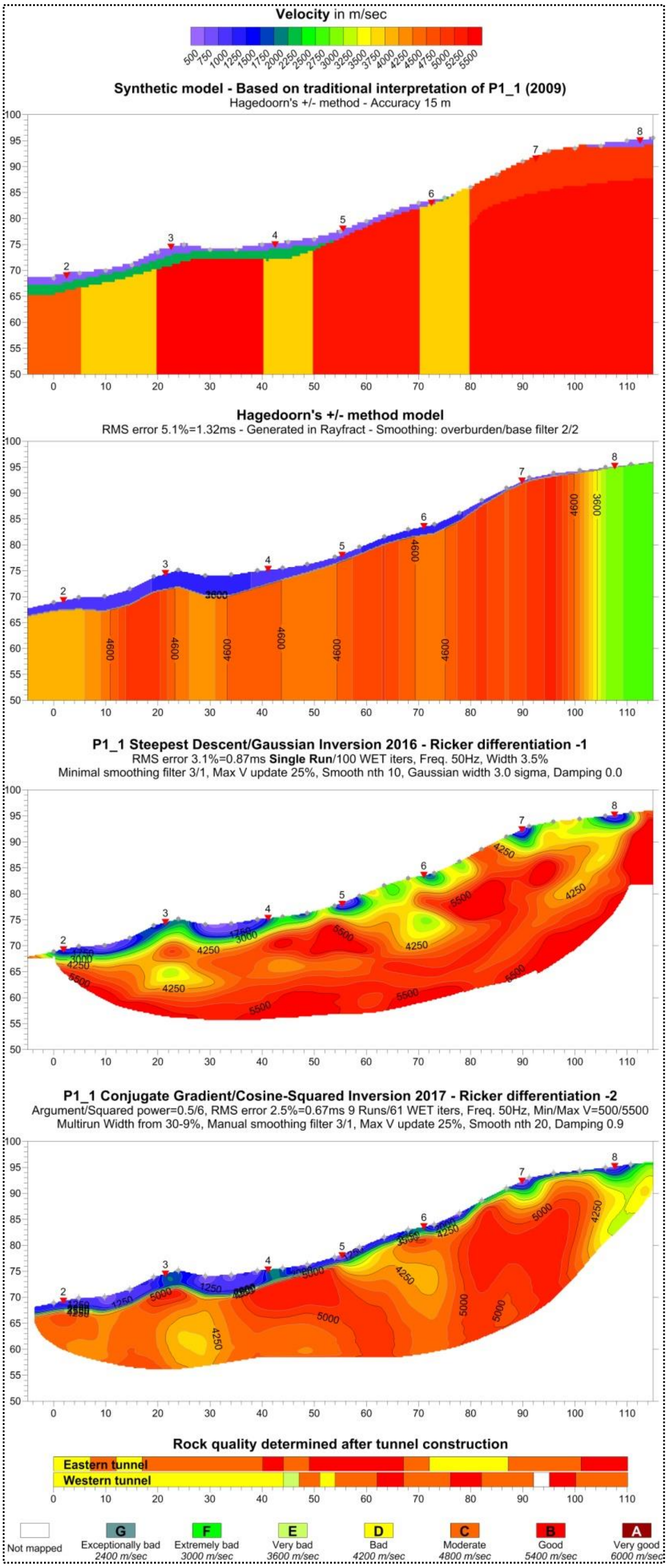

Figure 7.1.1: P1_1 comparison between old and new inversion result. From top to bottom: Traditional interpretation (Wåle, 2009) - 2D Plus-Minus method model as constructed in Rayfract® - Result using Single-run Steepest Descent/Gaussian inversion (Rønning et al., 2016) - Result using the Multi-run Conjugate Gradient/Cosine-Squared inversion - Rock quality inside the east and west tunnel.

