Feasibility of anisotropic inversion based on P-wave travel–time curves

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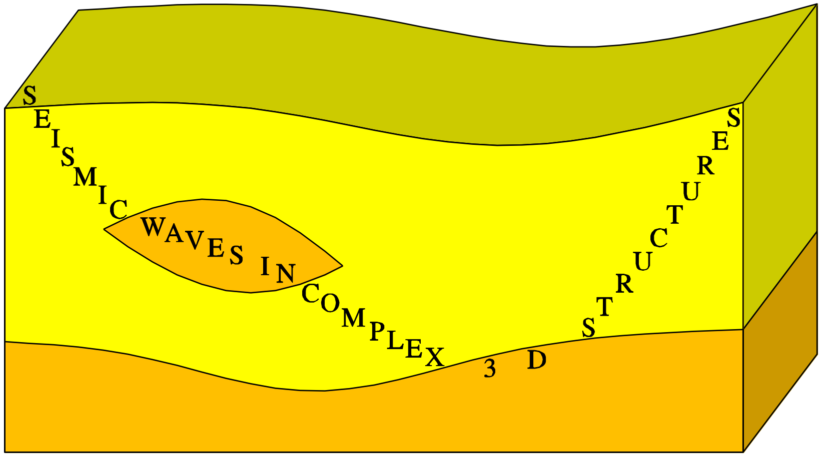


http://sw3d.cz

IWSA 2018 meeting, Jerusalem, Israel, November 4-9. 2018

Motivation

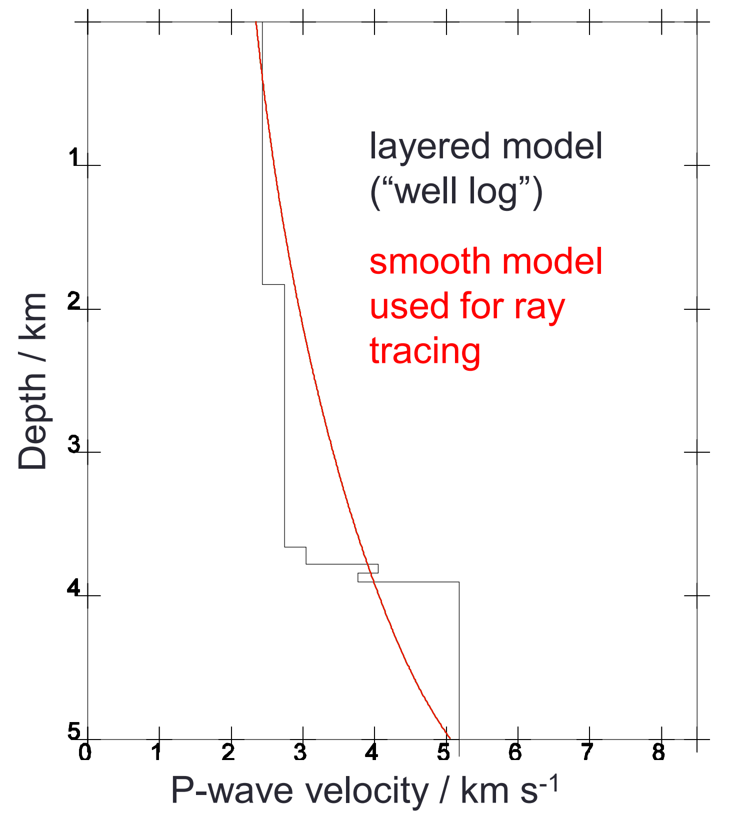
- a site with known 1-D P-wave velocity model
- a refracted P-wave travel-time measurement is planned at the surface
- - which structural features can be resolved ???

  - can we resolve the anisotropy caused by vertical cracks ???

  - how to optimize the measurement settings ???

Methodology

- We build velocity models
  - use realistic velocities simulating a well log
  - smooth the velocities to obtain model suitable for ray tracing
  - prepare several versions of possible models:
    - smooth continuous model
    - model with two layers separated by structural interface with velocity discontinuity
    - models with vertical cracks causing anisotropy
    - models with inclined interface
    - models with low-velocity channels



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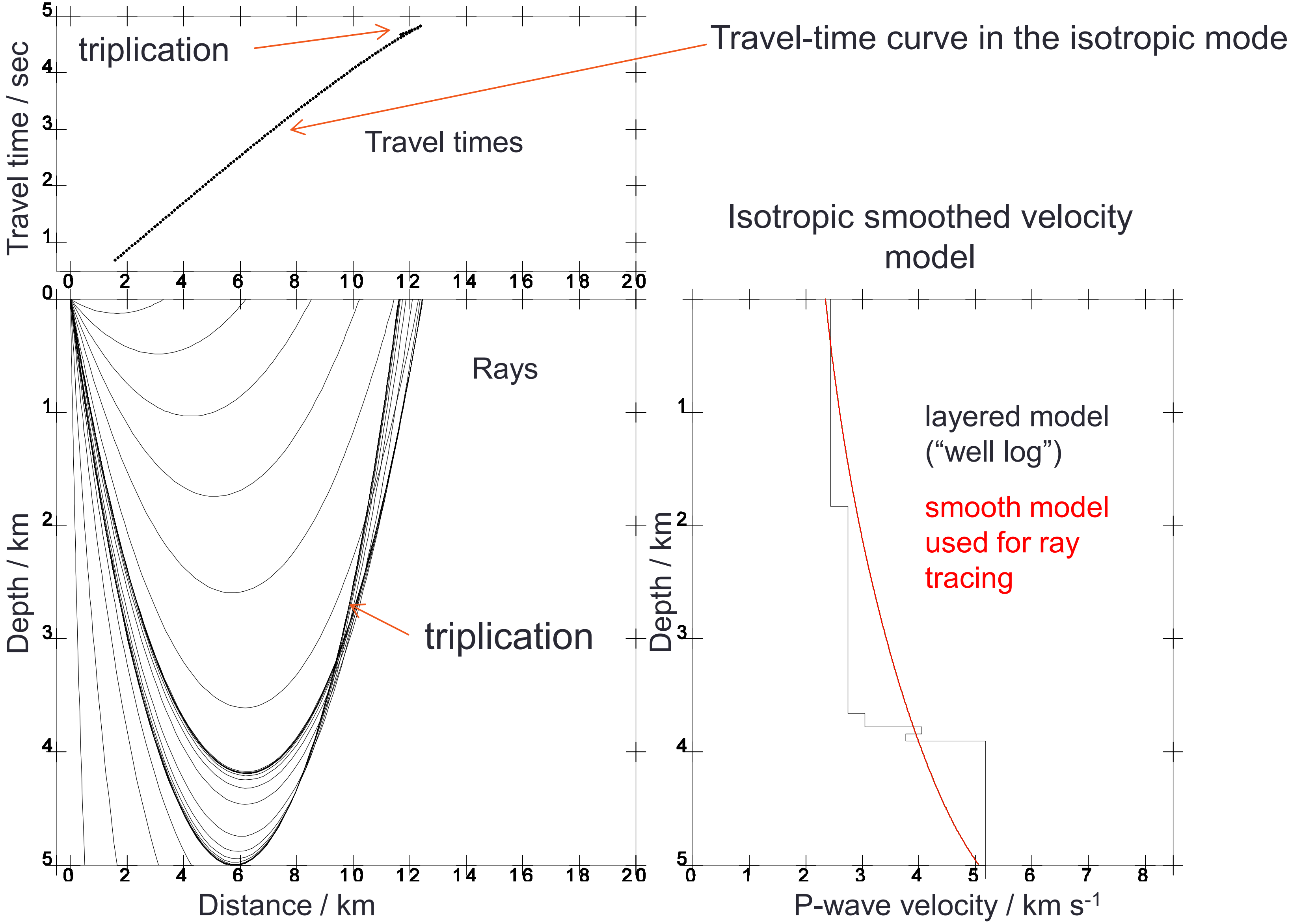
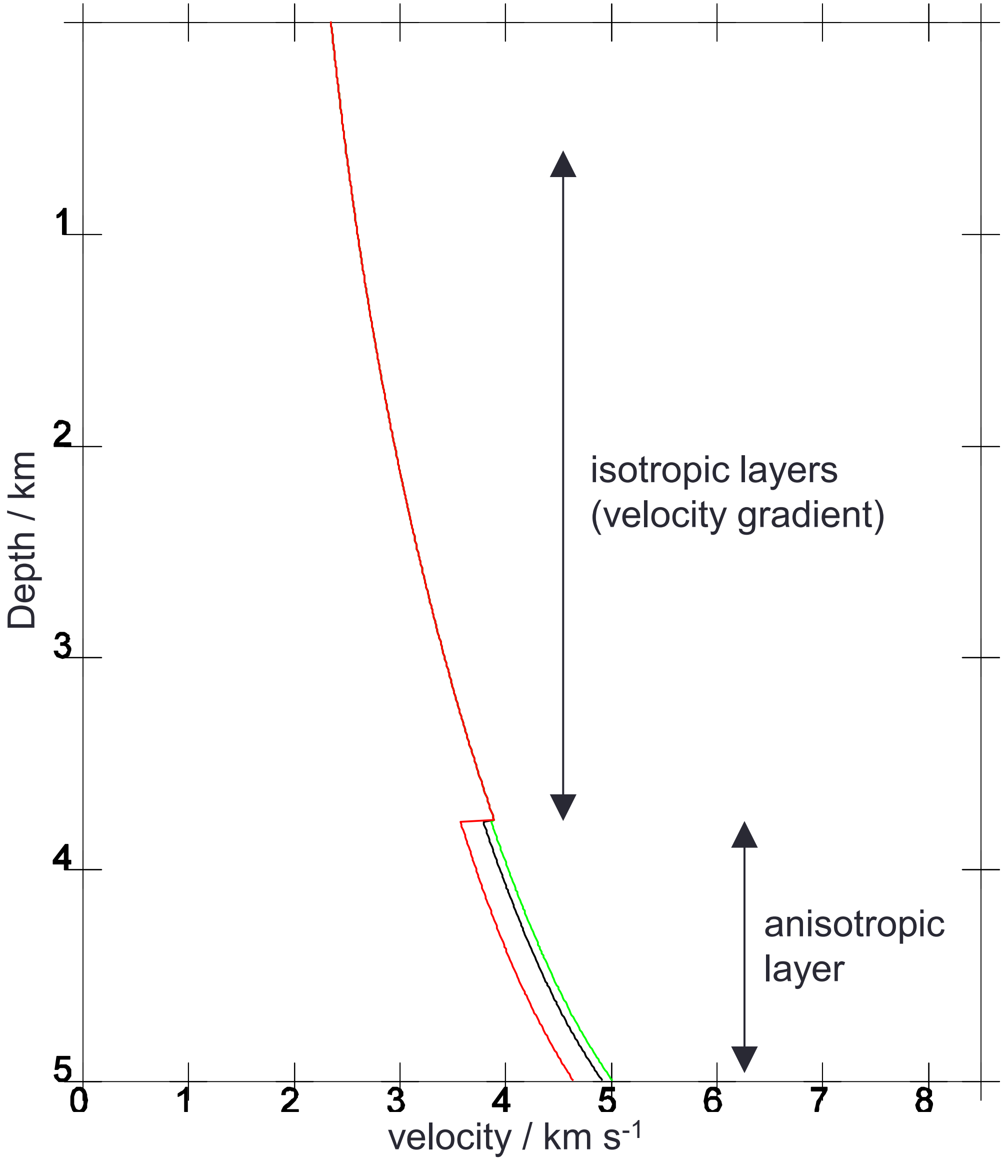
- Trace P-wave refracted rays through the models, calculate the travel-time curves, and analyze the influence of the models on the travel-time curves in order to understand which structural features can be resolved from the surface measurement of the refracted P-wave travel-time curves.

Isotropic model



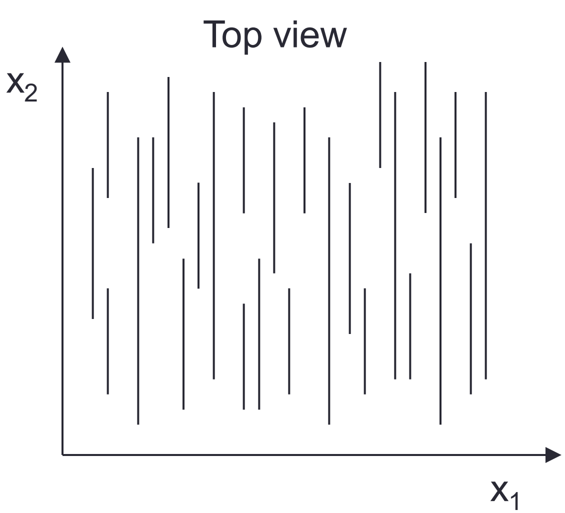
Building of the anisotropic model from fracture density

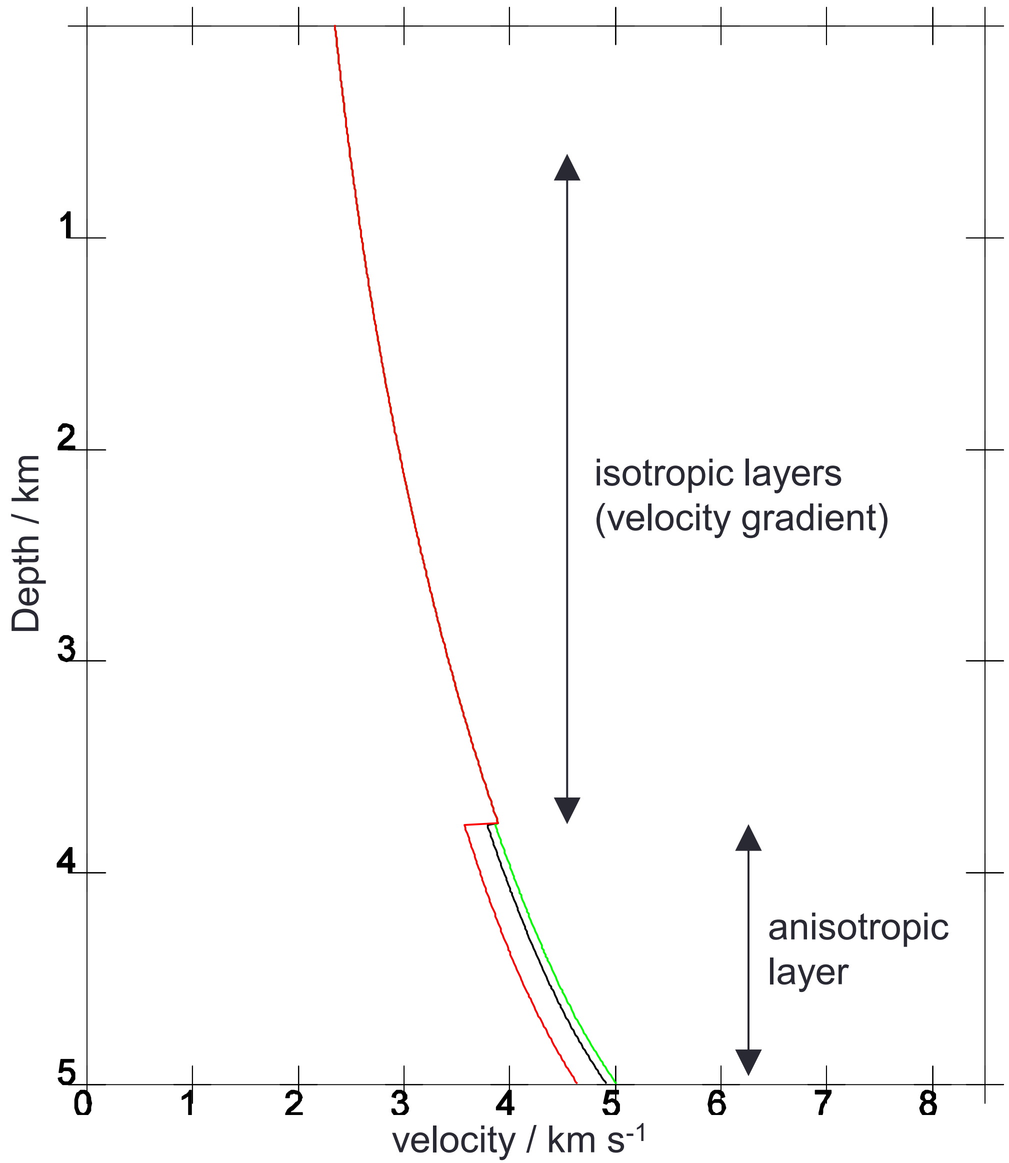
- Overburden: isotropic
- Lower layer: contains cracks
  => anisotropic layer



Building of the anisotropic model from fracture density

- Overburden: isotropic
- Lower layer: contains cracks
  => anisotropic layer
- Cracks are oriented parallel to x_2 direction





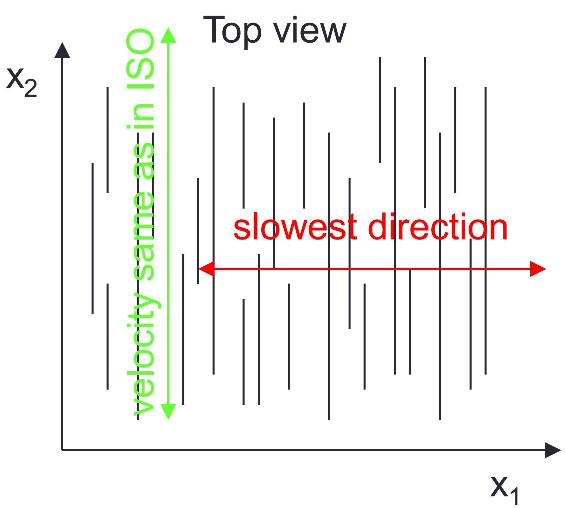
Building of the anisotropic model from fracture density

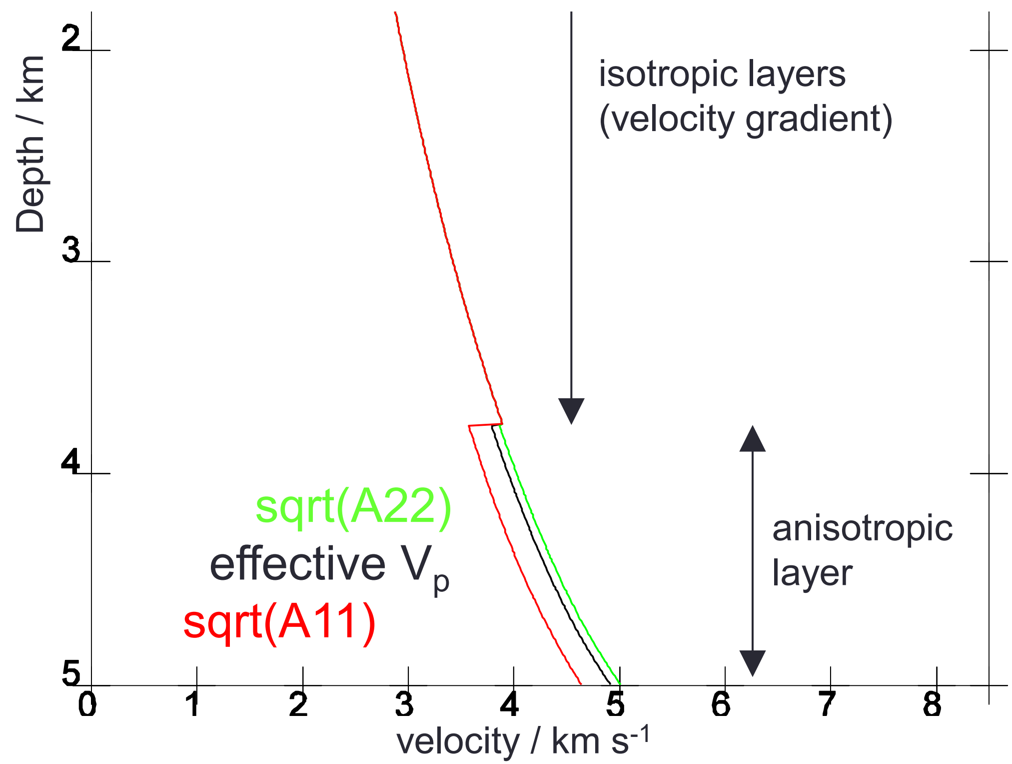
Cracks are oriented parallel to the x_2 direction
=> propagation in the x_1 direction is slower, while propagation in the x_2 direction remains almost unchanged
($\sqrt{A11} < V_p^{iso}$, $\sqrt{A22} \sim V_p^{iso}$)

stiffness tensor A_{ij}:

$$\begin{array}{cccccc} A_{11} & A_{12} & A_{13} & A_{14} & A_{15} & A_{16} \\ & A_{22} & A_{23} & A_{24} & A_{25} & A_{26} \\ & & A_{33} & A_{34} & A_{35} & A_{36} \\ & & & A_{44} & A_{45} & A_{46} \\ & & & & A_{55} & A_{56} \\ & & & & & A_{66} \end{array}$$

in isotropic model $A_{11}=A_{22}=A_{33}=(v_p)^2$





Estimation of the material parameters of the anisotropic layer:

- isotropic background + dry penny-shaped cracks
- theory by Schoenberk & Sayers (1995) in the description by Grechka (2009)

Estimation of the material parameters of the anisotropic layer:

- isotropic background + dry penny-shaped cracks
- theory by Schoenberk & Sayers (1995) in the description by Grechka (2009)
- cracks understood as sources of extra strain in the medium, described by additional term $\Delta\mathbf{S}$ to the background compliance tensor $\mathbf{S}_b$:

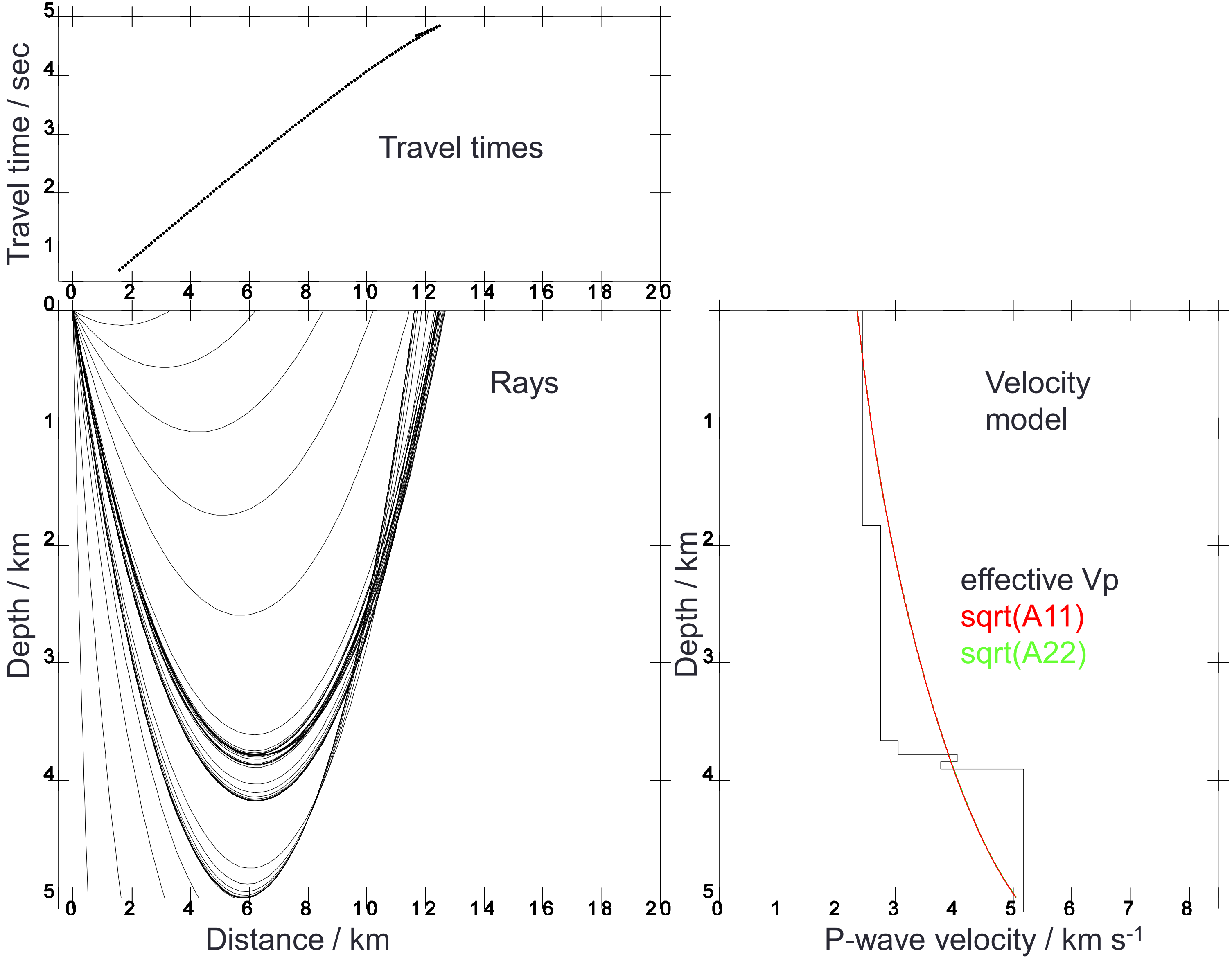
$$\mathbf{S}_e = \mathbf{S}_b + \Delta\mathbf{S}$$

where $\mathbf{S}_e$ is the effective compliance tensor of the medium, defined as inverse to the effective stiffness tensor $\mathbf{C}_e$:

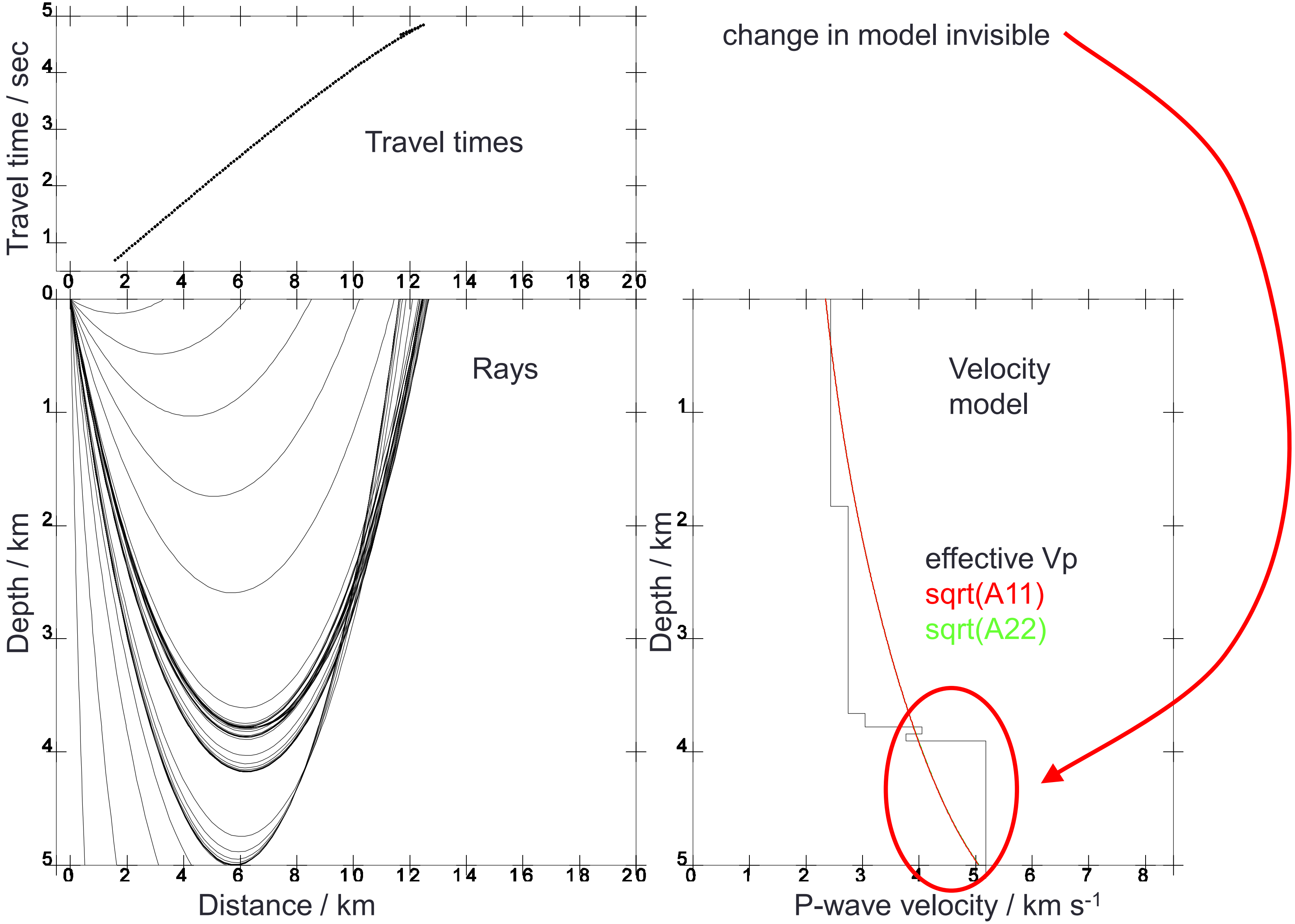
$$\mathbf{S}_e = (\mathbf{C}_e)^{-1}$$

- degree of anisotropy given by crack density *e*

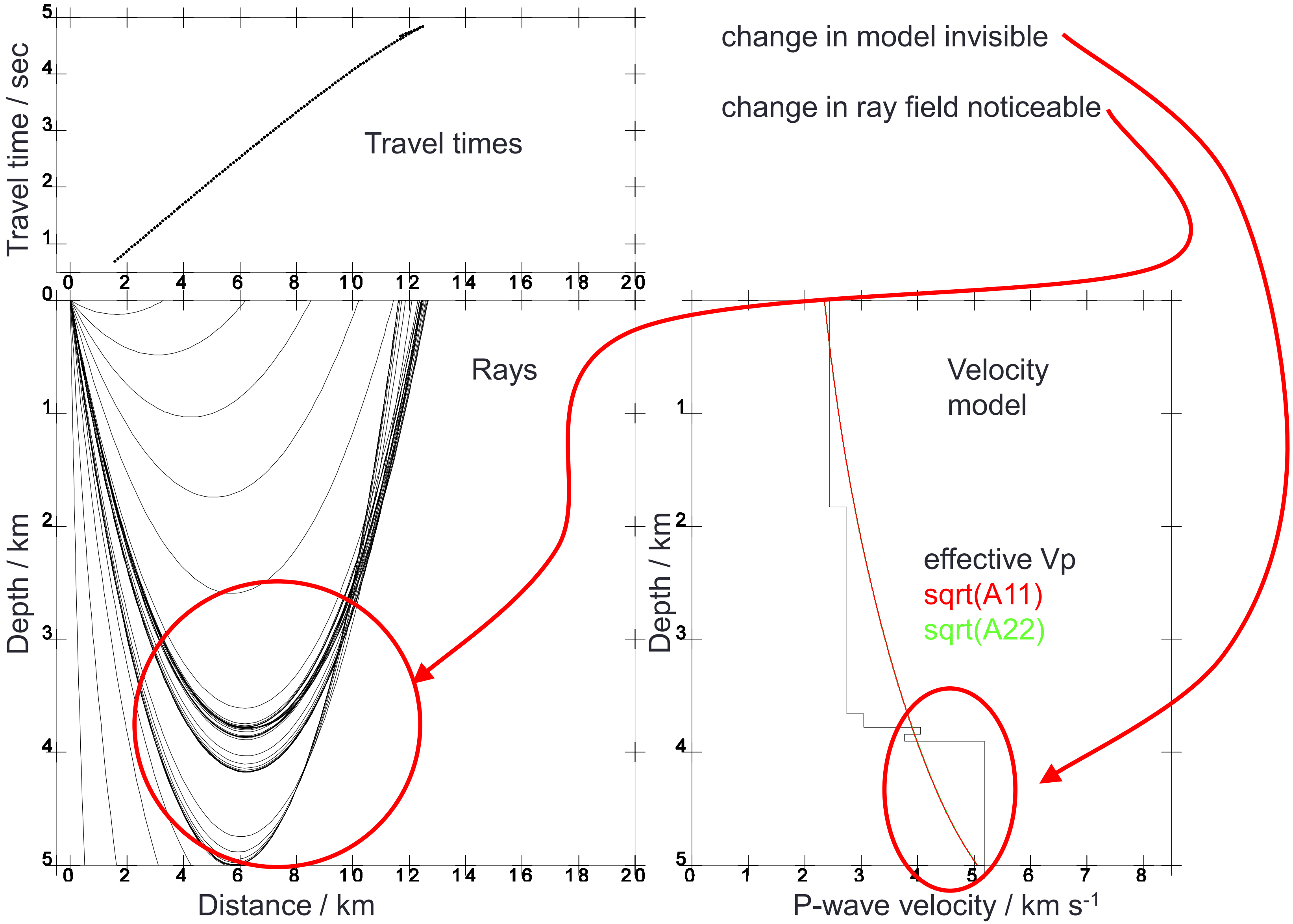
Anisotropic model 1 – crack density *e* = 0.0003



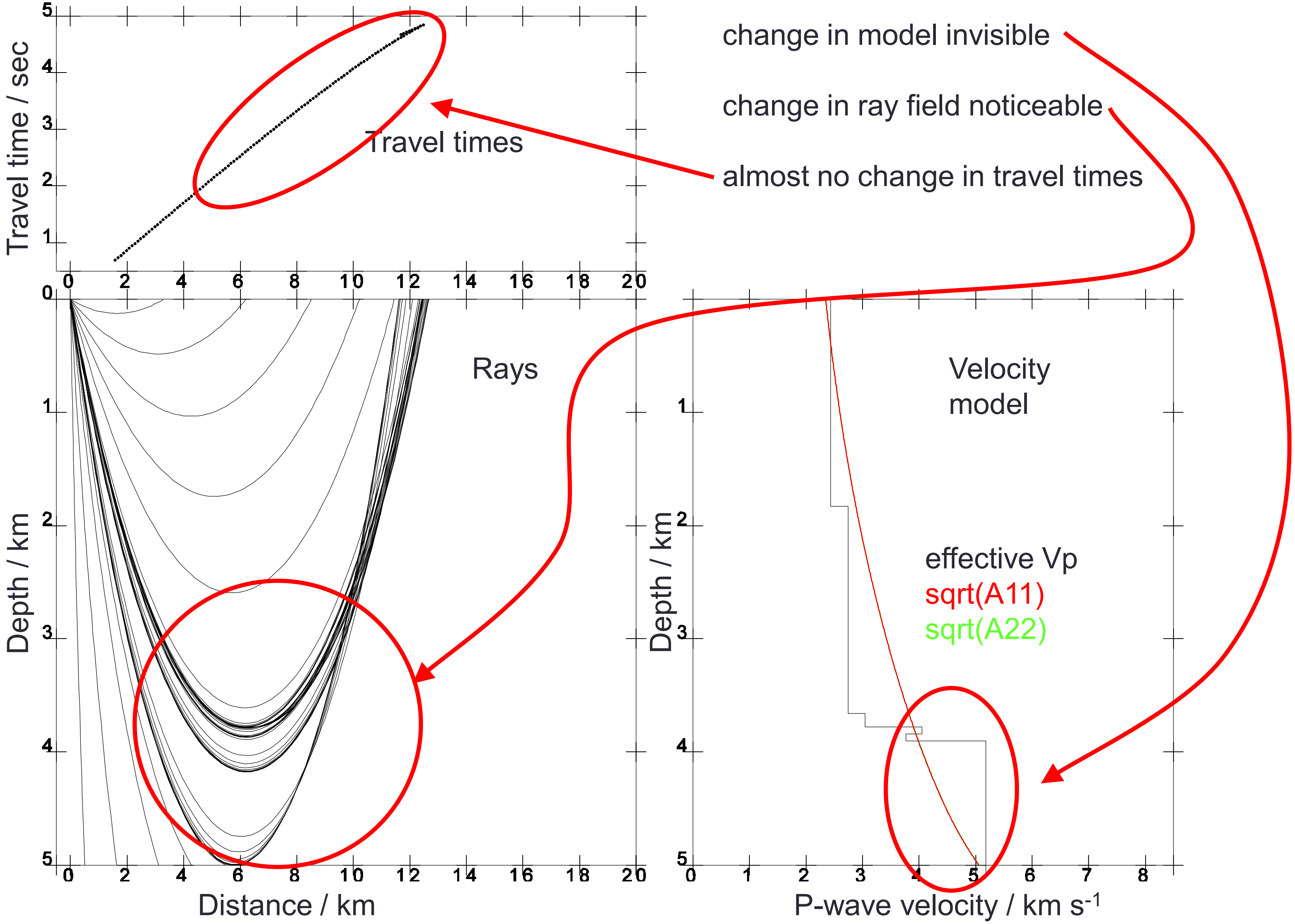
Anisotropic model 1 – crack density *e* = 0.0003



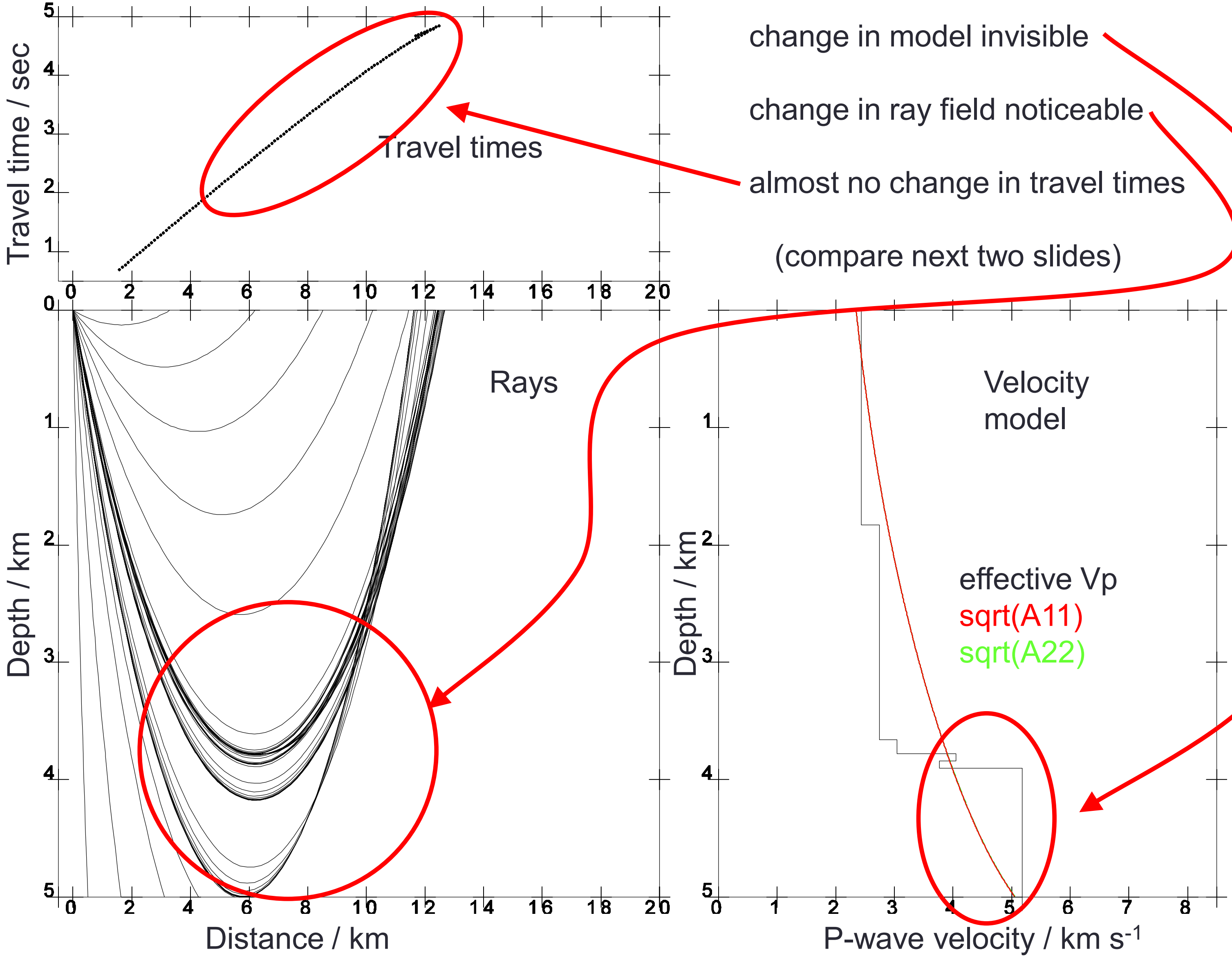
Anisotropic model 1 – crack density e = 0.0003



Anisotropic model 1 – crack density *e* = 0.0003



Anisotropic model 1 – crack density e = 0.0003



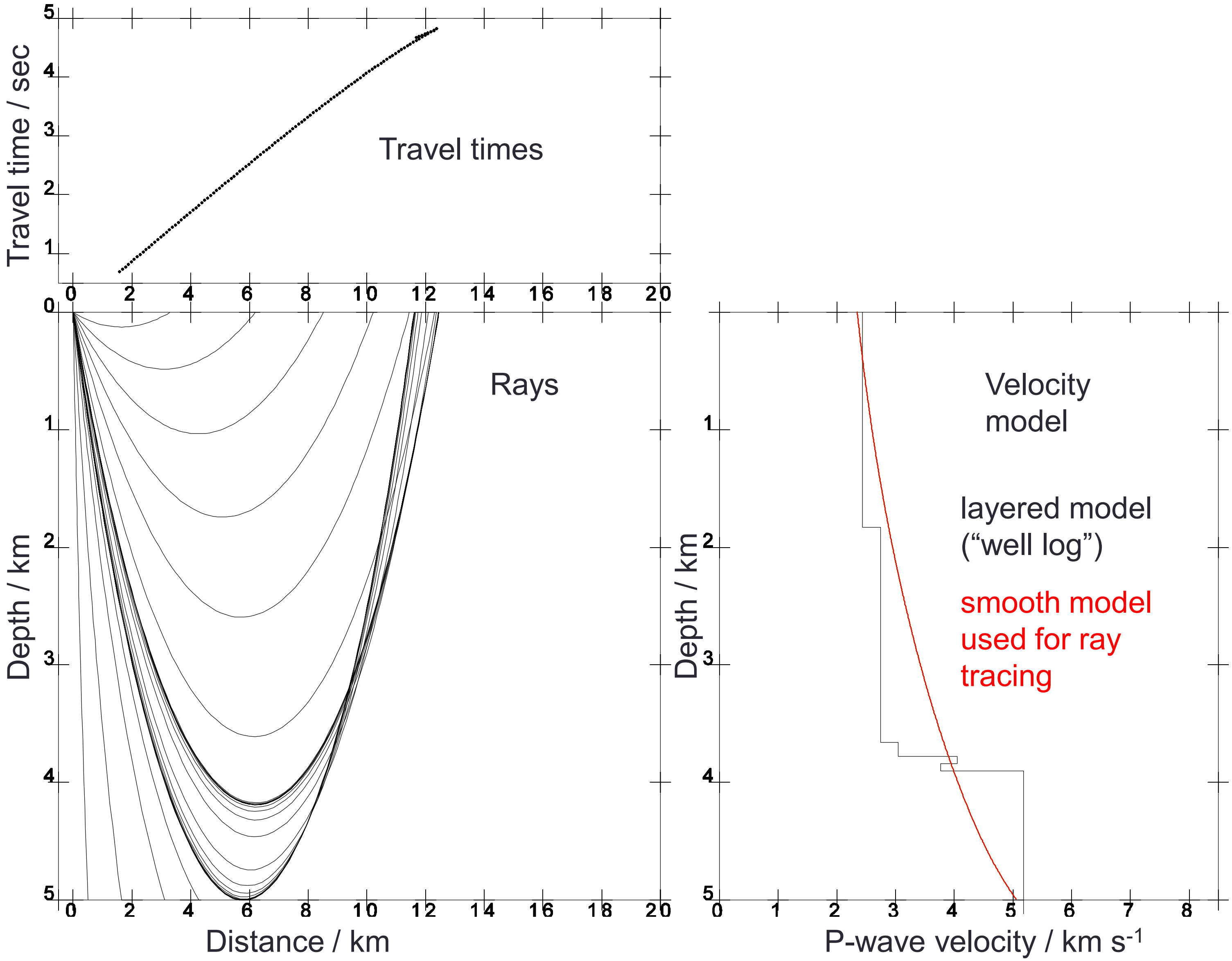
change in model invisible

change in ray field noticeable

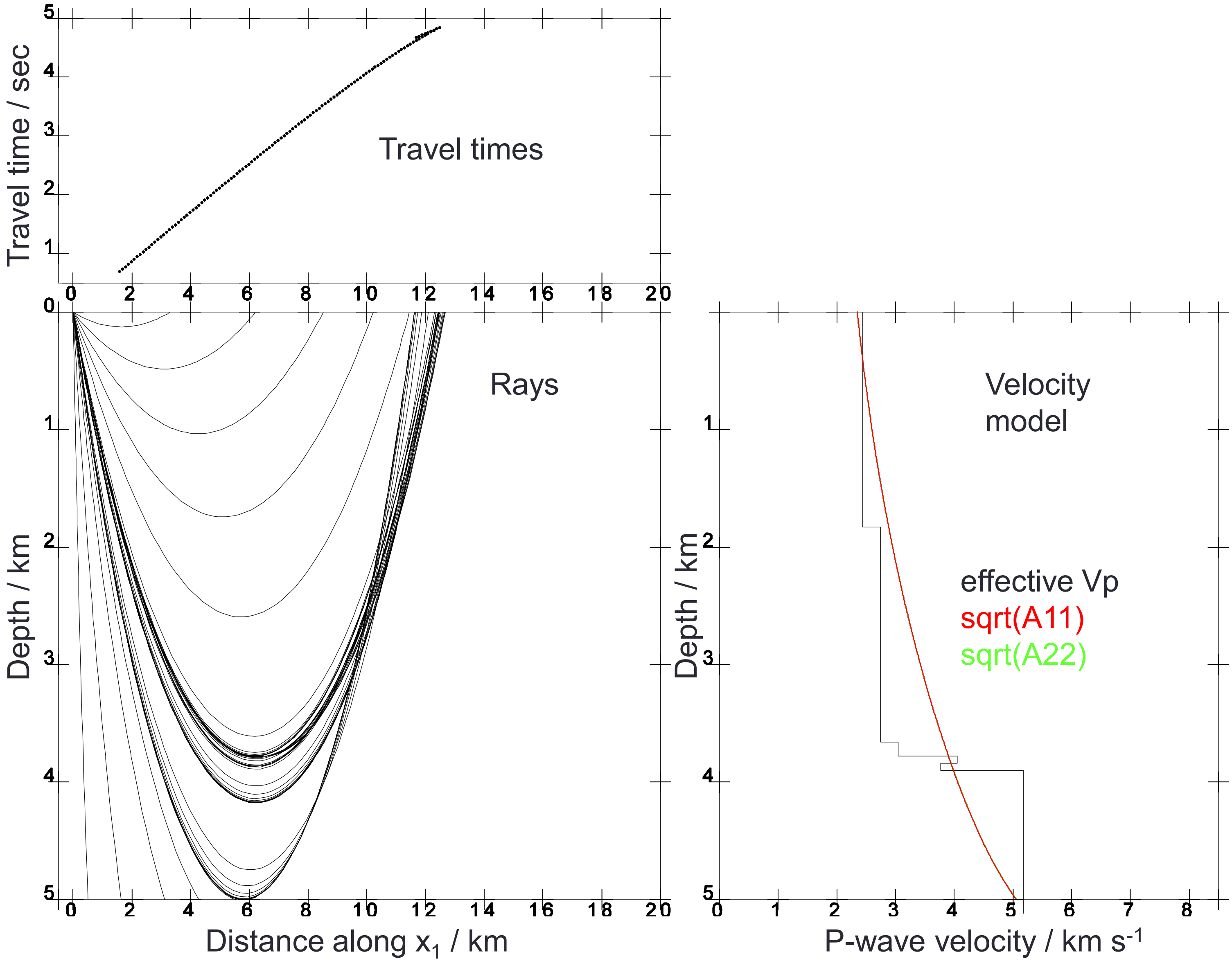
almost no change in travel times

(compare next two slides)