7.2 Reprocessing of profile P1_6-7

Figure 7.2.1 follows the same presentation format. The top profile is again the traditional interpretation offered by Wåle (2009) and it shows a medium-sized soil cover (15 meters depth at its deepest part) covering a double fracture zone whose left counterpart has a higher velocity than its right. This soil cover is confirmed with the 2D Plus-Minus model we constructed in Rayfract® but its depth is smaller because the array used does not allow to realistically differentiate the basin into two layers, as done in the traditional interpretation. Therefore, instead of a 15 m deep basin of 600 and 1700 m/s, we have an 8 m deep one with velocity equal to 500 m/s.

Below that basin, in bedrock, inversion data deviate from the traditional interpretation. We should note that we use moderate smoothing overburden and base filters this time (5/5), since these values are enough for the Plus-Minus algorithm to fragment the bedrock but not too much as with lower ones. The calculated model reveals a wide area of low velocities which continues spanning long after the double zone seen in the top profile between position 100 and 123 in **figure 7.2.1**. The velocities in the zone are again somewhat higher than the traditional interpretation and the differentiation within the zone is not formulated in the software-generated 2D Plus-Minus model. Another interesting feature in this low-velocity area, is a 3500 m/s and 10 m wide zone seen at the limit of the basin. It is interesting to see how this low-velocity column will affect the inversion result since we now know that basin edges are prone to artificial effects. However, there is a chance that the low-velocity zone shown at the limit of the basin (inline offset 160 m) in **figure 7.2.1** may be a Plus-Minus artefact due to strong topography (topography curvature) at that location.

The third profile in **figure 7.2.1** represents the single-run WET inversion result (50 Hz, 3.5 % width and 100 iterations - Rønning et al. 2016) and shows an image which is closely tied to the previously described 2D Plus-Minus model. The low-velocity soil cover basin is shaped up in close connection to the Plus-Minus model and with a similar velocity. The area beneath this basin though is a bit more difficult to interpret. A low-velocity tongue between shot 7 and 8 seems to be extending towards the depth while forming a limited high-velocity area in the identical position where the thick weak zone appears in the traditional interpretation and a very thin low-velocity zone is projected in the Plus-Minus method model. This high-velocity concentration separates this tongue from a smaller one to its right which is not as prominent. The low-velocity column appearing exactly after the basin's end seems to be showing up on the single-run result but the coverage depth in this part of the profile is small and thus inadequate for interpretation.

The results of reprocessing profile P1_6-7 are displayed as the fourth model in **figure 7.2.1**. The inversion scheme is very similar to the one used on profile P1_1 (section 7.1) and the only crucial changes made refer to different smoothing filter dimensions (7/1 instead of 3/1) and a higher smooth nth iteration number (30 instead of 10). The application of Conjugate Gradient/Cosine-Squared WET multi-run inversion returns an image which is similar to outcome obtained with single-run but not entirely. The soil cover basin is of course still delineated but in this case, there is a clear differentiation between what happens within and beneath it.

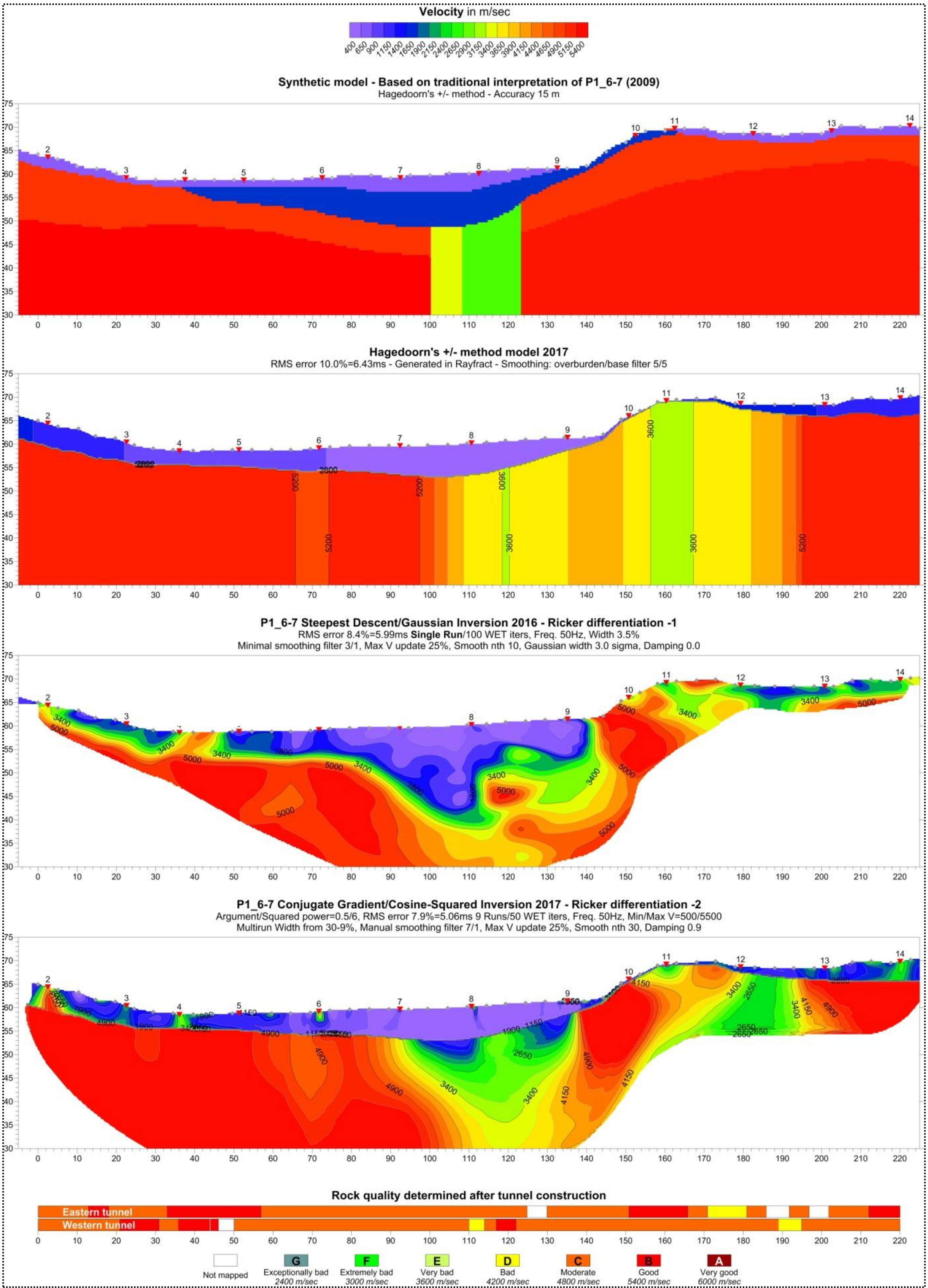

Figure 7.2.1: P1_6-7 comparison between old and new inversion result. From top to bottom: Traditional interpretation (Wåle, 2009) - 2D Plus-Minus method model as constructed in Rayfract® - Result using Single-run Steepest Descent/Gaussian inversion (Rønning et al., 2016) - Result using the Multi-run Conjugate Gradient/Cosine-Squared inversion - Rock quality inside the east and west tunnel.

The low-velocity area between the 7th and 9th shot point appears continuous and more consistent, while the even lower velocity tongues at the top between the same shot points still appear separated but not as dramatically as in the single-run result. As for the area after the basin, there appears to be some more zoning happening with a clear low-velocity structure appearing after the 12th shot which is misplaced compared to the position it appeared to be in the 2D Plus-Minus model. Once again, we note that a central zone presented in the traditional interpretation, having this size and velocity properties, should manifest in the 2D Plus-Minus model easily and subsequently to the multi-run inversion. However, this is only the case for the last inversion result.