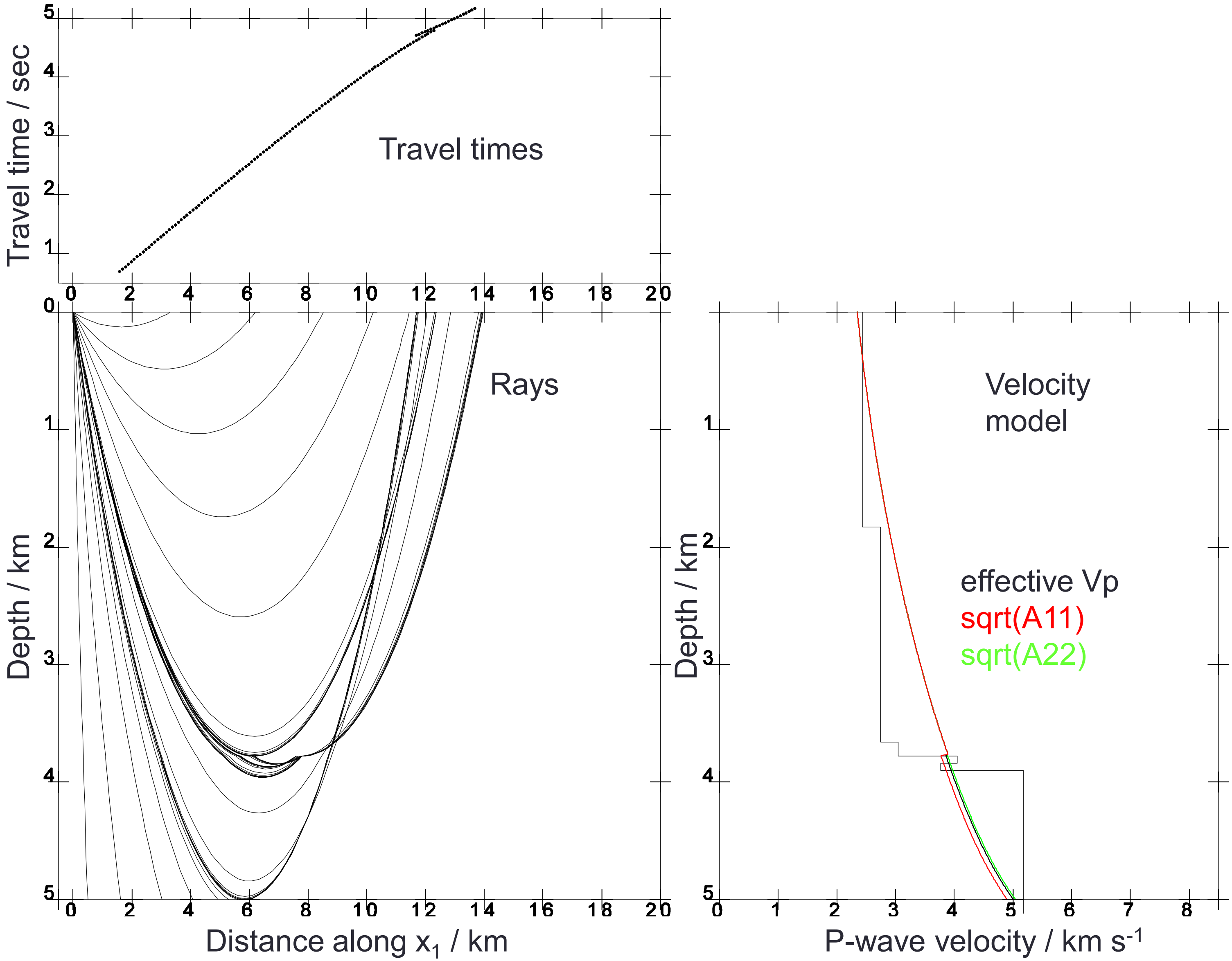
Isotropic model



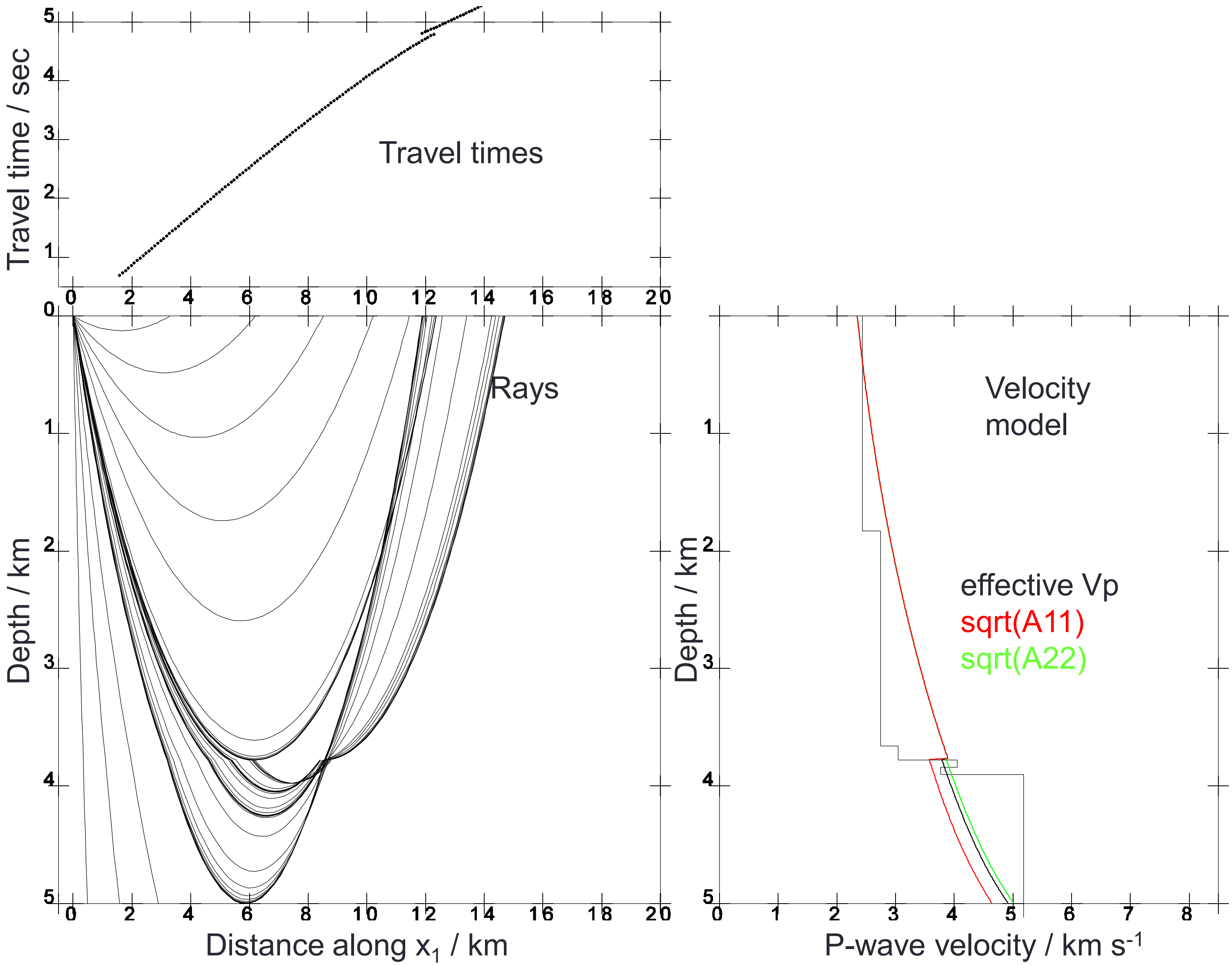
Anisotropic model 1 – crack density e = 0.0003



Anisotropic model 2 – crack density e = 0.001



Anisotropic model 3 – crack density e = 0.03



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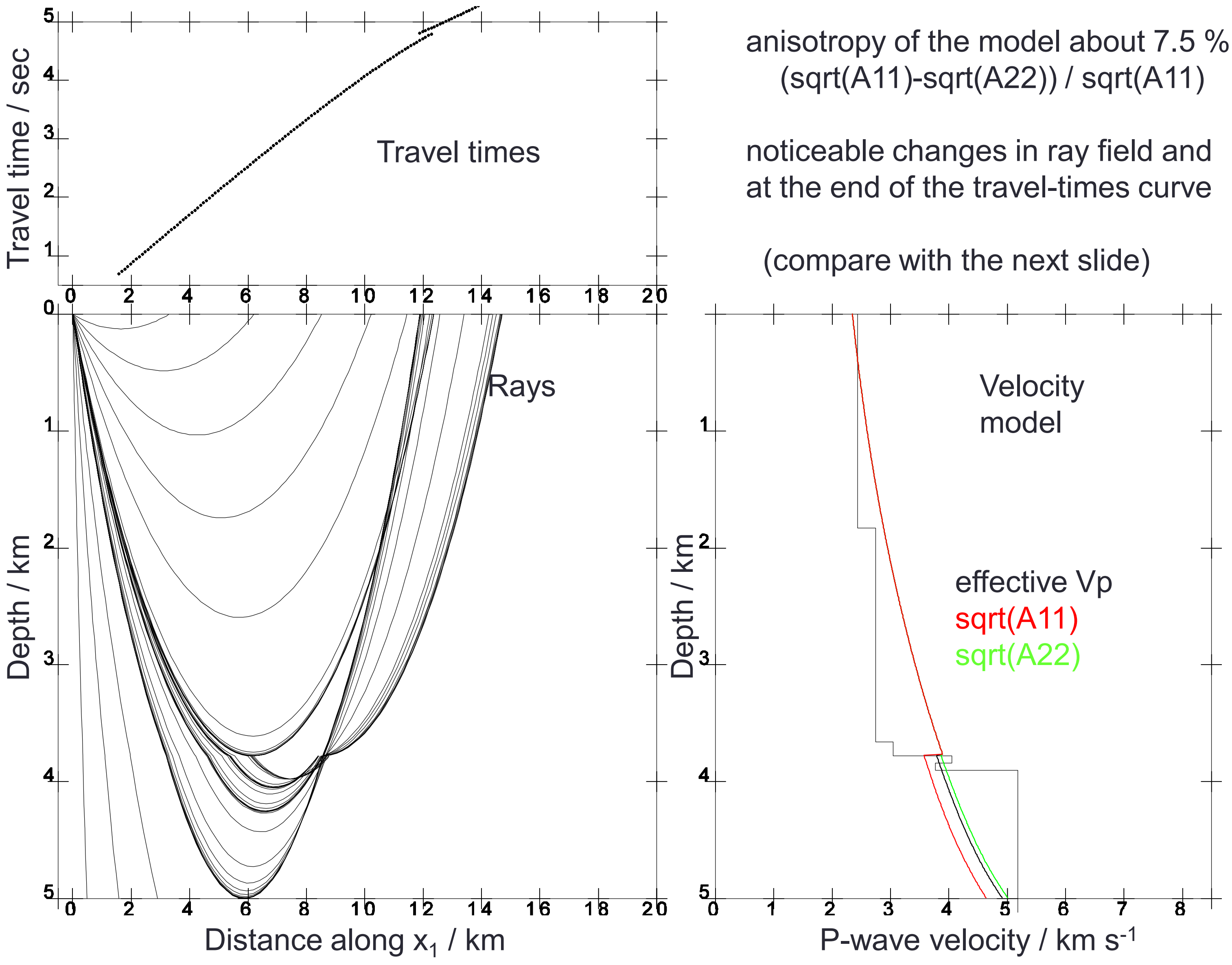
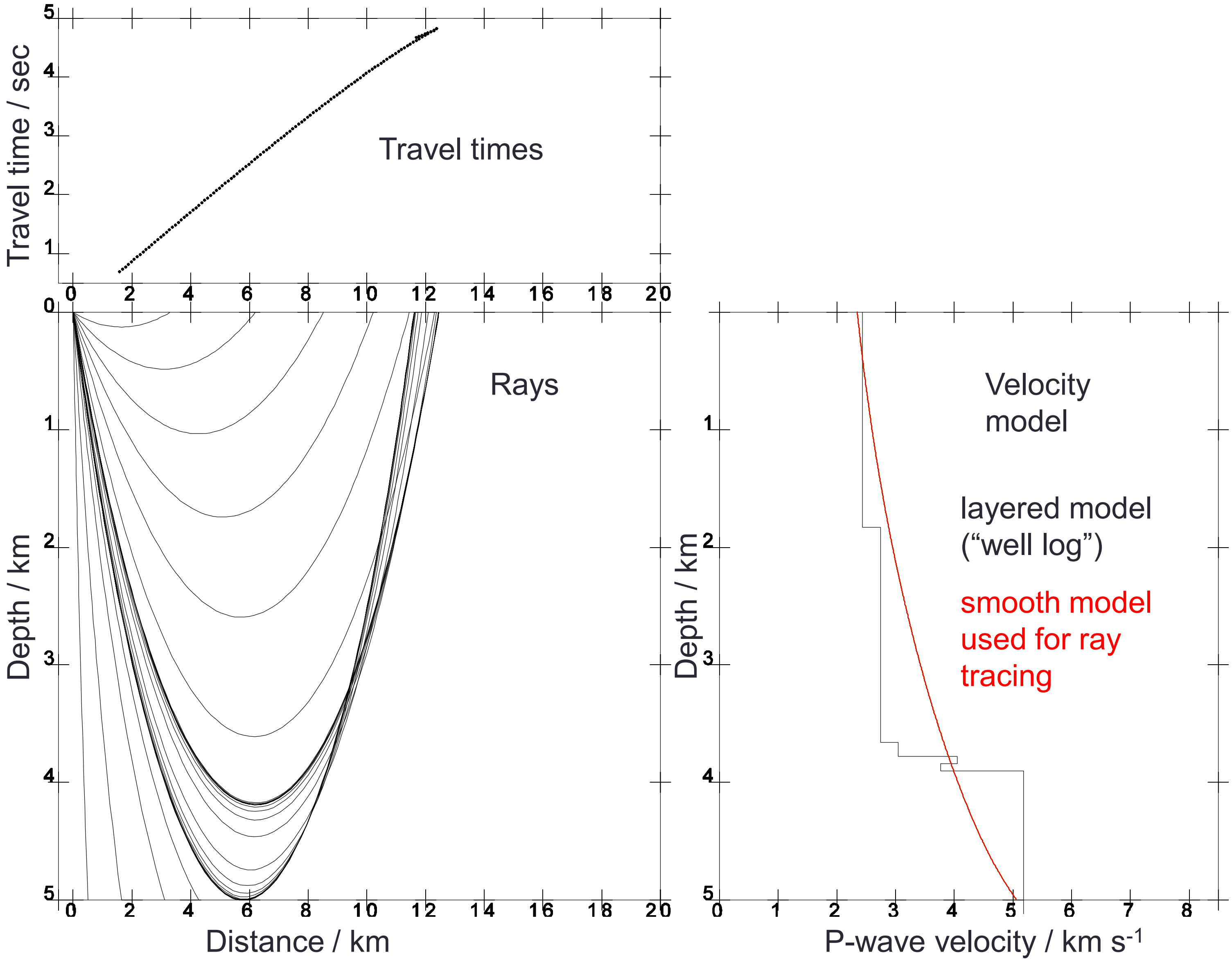


anisotropy of the model about 7.5 %
(sqrt(A11)-sqrt(A22)) / sqrt(A11)

noticeable changes in ray field and at the end of the travel-times curve

(compare with the next slide)

Isotropic model

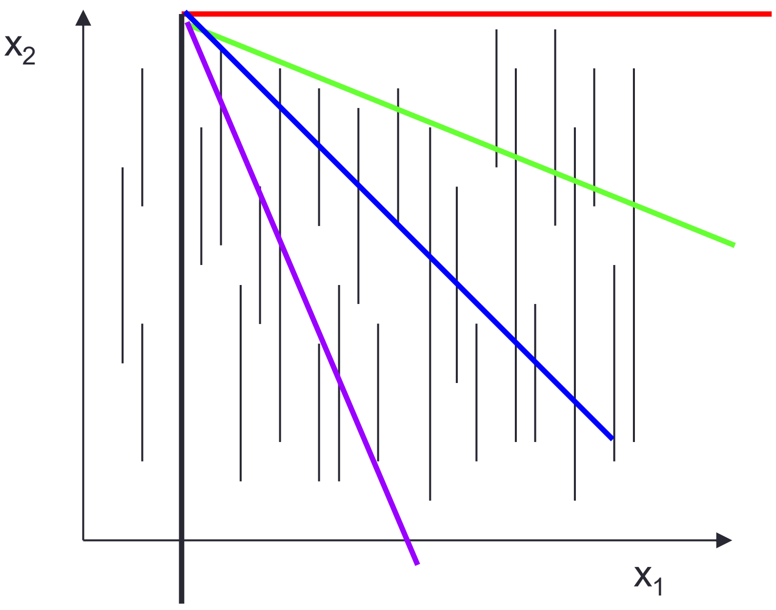


Anisotropic model 3 – crack density *e* = 0.03

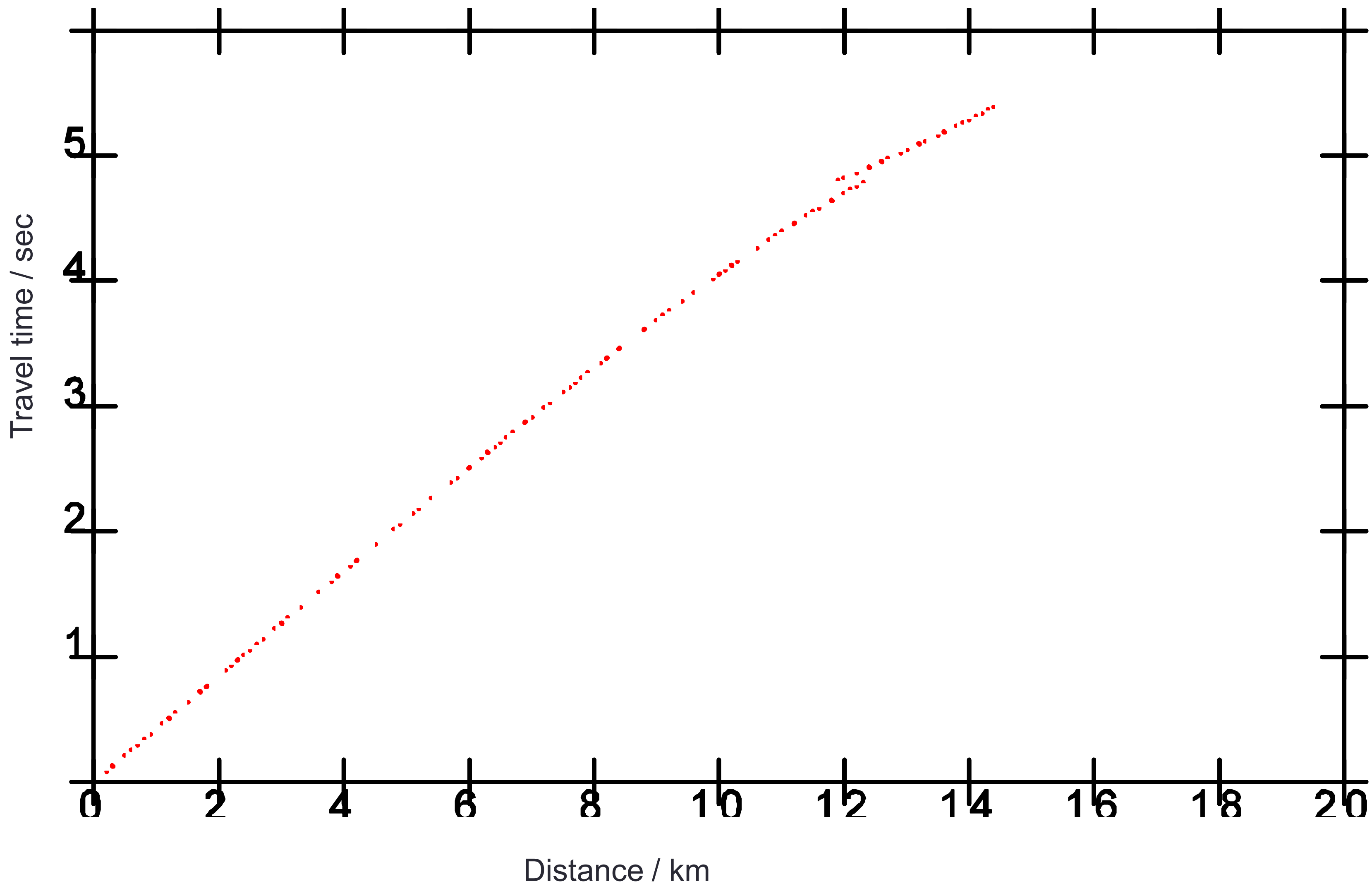
5 profiles at the surface of the model:

0 degree
22.5 degree
45 degree
67.5 degree
90 degree (with respect to x_1 direction)

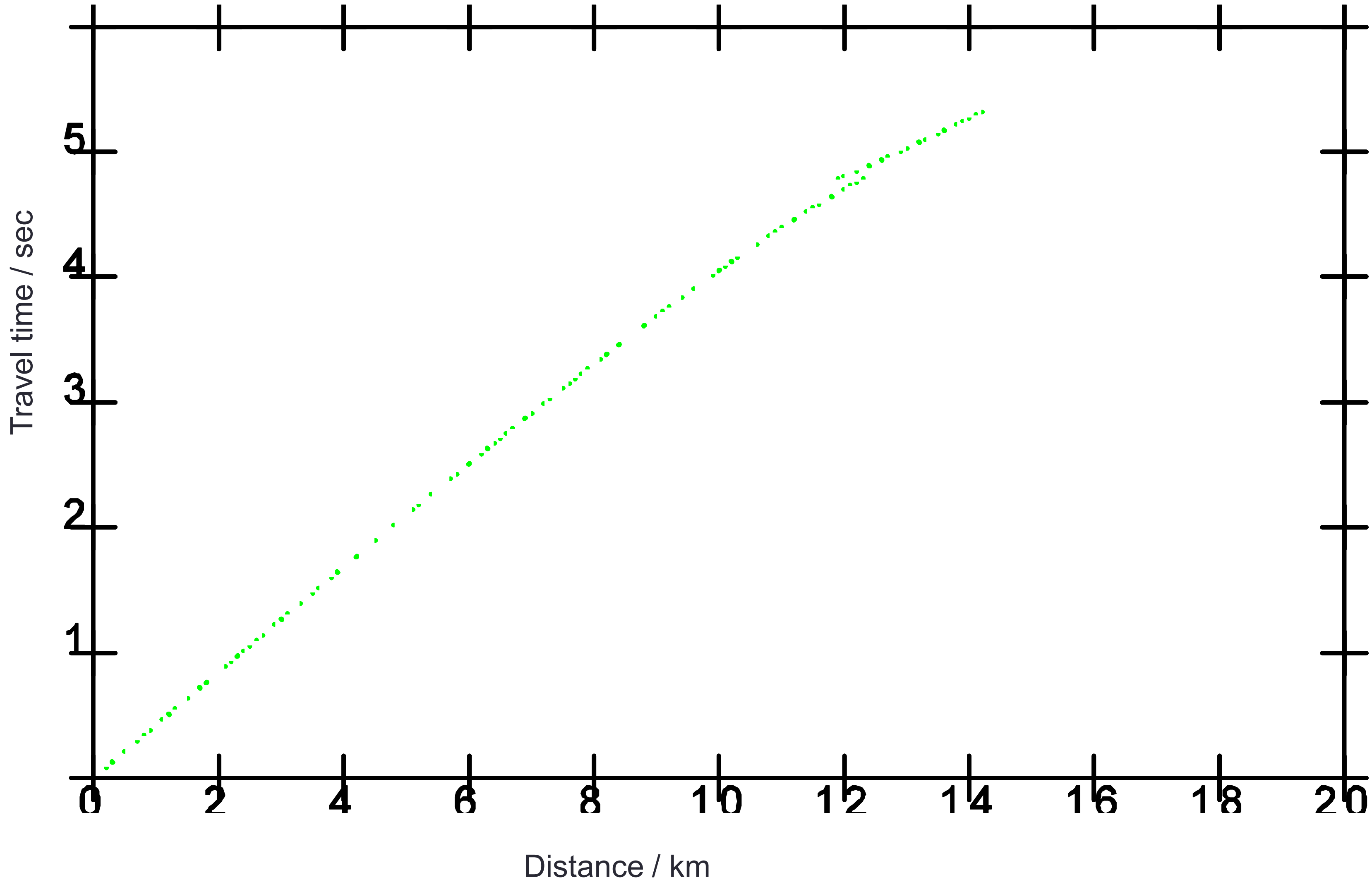
Top view



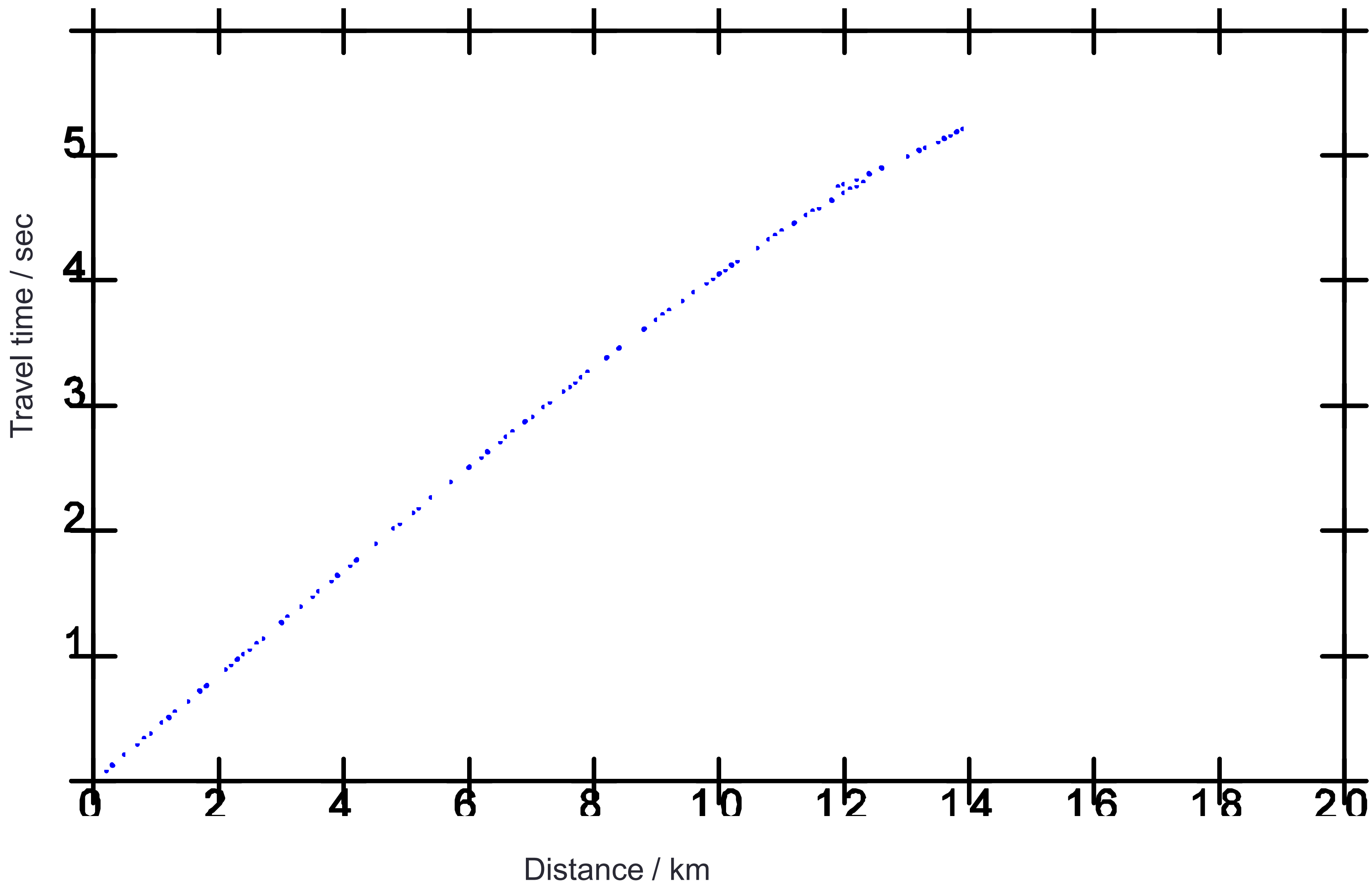
Anisotropic model 3 – crack density *e* = 0.03 - profile 0 degree