The last part of **figure 7.2.1** is once again the geological evaluation of bedrock quality from the tunnel excavation (Rønning et al. 2016) intuitively linked to the velocity spectrum shown in the inversion results. Moreover, it is essential to note that the tunnel level was still unreachable (located at 20 m.a.s.l.) but this profile's coverage comes closer than profile P1_1. The main focus here is to discern whether a fracture zone of the proposed size in all seismic interpretations is validated in the tunnel. The answer is partly yes. Low bedrock quality in the tunnel coincides quite well with both the fracture zones that inversion has revealed. Low velocities found between 110 and 130 m and the zone around 170 - 190 m of horizontal distance at the lower profile in **figure 7.2.1** are reflected in the evaluation done by the geologists at the Knappe tunnel, but with much smaller width. As a matter of fact, the zone seen at 170 -190 m was not depicted in the original traditional interpretation and it is one good example of how inversion managed to pick up a detail that traditional interpretation missed. The reasons for the discrepancies in width are discussed in the following section.

8 DISCUSSION

In this section we discuss the inversion procedure and possibilities to locate and characterize low-velocity zones (weakness zones) in bedrock with refraction seismic tomography using the Rayfract® software.

8.1 Inversion procedure and parameters

First and foremost, this modeling procedure has proven that refraction seismic tomographic inversion can be used to detect and characterize fracture zones in bedrock. Rayfract® is a software adequate to see this task through. The software provides a large range of procedures and parameters that can be changed when running inversion on any dataset and offers a variety of approaches when trying to locate the position and attributes of a weak zone. It is also a programme that is constantly updated with newer and more powerful tools which were not ignored during the compilation of this report, even at the cost of redoing inversion on whole modeling subsections. The complexity of this software requires a skilled person to perform a reliable inversion.

Generally, the success of applying WET inversion is determined by both the underground conditions and the processing scheme that we choose. It is easily understood that wider zones, with higher velocity contrast in relation to the hosting bedrock and thinner overburden layers above them are easier to detect and do not require detailed approaches except for the case when inclined zones are present. The real challenge of this modeling procedure begun when these conditions became less favorable i.e. the zones were not as wide, their velocities did not deviate much from unfractured bedrock and the overburden layer above them had significant thickness. This is when the user doing the processing of the data need a deeper knowledge of the Rayfract® program in order to cope with these challenges.

This project provided us the opportunity to obtain a better knowledge of the software's capabilities but it is not nearly enough to decode every parameter's effect. This is due to the fact that most of the time we are referring to combinations of these options which lead to different results. The other problem related to modeling in general, is that we of course knew the models from which the traveltime curves were synthesized. This means that we were able to judge whether a modified inversion process was more successful by matching its result with the original model. However, this is never the case in real conditions and actual refraction seismic surveys. In some of the most complicated cases such as the dipping fracture zone scenario and the presence of an overburden layer, we had to use rather specialized inversion schemes for obtaining images which resembled the synthetic models as good as possible. However, this doesn't mean that these inversion schemes can be applied to all possible cases.

What we tried to achieve from this study was a set of so-called 'conservative' inversion schemes whose effect on known structures would be documented and analyzed. We also tried to find ways to accommodate the manifestation of vertical structures on our inversion results. Generally, we have discerned that if vertical zones are indeed present in the underground, tomographic inversion can locate them. As a matter of fact, such zones will become apparent even at the stage of manufacturing an initial model within Rayfract® by using Hagedoorn's Plus-Minus method. The real question is whether we will be choosing the right inversion parameters in order to our interpretation to be also accurate quantitatively.

We have discerned that lowering the smoothing overburden and base filter values when constructing the 2D Plus-Minus initial model, will result in fragmenting of the lower layer. However, this has to be controlled intuitively according to the dataset processed because extreme fragmenting may enable the inversion to calculate a zone for every individual "low" velocity column found in the initial model. This happens because we have to reduce overall smoothing in order to locate vertical zones with Rayfract®. The most parameters important in this direction are the dimensions of the smoothing filter (usually set manually with a reduced half height and a small half width), the maximum velocity update percentage (usually lower than default 25%), the smooth nth iteration number (usually higher than default 10) and the damping (varying according to the case investigated). Also using a Gaussian smoothing filter instead of a uniform filter helps to improve resolution.