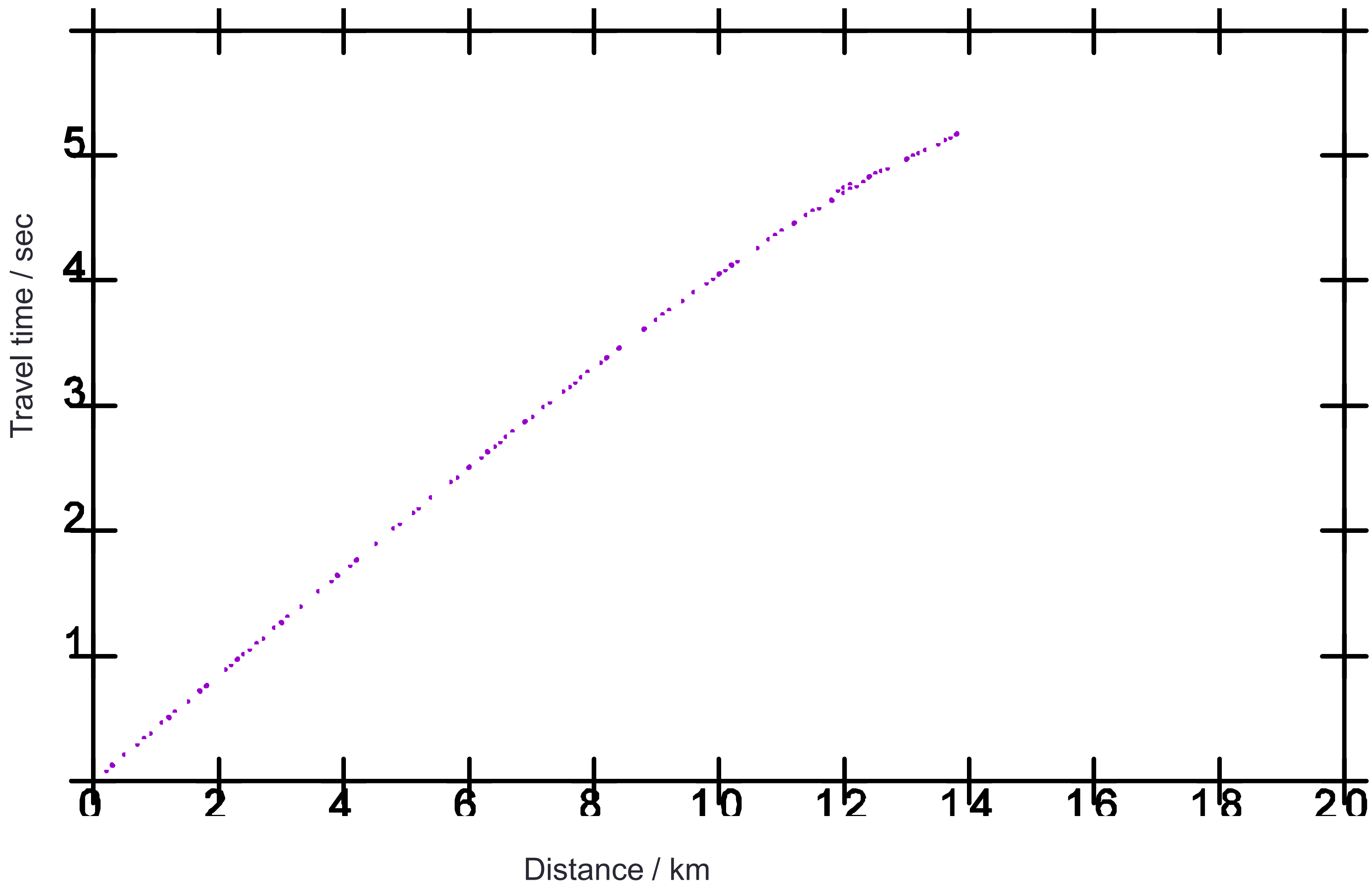
Anisotropic model 3 – crack density e = 0.03 - profile 22.5 degree



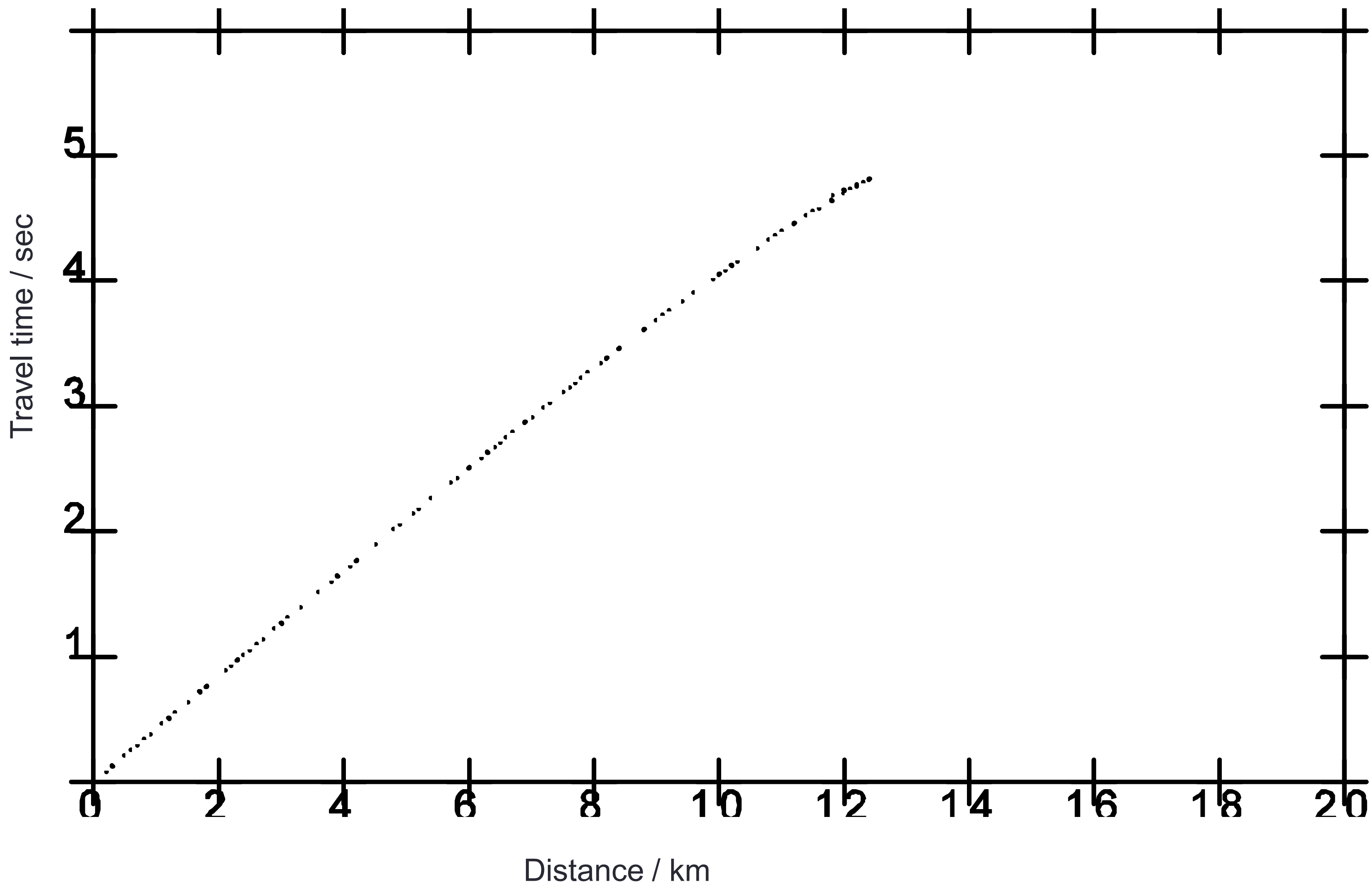
Anisotropic model 3 – crack density e = 0.03 - profile 45 degree



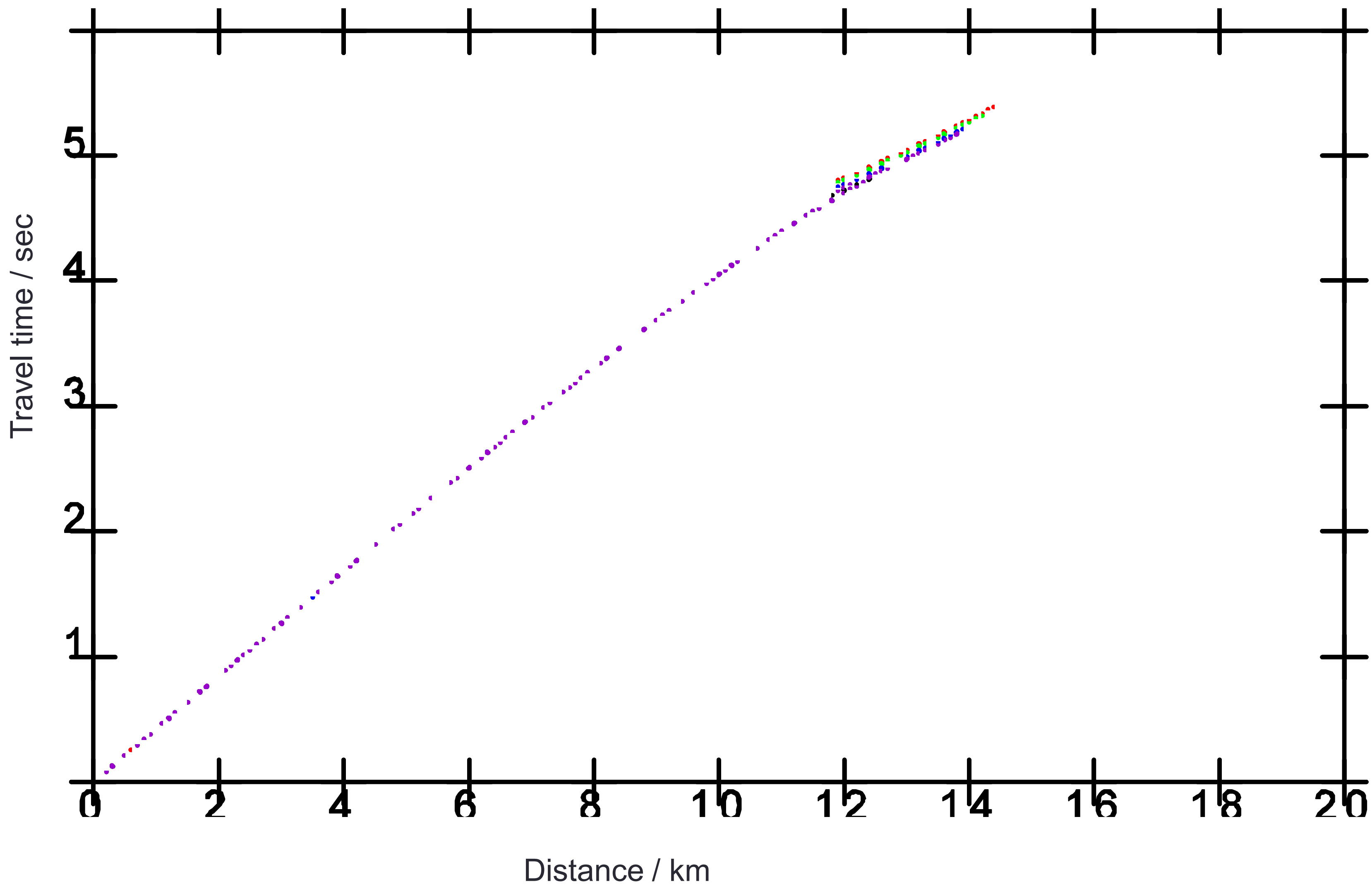
Anisotropic model 3 – crack density *e* = 0.03 - profile 67.5 degree



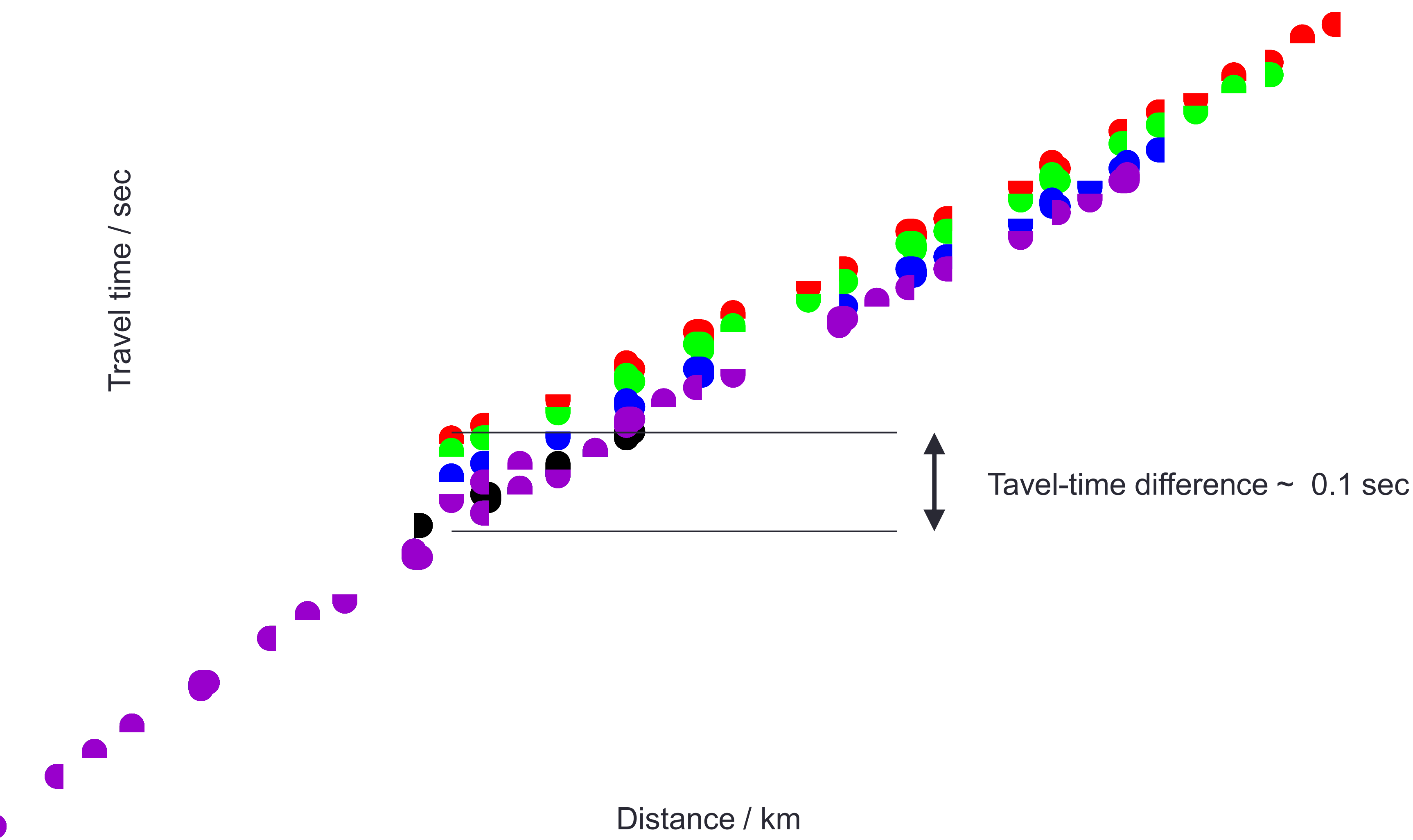
Anisotropic model 3 – crack density e = 0.03 - profile 90 degree



Anisotropic model 3 – crack density e = 0.03 - all profiles



Anisotropic model 3 – crack density *e* = 0.03 - all profiles - detail

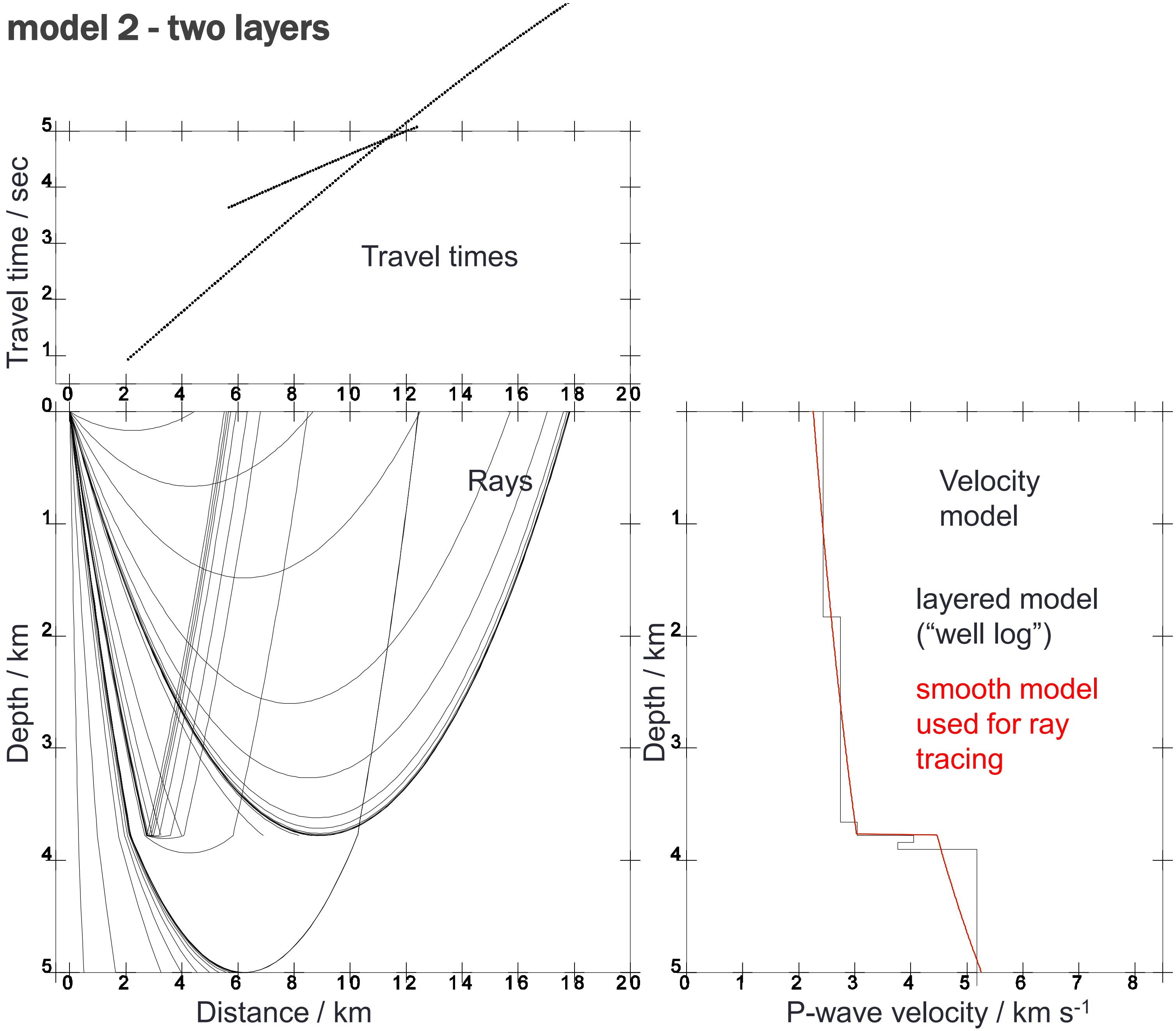


Isotropic versus anisotropic model - conclusions

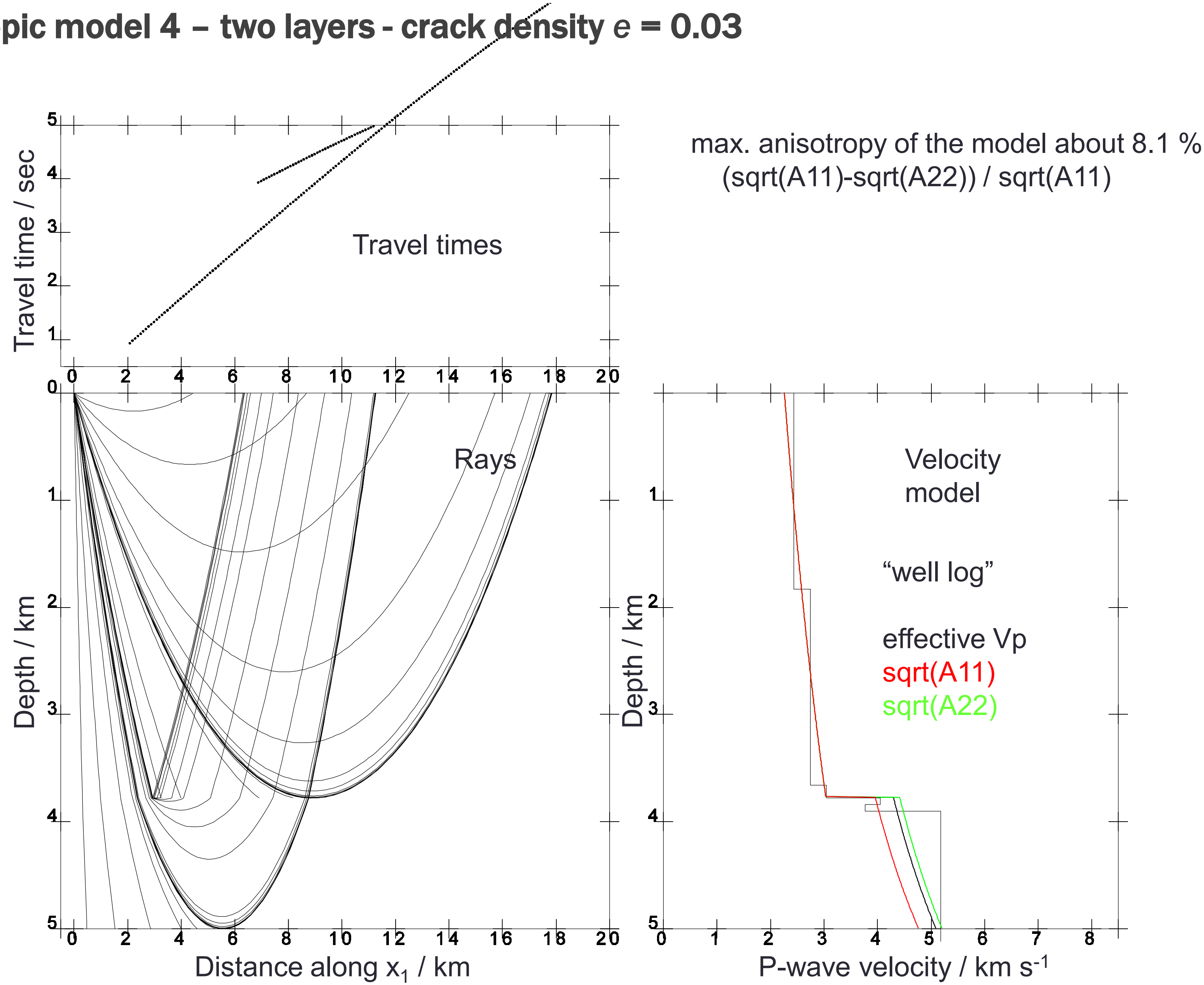
- In the velocity model under investigation, the crack-induced anisotropy in the lower layer of the model starts to be visible on the surface travel-time curve from the anisotropy of 7.5 %

- The anisotropy induced by vertical cracks affects most the profile oriented perpendicularly to the cracks, its effect on the profile oriented parallel to the cracks is negligible

Isotropic model 2 - two layers



Anisotropic model 4 – two layers - crack density e = 0.03



Anisotropic model 4 – two layers - crack density *e* = 0.03

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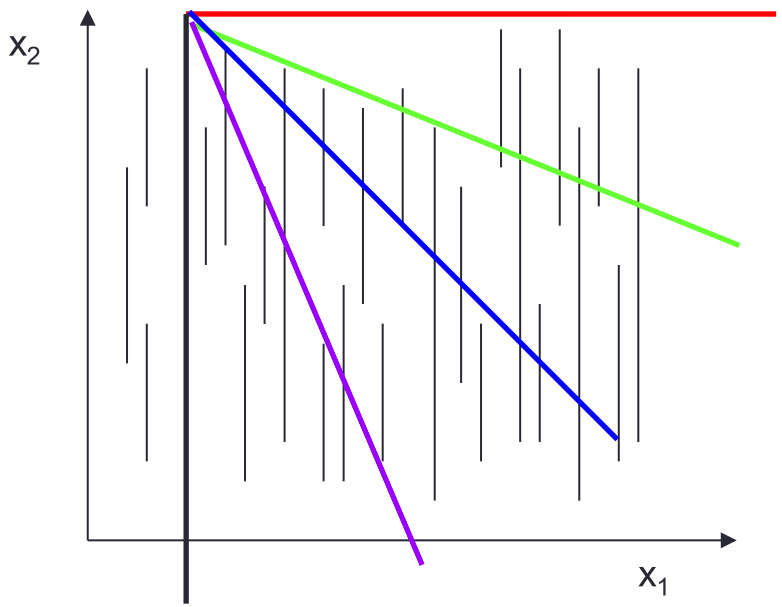
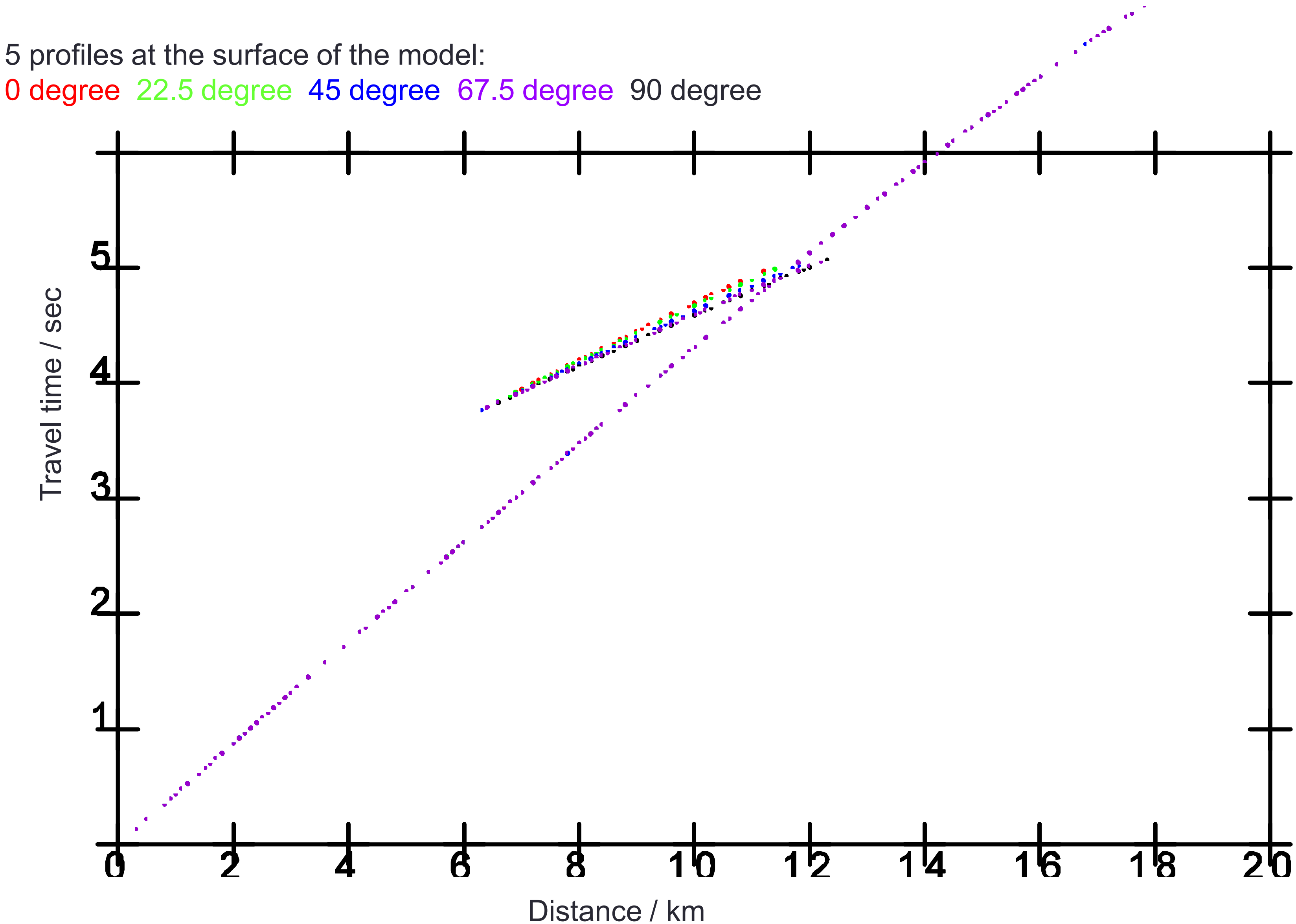
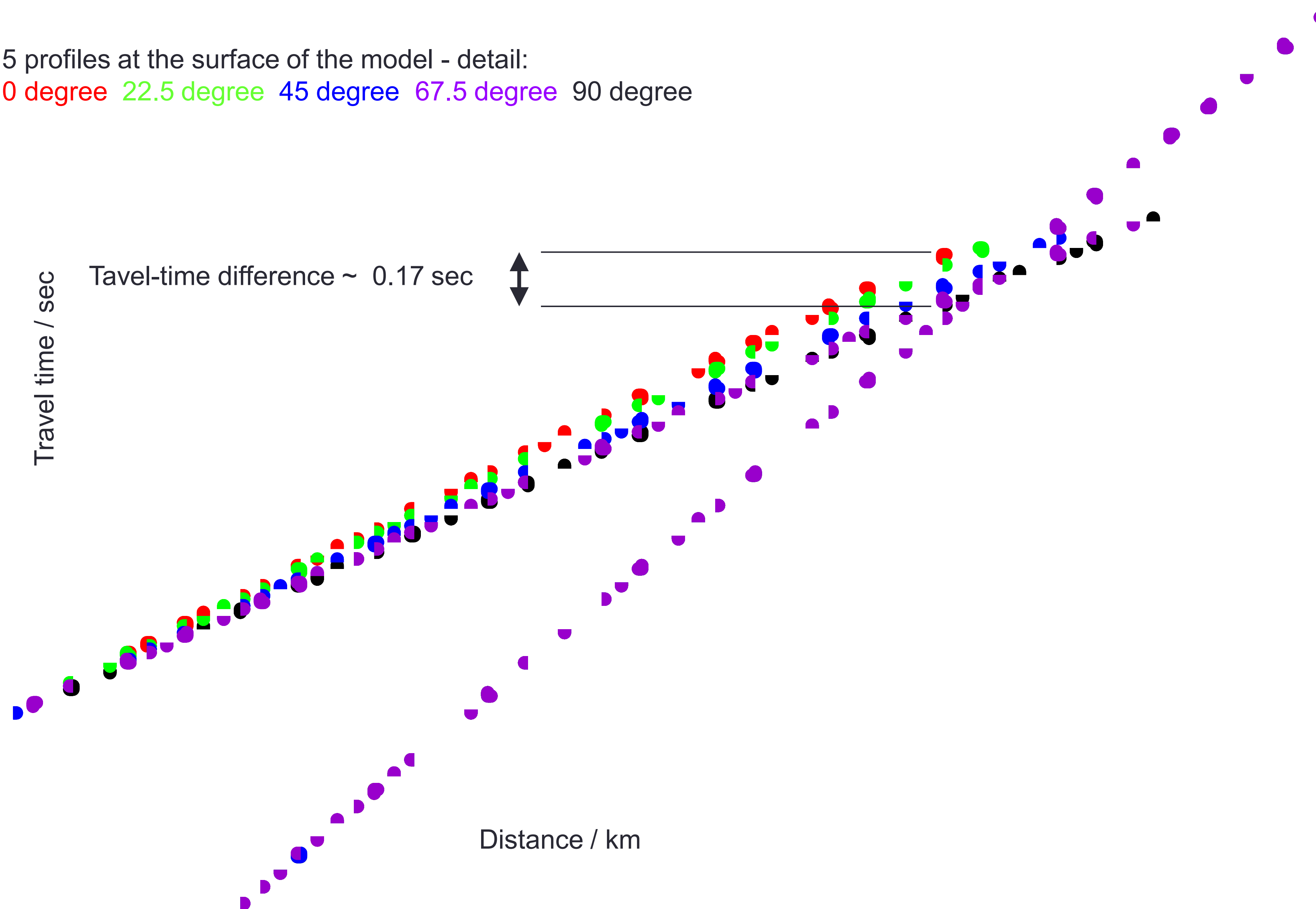
Top view



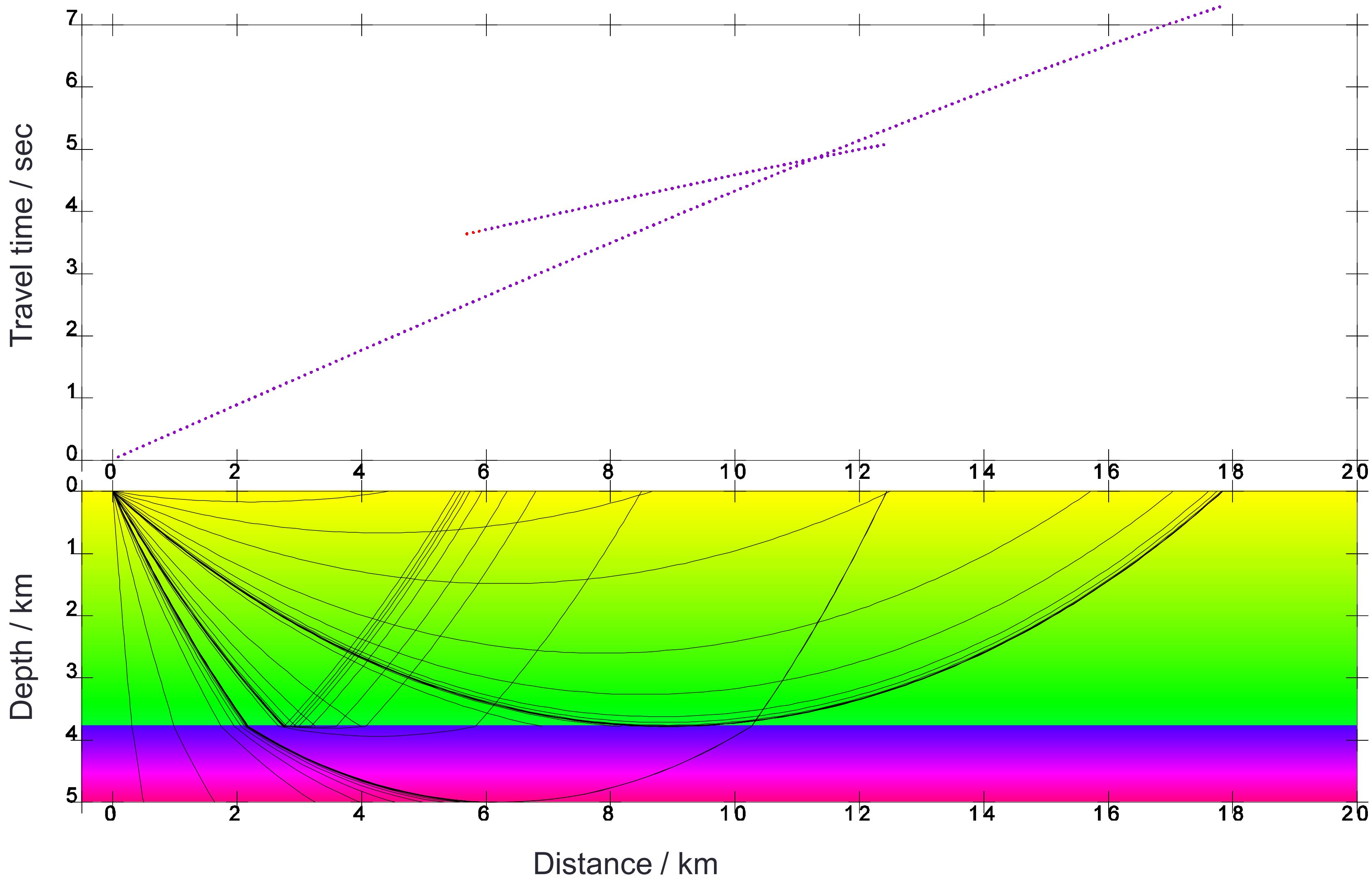
Anisotropic model 4 – two layers - crack density *e* = 0.03



Anisotropic model 4 – two layers - crack density e = 0.03



Isotropic model 2



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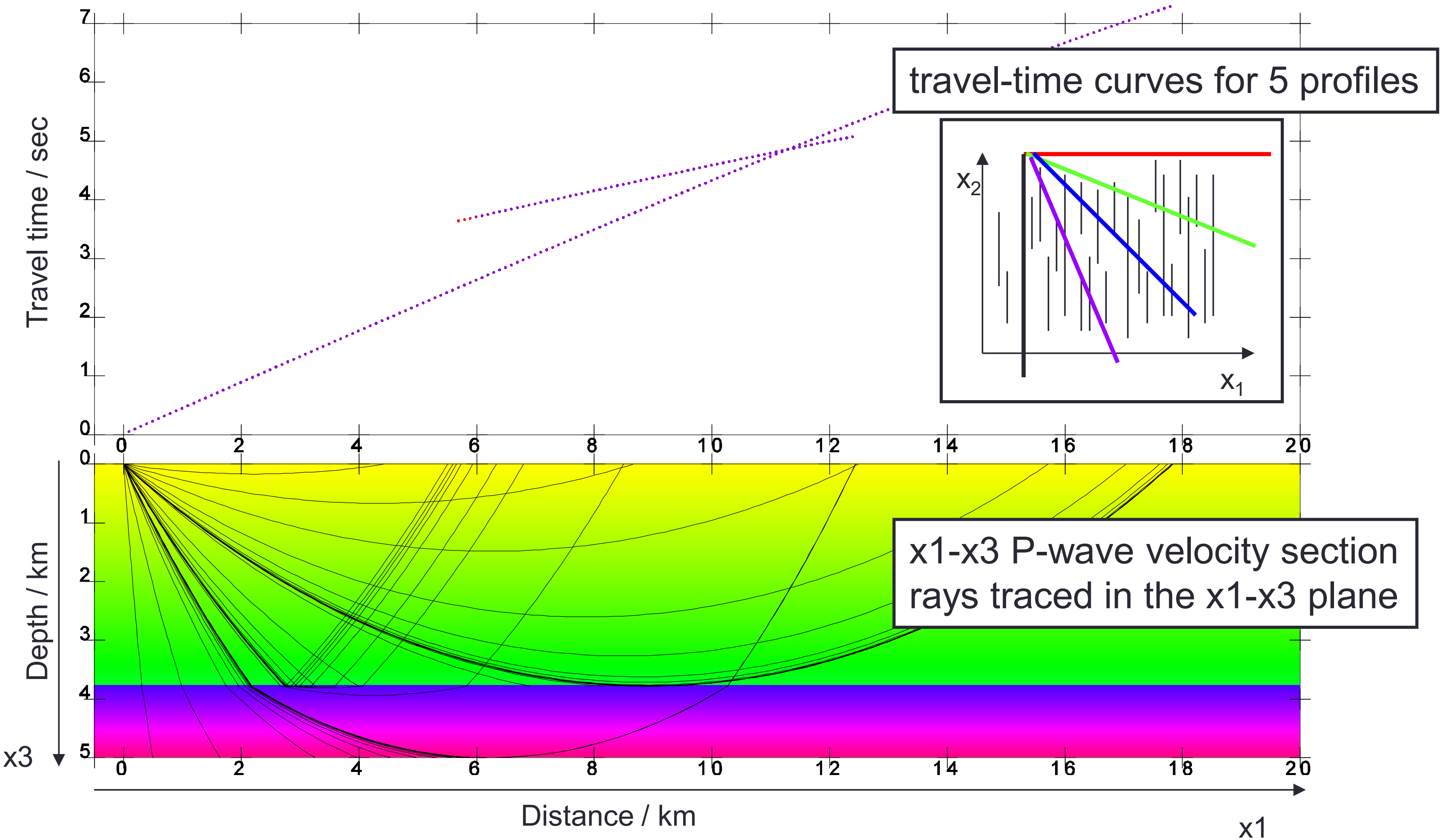

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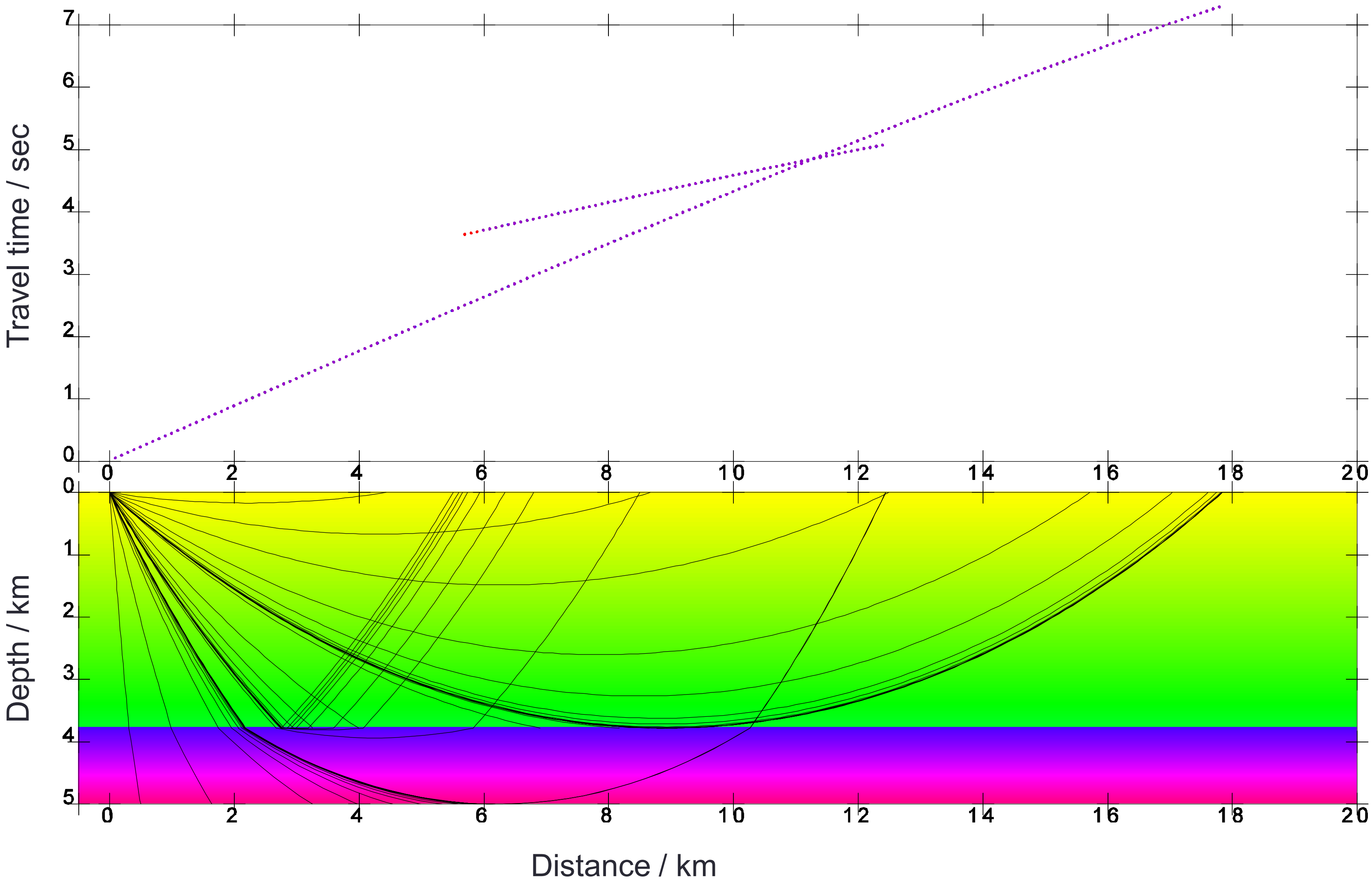
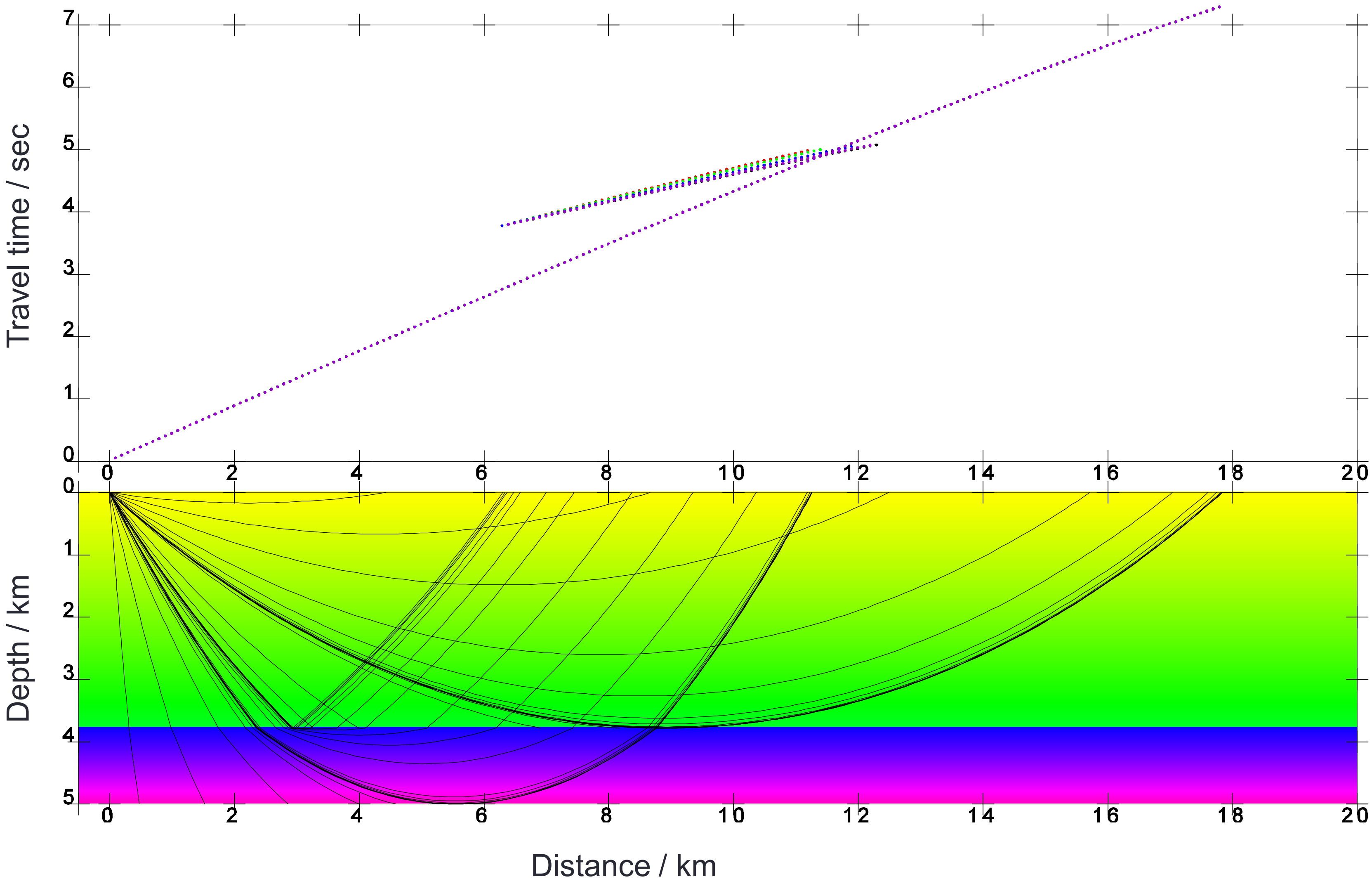