It was evident that we obtained the best possible results by using multi-run inversion instead of single-run, with decreasing width of variable intensity and by using default frequency (50 Hz) and a variable number of iterations in connection with the mathematical error of the inversion result (inversion would stop when some error standards would be reached). Moreover, the best inversion scheme consisted of multi-run Conjugate Gradient search method combined with Cosine-Squared weighting. This combination was validated when the reprocessing of Knappe tunnel data took place, when Steepest Descent/Gaussian weighted failed to give equally good results.

Last but not least, we should mention that implementing Hagedoorn's Plus-Minus method in Rayfract® gives a relatively accurate qualitative result i.e. the number and approximate position of possible fracture zones will be marked. However, the dimensions and velocity of these detected zones will be overestimated in relation to the modeled values. Therefore, inversion has to be designed accordingly to resolve this issue. Nevertheless, this is an intuitive procedure and if we unwillingly push too hard with the lowering of smoothing, inversion might result in underestimated zone velocities which could even be 500 m/s lower than the modeled value. This is something that we will take into consideration in the future.

Figure 2.1 illustrates that the Rayfract® software has much more options for processing data than we have been able to evaluate in this project. Our choices are guided by previous experience and advice given by Siegfried Rohdewald, the developer of the software.

Based on our experience achieved in this project, the best processing sequence for detection and characterization of fracture zones in bedrock using the Rayfract® software should be **multi-run Conjugate Gradient inversion method with Cosine-Squared weighting using Hagedoorn's Plus-Minus method to create the starting model (if possible) and with minimal WET smoothing**.

8.2 Location and characterization of fracture zones in bedrock

The main question regarding this report is whether it is possible to locate low-velocity zones using the Rayfract® software. The answer is a little bit more complex than a single yes or no, but the most satisfying response in our opinion is yes given that certain requirements are met. These requirements are controlled by the underground structure over which we have no control and the interpreter's competence and knowledge of the software. Qualitatively, vertical zones are easily detectable using tomographic inversion but the accurate calculation of their quantitative characteristics depends on the inversion scheme employed and is not as easily achieved.

Therefore, given that the user of Rayfract® has an adequate knowledge of the software, the above question can be rephrased as such: can we decisively compile inversion schemes that will help us characterize the zones with respect to velocity, width, depth extent and dip? The answer to this question is pretty much yes although a certain understanding of what kind of miscalculations each scheme may lead to is essential. This is what we believe this report offers: a documentation of the results obtained when using ‘conservative’ inversion schemes and the understanding these results provide judged by the synthetic models. In other words, we have documented both successes and failures of tomographic inversion in the detection of fracture zones and that can be put to use in future studies.

Generally, the specific inversion schemes that we came up with for the most complex cases may result in both **velocity** over and underestimations according to the ‘intensity’ of the parameter combination used. This intensity is always controlled by the smoothing parameters and how much we have limited smoothing prior to inversion. It is hard to predict the point at which the smoothing removal becomes too little or too much, but a simple comparison with the initial model created interactively with the Plus-Minus method can help. In all cases, the zones velocity detected using the Plus-Minus method in Rayfract® were overestimated. At this point, it is important to clarify what is meant by such descriptions. In all cases, we are referring to the velocity value of detected zones compared to the modeled one and not the effect that they might cause. Therefore, by overestimation we mean that the calculated velocity is higher than modeled (i.e. smaller velocity contrast with bedrock) and by underestimation we mean the exact opposite (i.e. higher velocity contrast).

Furthermore, **width** estimation appears to be good in the majority of cases. The zone **depth extent** is not always followed and seems to be limited to ca. 20 meters. This is probably due to the 48 geophone array used and the 5 m geophone spacing which has of course a maximum depth penetration under which resolution is lost. One additional explanation could be that the velocity contrast between overburden and bedrock is large and the seismic rays travel faster via the interface instead of inside the bedrock mass itself. The detection of the **inclination of a zone (dip)** on the other hand, has proven to be indicative but not easy to discern quantitatively. However, steeply dipping zones (over 45º deviation from the vertical) can be easily differentiated from the mildly dipping ones (below 45º).