Anisotropic model 4



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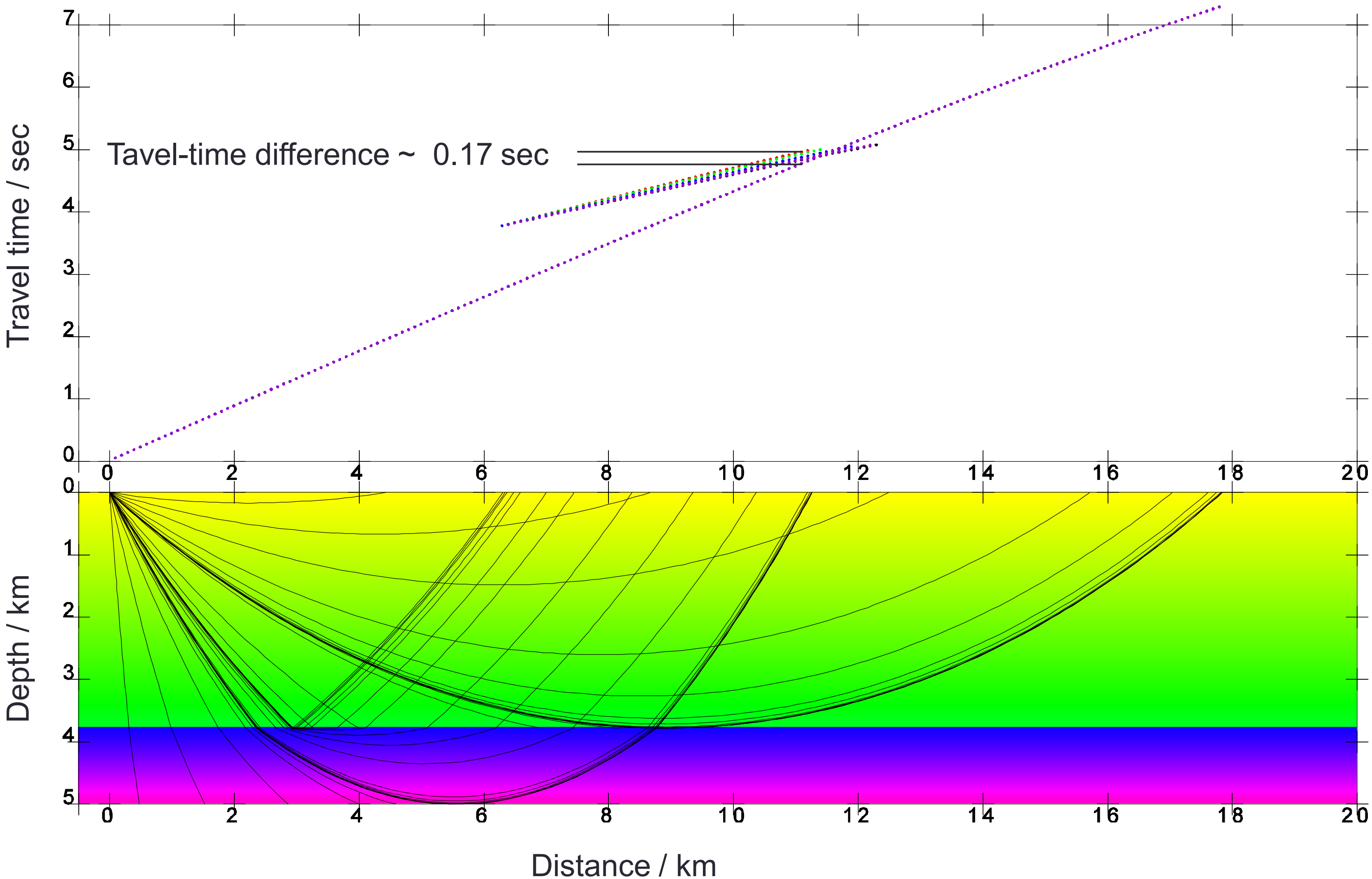
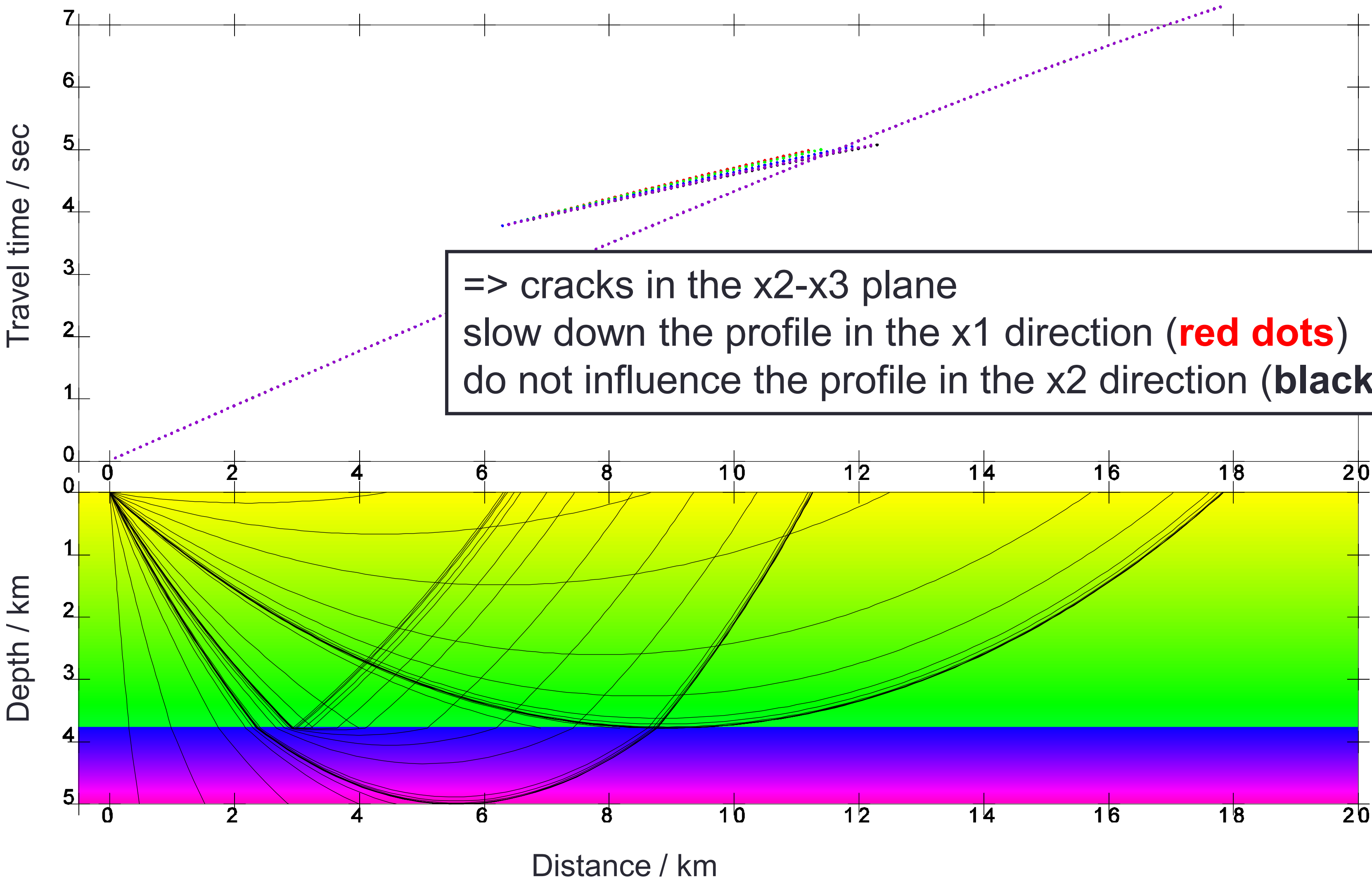
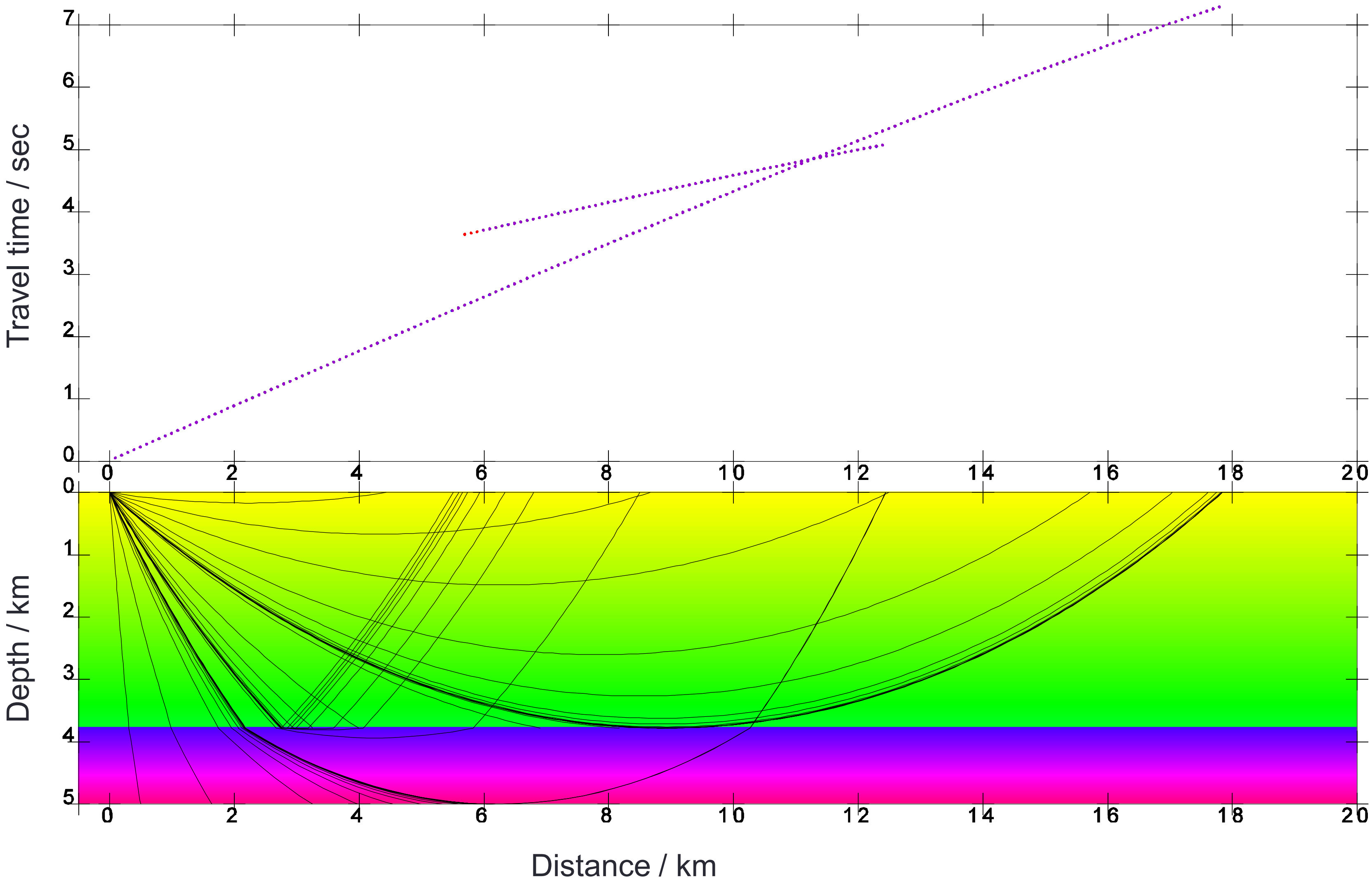


Anisotropic model 4

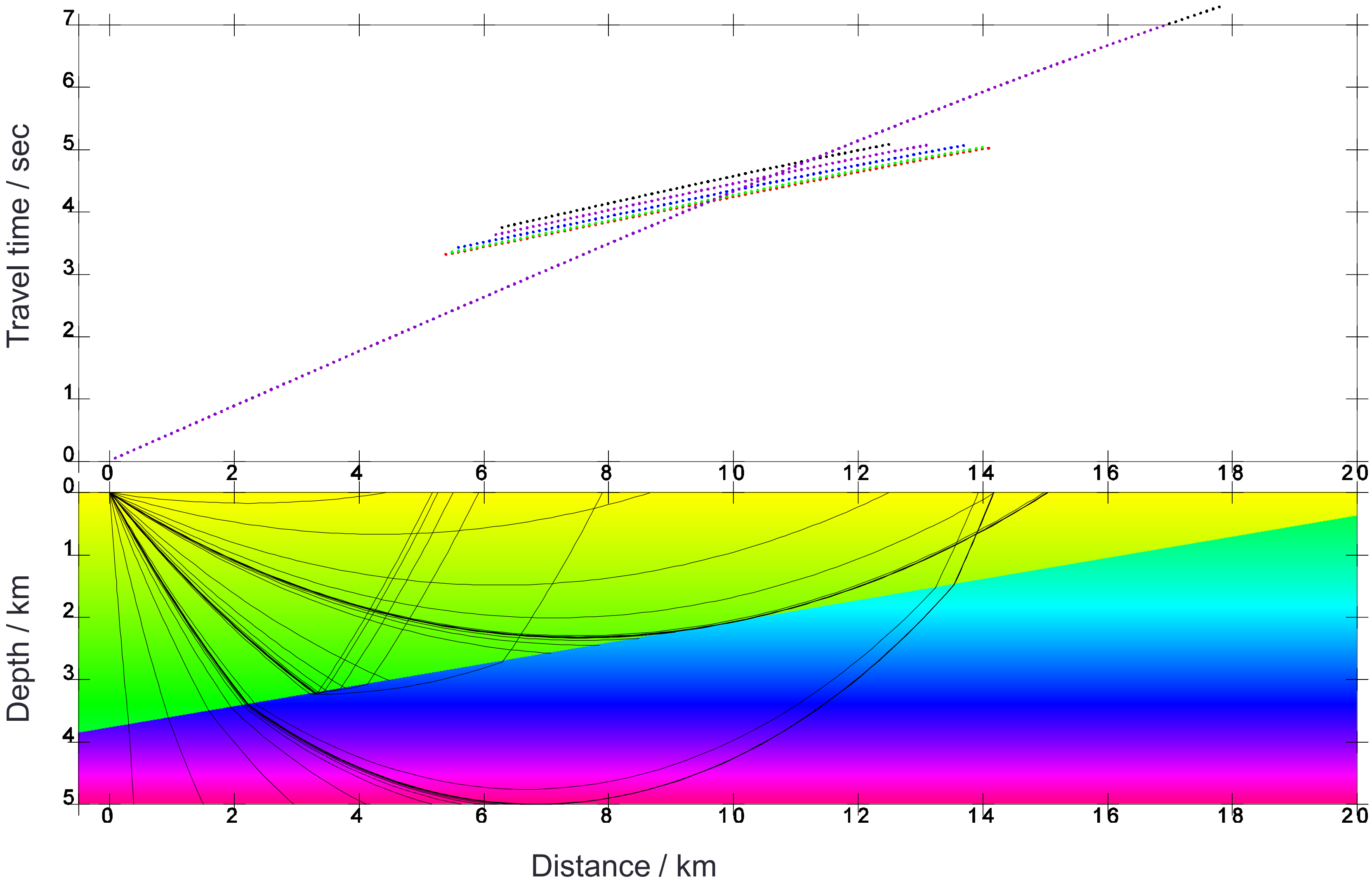


=> cracks in the x2-x3 plane
slow down the profile in the x1 direction (**red dots**)
do not influence the profile in the x2 direction (**black dots**)

Isotropic model 2



Isotropic model 2 – inclined interface



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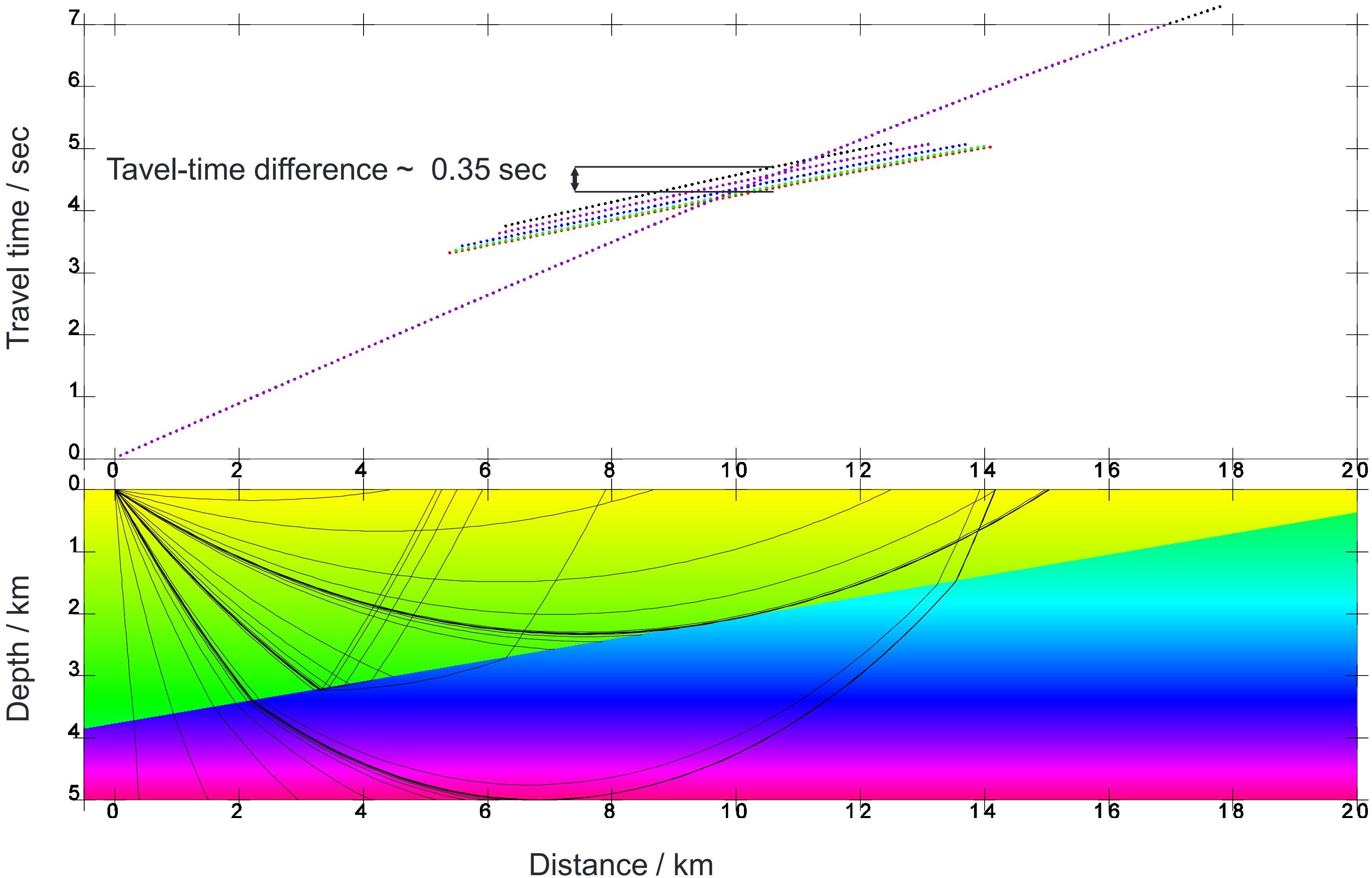