The distinction of **overlaying soils** is limited by the number of branch points available for picking (1 or 2 per traveltime curve) which is in turn controlled by the shot and geophone spacing used. In most of our models, only 1 branch point (crossover point) per traveltime curve was possible to pick therefore all overburden layers were averaged into one layer (both in velocity and thickness). However, when only one soil layer was present, its depiction was as accurate as the picking of branch points. Subsequently, denser geophone spacing will allow the picking of one extra branch point per traveltime curve, i.e. one extra horizontal layer to be depicted. Denser shot-spacing will also improve the inversion result thus it is recommended to use the ideal shot coverage (2-3 times the geophone spacing), whenever possible.

8.3 Comparison between inverted data and tunnel geology, Knappe tunnel

After solidifying some efficient inversion schemes, we did a small scale reprocessing of the two Knappe profiles whose traditional interpretation offered the basis for our two complex models. The newer inversion results we obtained for these real data appear to be more sophisticated than the ones presented in Rønning et al. (2016), and they match the data collected after the construction of the tunnel better. Some discrepancies can be seen especially in profile P1_1, but the result is relatively satisfying. The reasons for these discrepancies could be focused in two points: 1. the fracture zones may be terminated above the level of the tunnel which is not reached by the seismic profiling and 2. some truncated zones can go deeper than indicated on the velocity sections as already shown. Regardless, in profile P_6-7 a fracture zone that has been verified in the tunnel and missed by the traditional interpretation, was detected using our most efficient inversion scheme. This highlights the fact that there is merit in using tomographic inversion on refraction seismic data.

8.4 Future work

As discussed in the previous sections, our modeling has not tested all inversion options in the Rayfract® software. The experience we have achieved so far is that generating a starting model using the Hagedoorn's Plus-Minus method produces good inversion results. However, starting model generated with the wave front and the deltatV methods should also be tested on a limited amount of models.

In our attempt to test soil cover thickness, we had 20 m as a maximum value. In a continuation of the project, we should test greater thicknesses to really see how thick the overburden can be before we miss an underlying fractured zone of different thicknesses in bedrock.

Reprocessing of seismic data from the Knappe tunnel gave much better results when we used new inversion routines included in the Rayfract® software in the spring 2017 (multi-run Conjugate Gradient inversion). Inversion of all the data from the Knappe tunnel and comparison with resistivity data and results from tunnel excavation should be performed to get an updated evaluation of the tomographic inversion of seismic data using the Rayfract® software to locate and characterize fracture zones in bedrock.

9 CONCLUSIONS

In this report we have investigated the response of several synthetic models of variable complexity to tomographic inversion performed with Rayfract®. Through this process it has been clearly demonstrated that this is a fairly advanced and complex software which offers many different options and paths when inverting refraction seismic data. Its level of complexity makes it necessary for the user to have a fairly good knowledge of its parameters in order to obtain successful results, or at least to identify possible miscalculations.

When investigating the detection of fracture zones in bedrock, the software's parameters may be roughly grouped in three main categories: the inversion and update weighting method used, whether single or multi-run will be employed and the intensity of the smoothing. **We have discerned that multi-run Conjugate Gradient inversion method, with Cosine-Squared weighting and a 2D Plus-Minus starting model can give pretty good results.** However, the task that requires closer attention is choosing the parameters which will result in minimal smoothing. Low smoothing is essential for the quantitative characteristics of the detected zones to be calculated accurately, but this is a hyper sensitive procedure which may result in over or underestimations of zone velocity and in artefacts. Regardless of this, the complexity of Rayfract® guarantees that a successful combination is not unique in each case, which allows us some flexibility when processing and interpreting such data.

One important factor when determining how much to smooth is the shot and receiver spacing and the quality of the first break picks. Considering that during this modeling procedure our picks were as good as they could be and the geophone and shot spacing dense enough for the structures modeled to be detected, smoothing should not be a key factor and it should be minimized. However, it was shown that different cases called for different smoothing intensity. In addition, non-uniqueness of first break traveltime is a well known fact which is not connected with the software's complexity. It is rather that the problem at hand requires a complex set of available options and tools in order to be solved efficiently.

Generally, this modeling procedure has deemed it possible to locate and characterize fractured zones in bedrock albeit with some limitations. It has been found that the **position and inclination of zones (dip)** can be problematic especially when the zones are neighboring bedrock areas with small velocity contrast. The depth extent of modeled zones is limited and this is unavoidable from a certain depth and below (geological noise). Depth extend of fracture zones can be followed to a certain depth, but deep zones give the same response as shallow zones. The width of the zone is almost always quite close to reality and the overburden layers can be precisely defined when the interactive picking of branch points prior to inversion is done carefully. The soil thickness can also be resolved, but this is dependent on the possibilities to pick a sufficient number of branch points (crossover points). The velocity of a zone can be accurately calculated with right inversion parameter combination. Moreover, as was seen in reprocessing some the Knappe tunnel real data, tomographic inversion can pick up detailed zones that cannot be interpreted traditionally. Denser shot point and receiver spacing can bring about a noticeable improvement on the inversion results. Therefore, if there is a possibility for more shots when conducting a refraction seismic survey, they should be realized since they strengthen tomographic inversion processing.

Further information on the results of this report such as ray coverage graphs, can be obtained by contacting the authors.

10 REFERENCES

Barton, N. 2007: Rock quality, seismic velocity, attenuation and anisotropy. Taylor & Francis, London 2007, page 92.

Hagedoorn, J.G. 1959: The Plus-Minus method of interpreting seismic refraction sections. Geophysical Prospecting 7 (2), pp.158 – 182.

Lecomte, I., Gjøystdal, H., Dahle, A. & Pedersen, O.C. 2000: Improving modelling and inversion in refraction seismic with a first-order Eikonal solver. Geophysical Prospection, vol. 48, pp. 437 – 454.

Rayfract 2016a: Rayfract Seismic Refraction & Borehole Tomography- Subsurface Seismic Velocity Models for Geotechnical Engineering and Exploration. Downloaded from http://rayfract.com.

Rayfract 2016b: Rayfract help. Download from http://rayfract.com/help/rayfract.pdf

Reiser, F., Dalsegg, E., Dahlin, T., Ganerød, G.V. & Rønning, J.S. 2010: Resistivity Modelling of Fracture Zones and Horizontal Layers in Bedrock. NGU Report 2009.070 (117 pp.).

Rønning, J.S., Tassis, G., Kirkeby, T. & Wåle, M. 2016: Retolking av geofysiske data og sammenligning med resultater fra tunneldriving, Ringveg Vest i Bergen. NGU Report 2016.048 (48 pp. in Norwegian).

Schuster, G.T. & Quintus -Bosz, A. 1993: Wavepath eikonal traveltime inversion: Theory. Geophysics vol. 58, pp. 1314 – 1323.

Watanabe, T., Matsuoka, T. & Ashida, Y. 1999: Seismic traveltime tomography using Fresnel volume approach. SEG Technical Program Expanded Abstracts 1999: pp. 1402-1405. https://doi.org/10.1190/1.1820777

Wåle, M. 2009: Refraksjonsseismiske undersøkelser Ringveg vest, byggetrinn 2 Sandeide-Liavatnet. GeoPhysix, Rapport nr. 09171 (in Norwegian).

GEOLOGICAL
SURVEY OF
NORWAY
- NGU -

Geological Survey of Norway
PO Box 6315, Sluppen
N-7491 Trondheim, Norway

Visitor address
Leiv Eirikssons vei 39
7040 Trondheim

Tel (+ 47) 73 90 40 00
E-mail ngu@ngu.no
Web www.ngu.no/en-gb/