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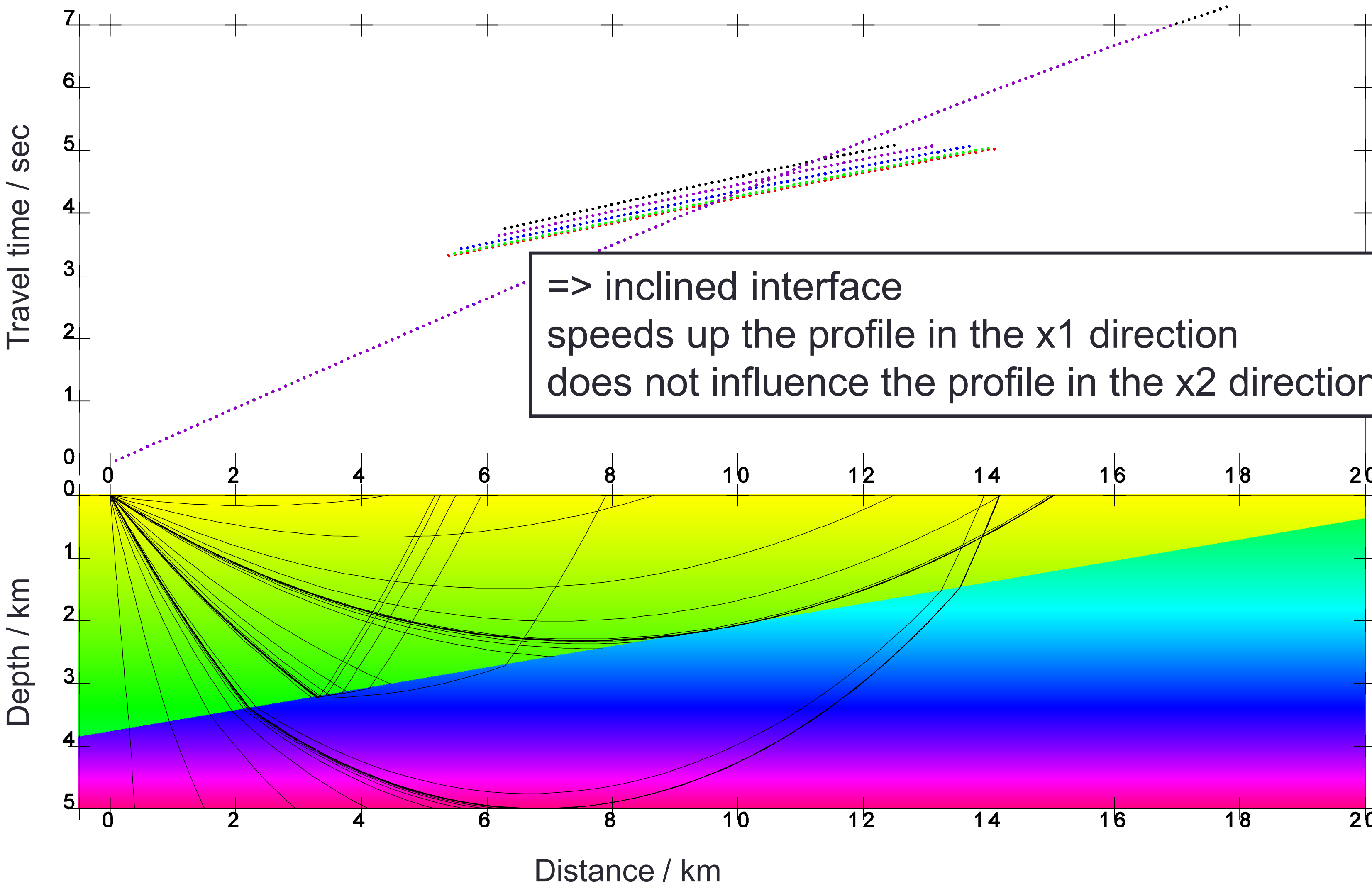
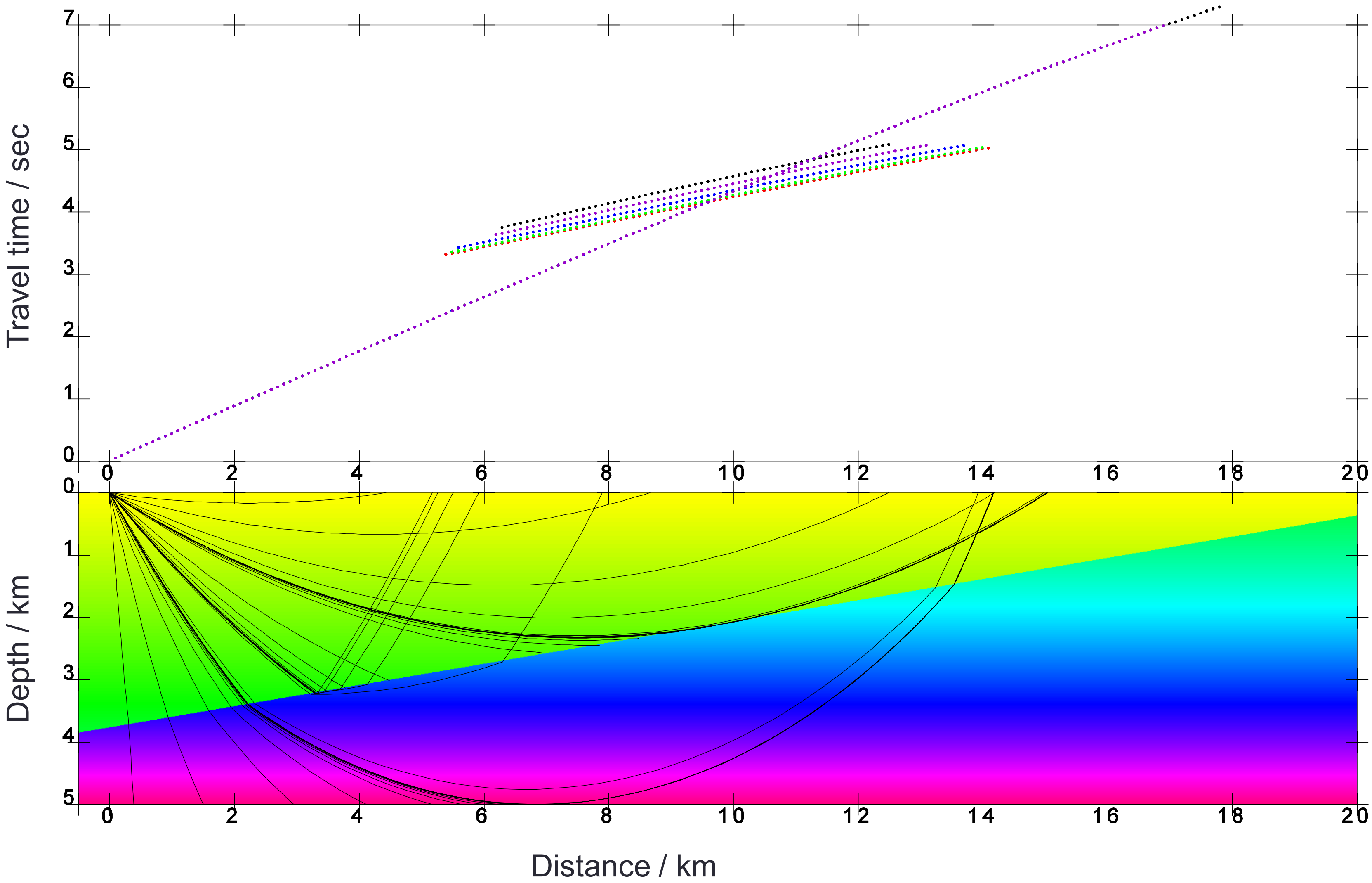
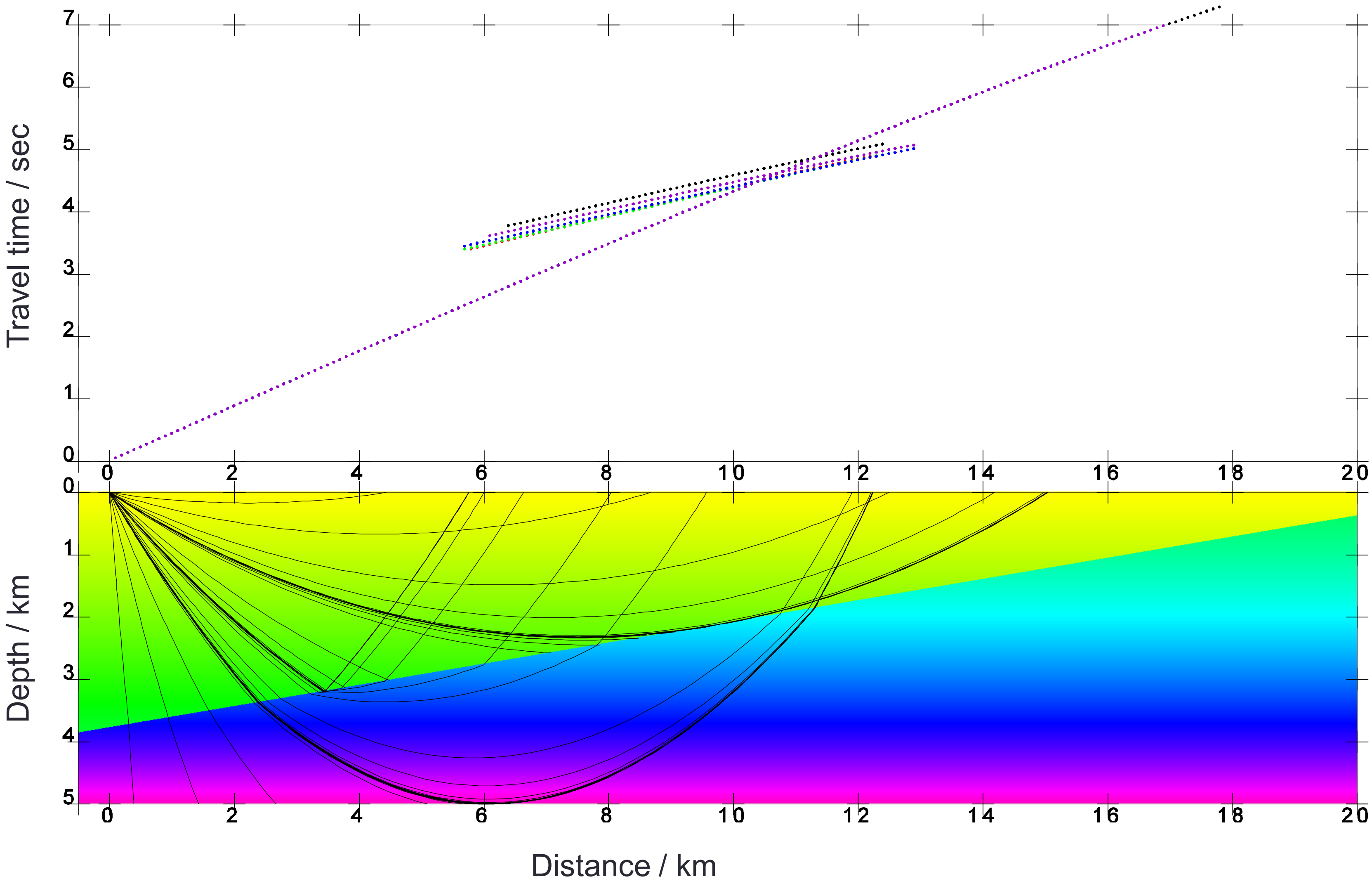


=> inclined interface
speeds up the profile in the x1 direction
does not influence the profile in the x2 direction

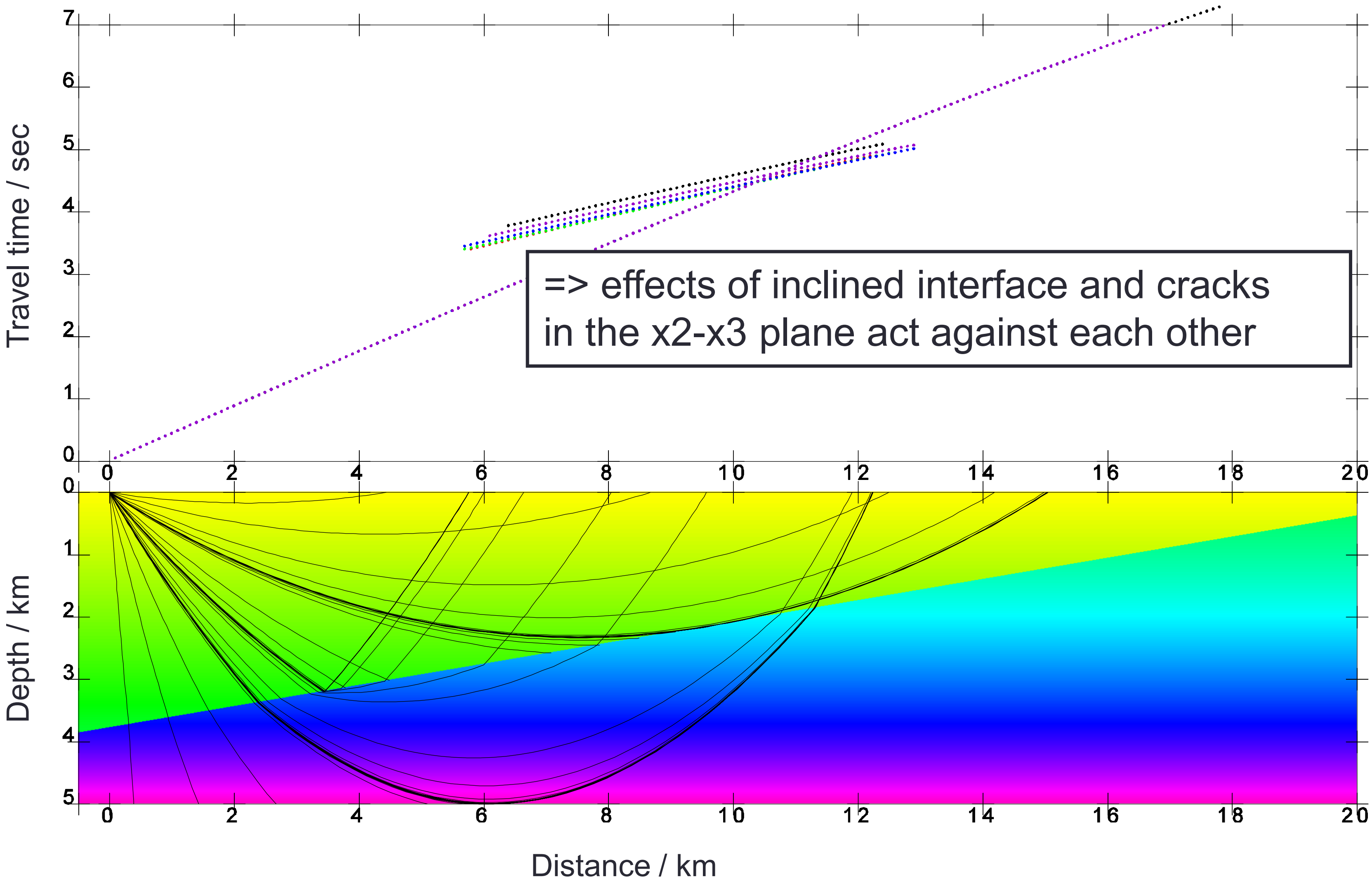
Isotropic model 2 – inclined interface



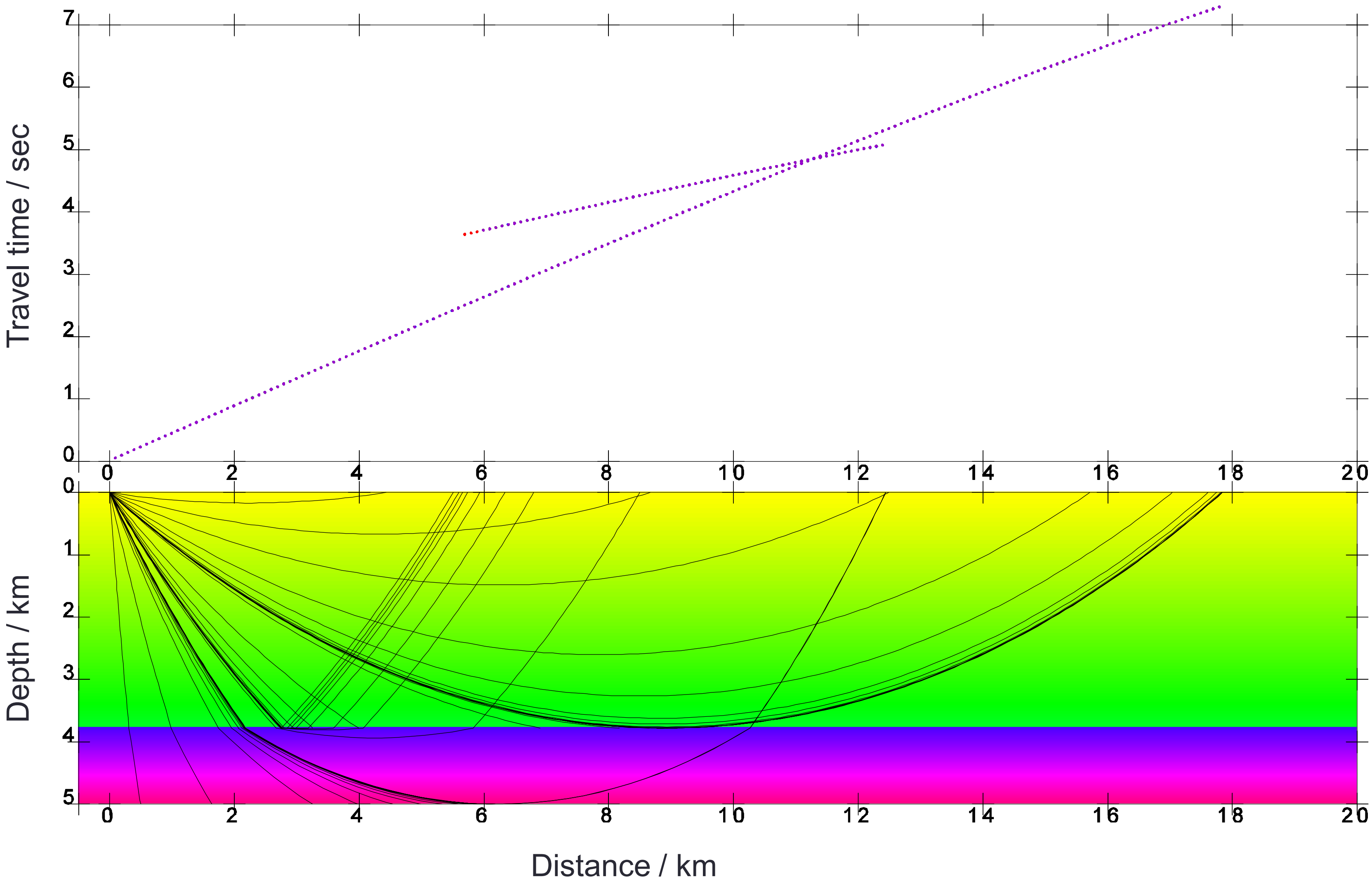
Anisotropic model 4 – inclined interface



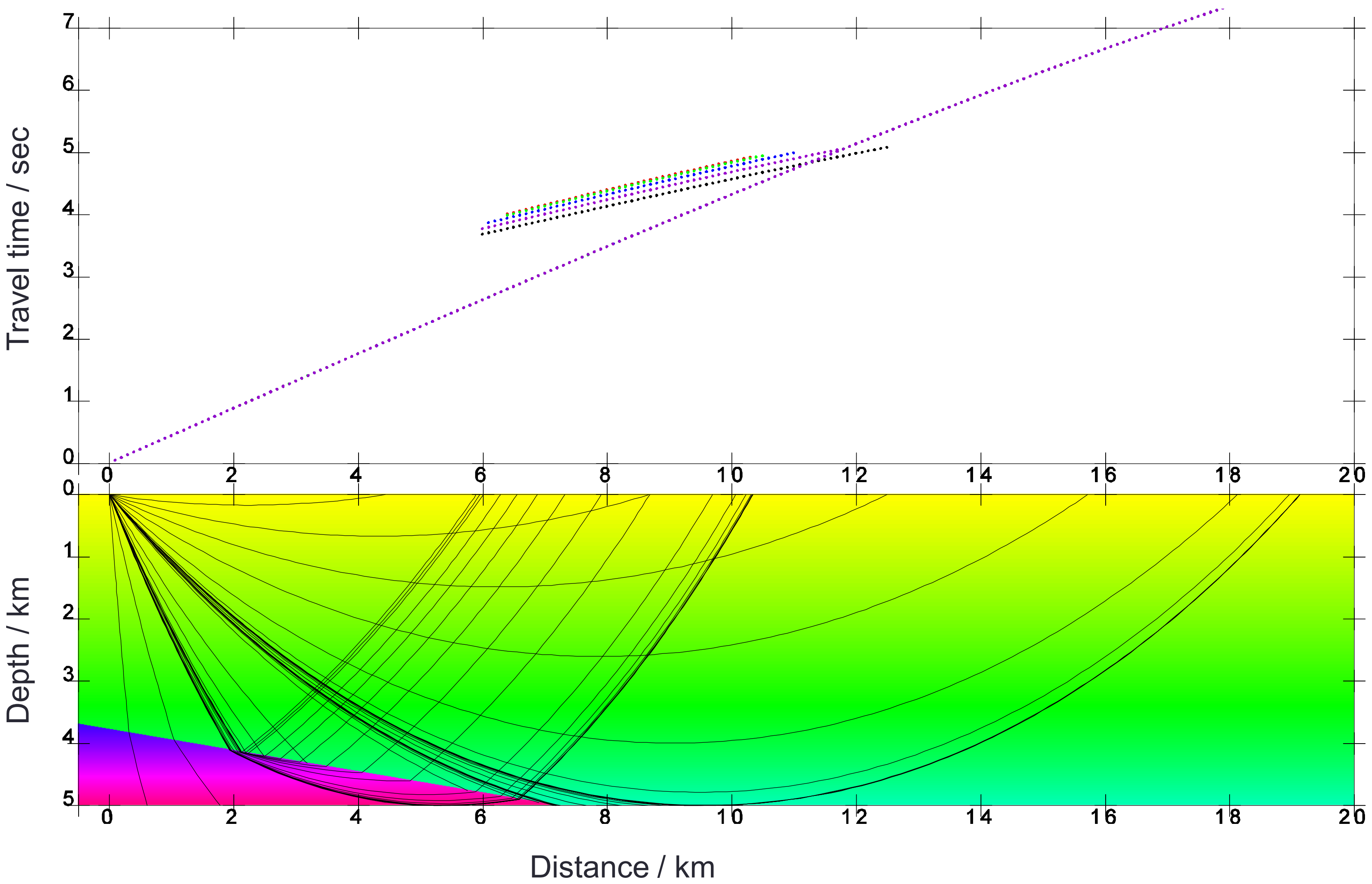
Anisotropic model 4 – inclined interface



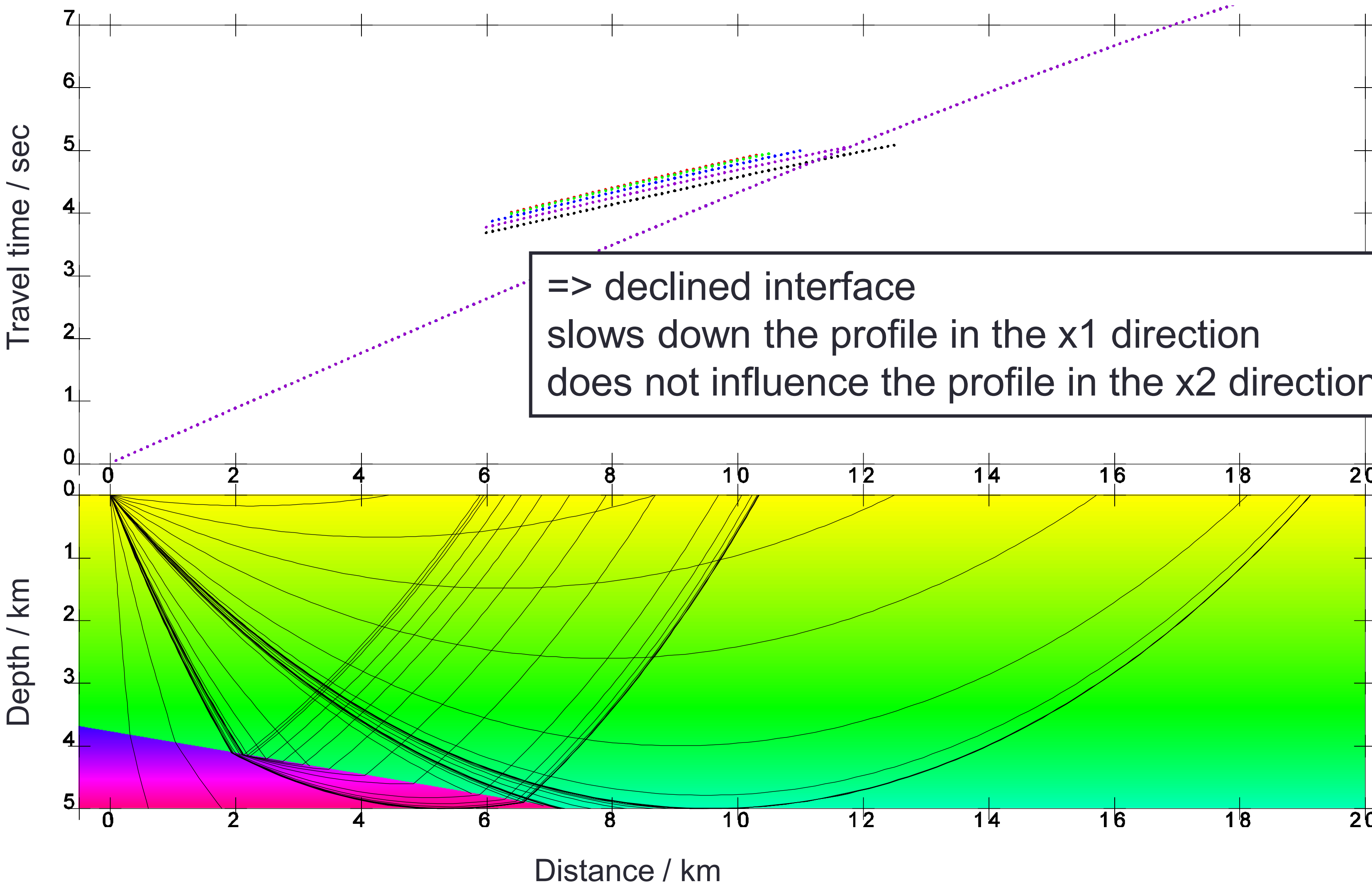
Isotropic model 2



Isotropic model 2 – declined interface

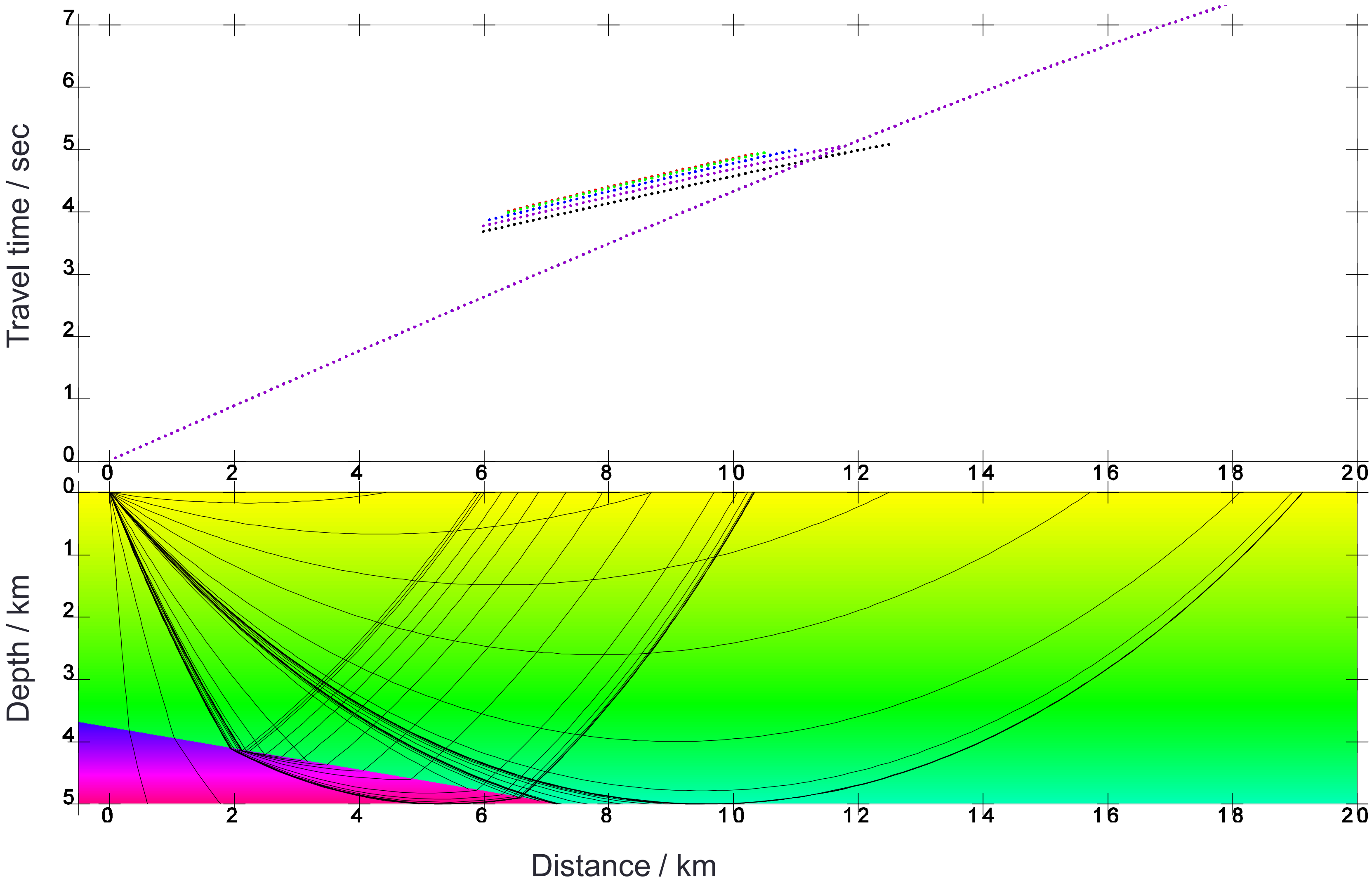


Isotropic model 2 – declined interface

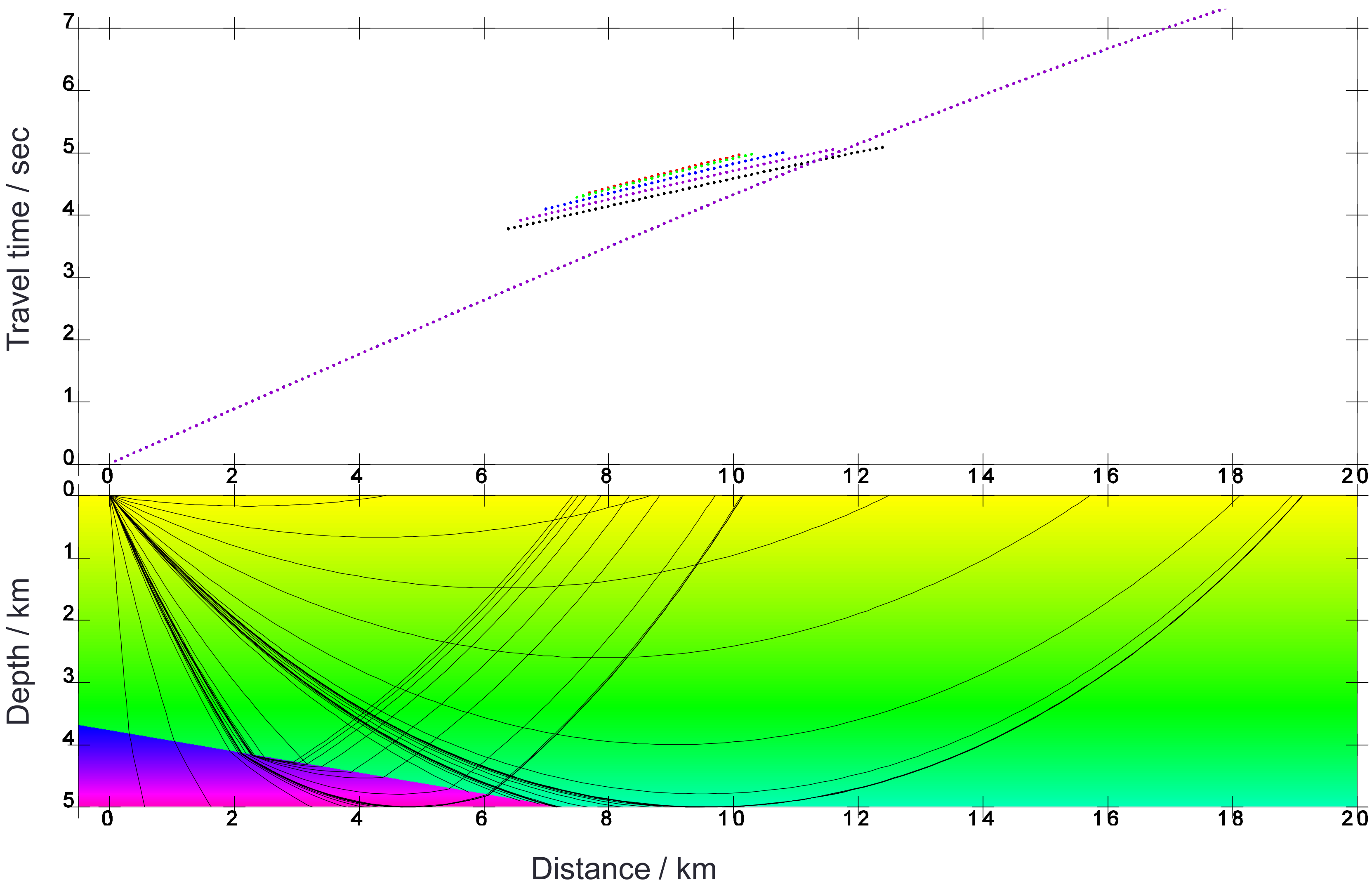


=> declined interface
slows down the profile in the x1 direction
does not influence the profile in the x2 direction

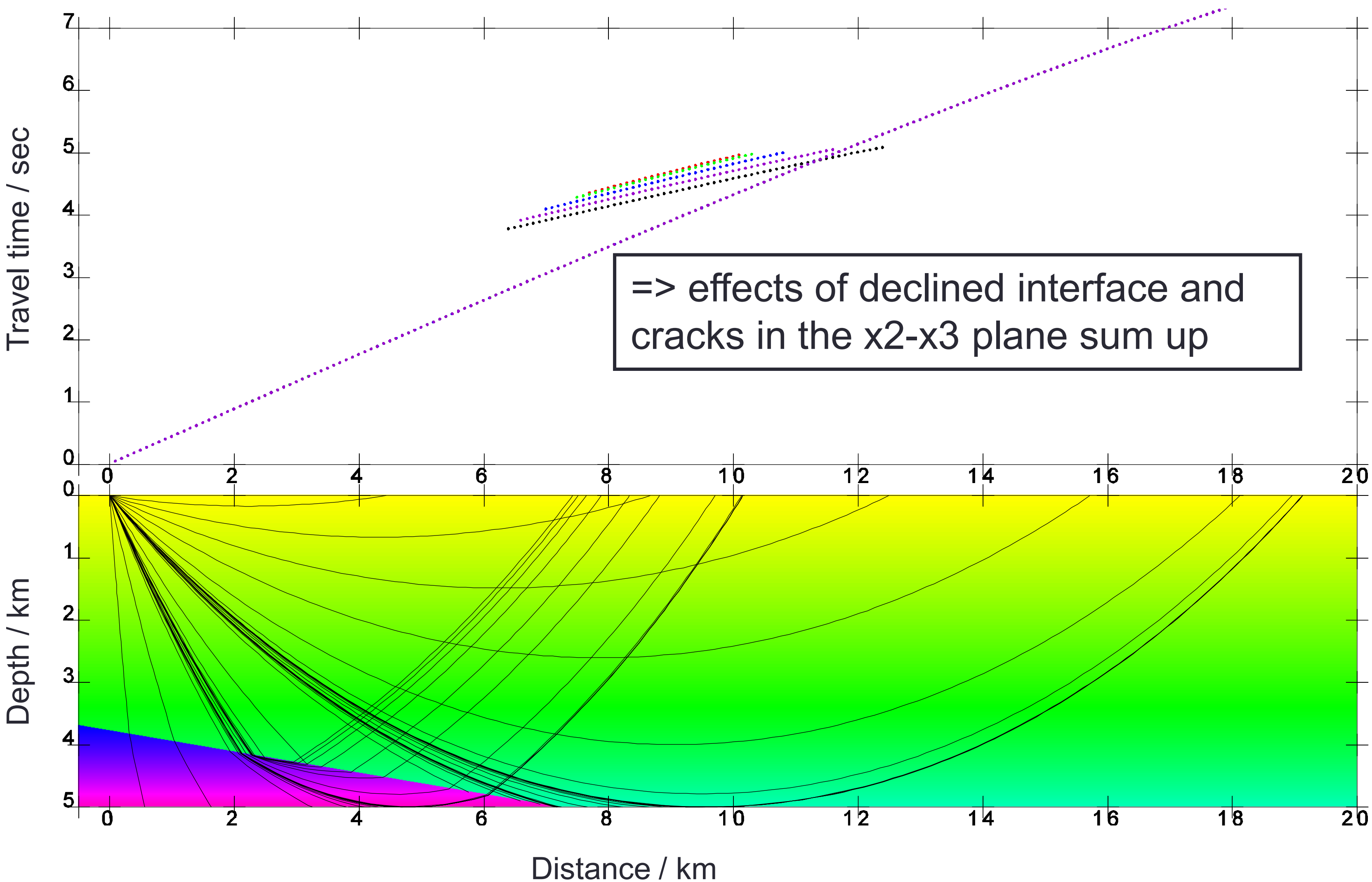
Isotropic model 2 – declined interface



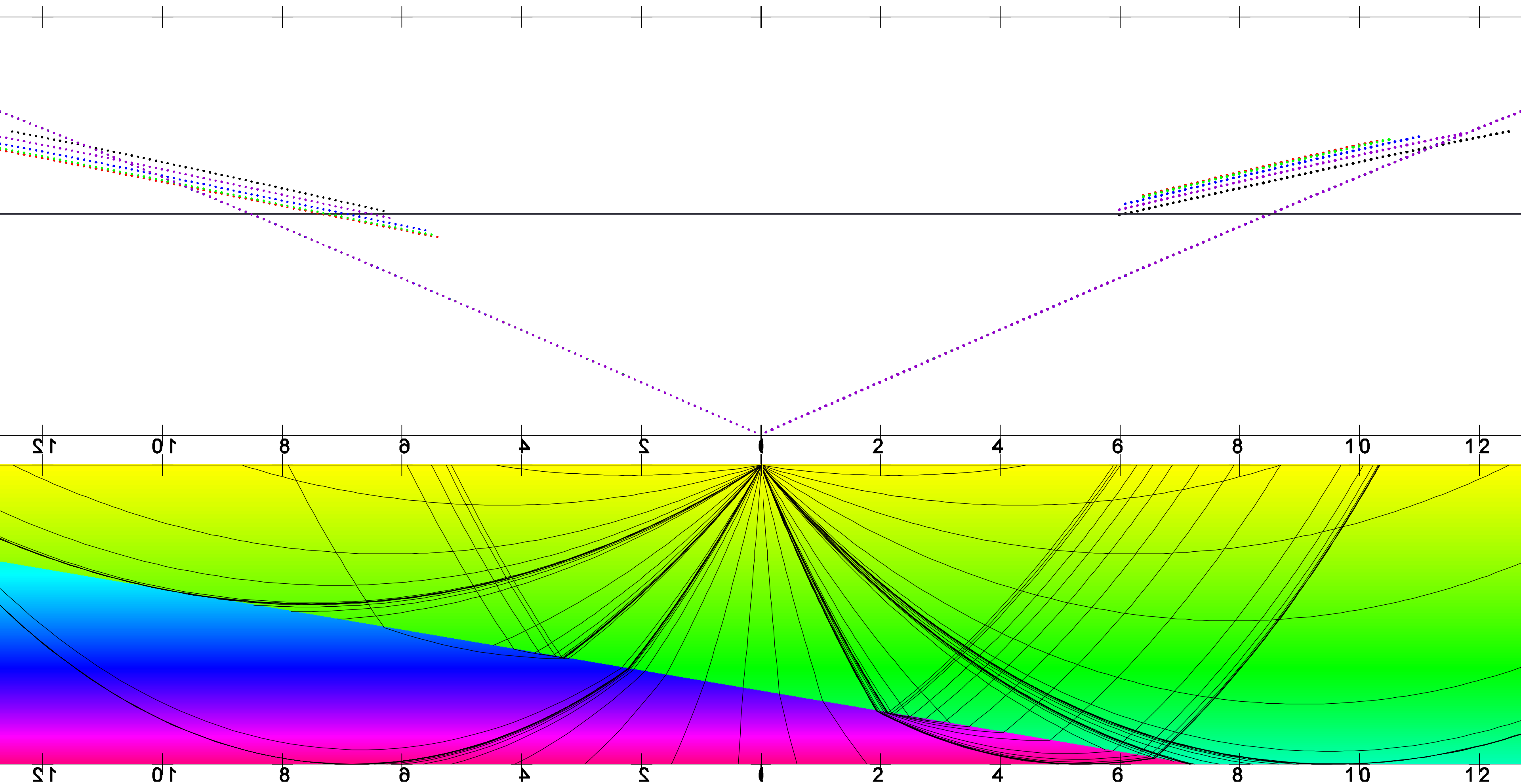
Anisotropic model 4 – declined interface



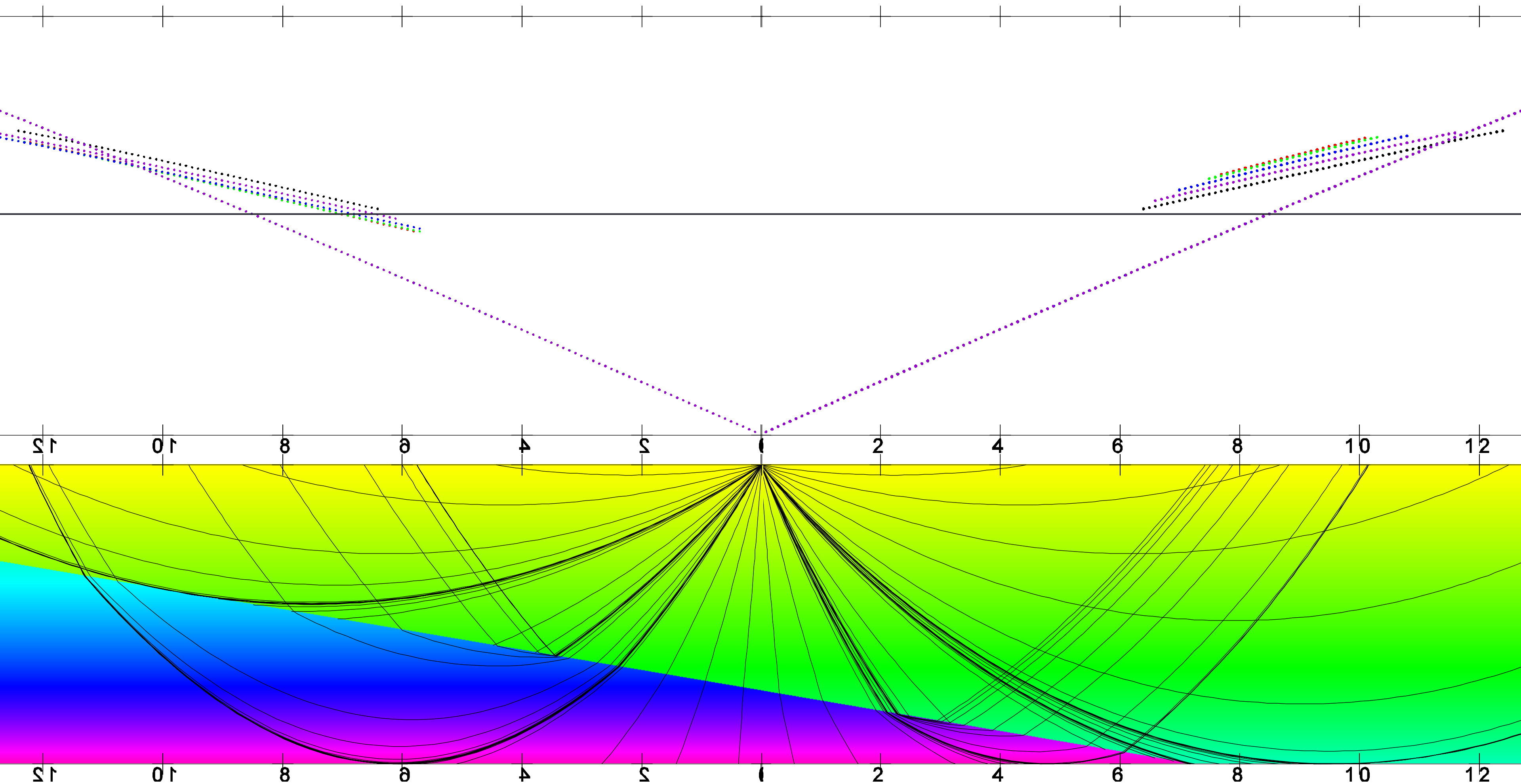
Anisotropic model 4 – declined interface



Isotropic model 2 inclined and declined – compilation of figures

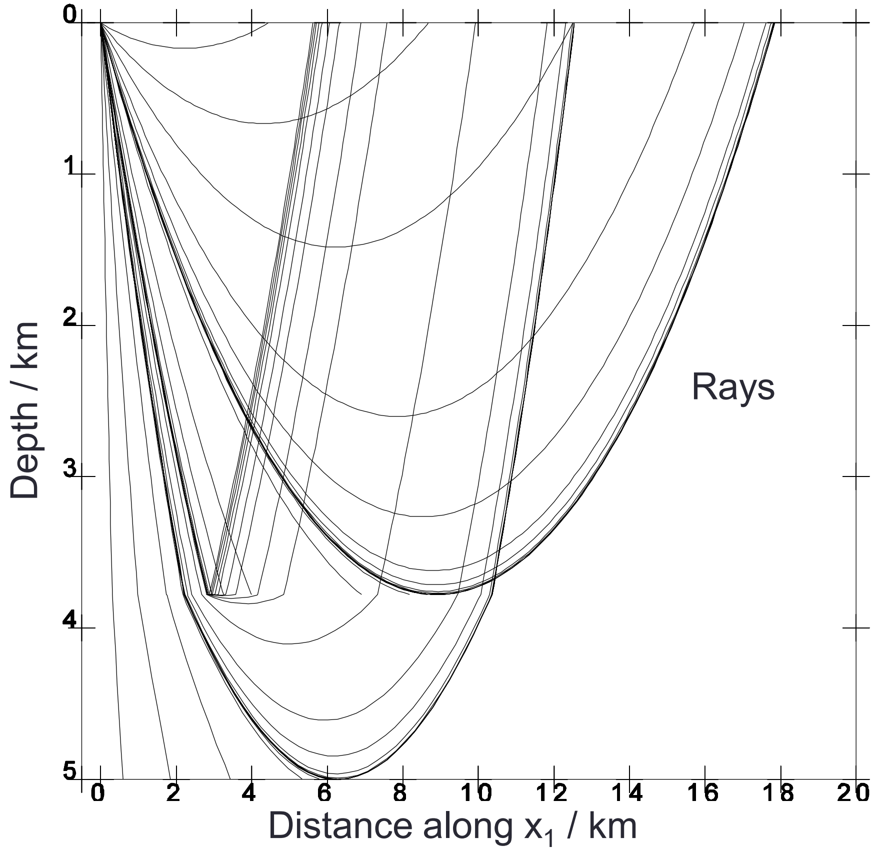


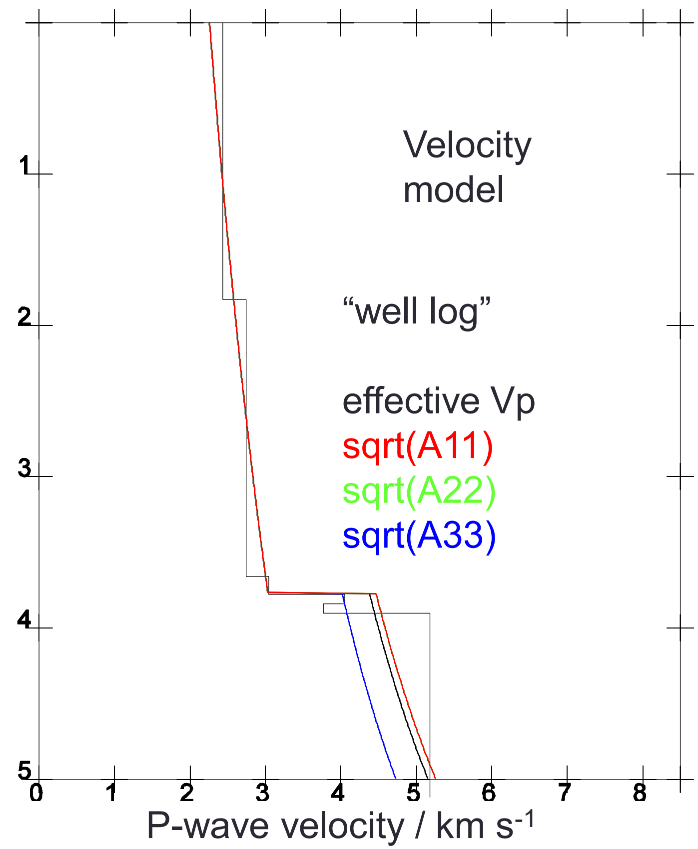
Anisotropic model 4 inclined and declined– compilation of figures



Anisotropic model 5 – lower layer VTI

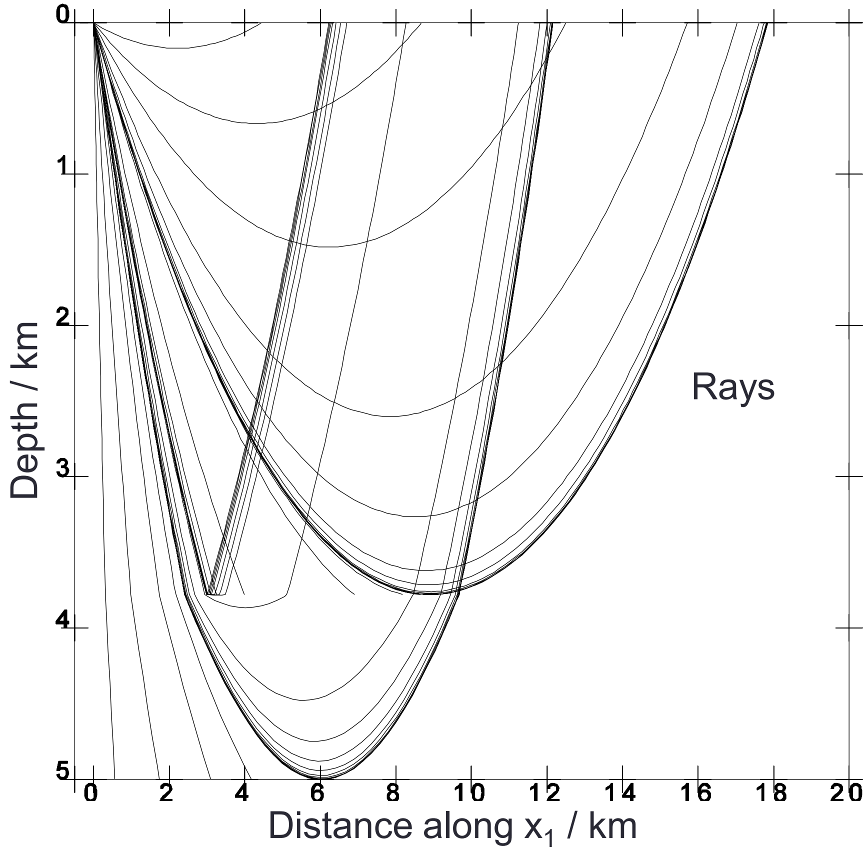
max. vertical anisotropy about 10 %
(sqrt(A11)-sqrt(A33)) / sqrt(A11)

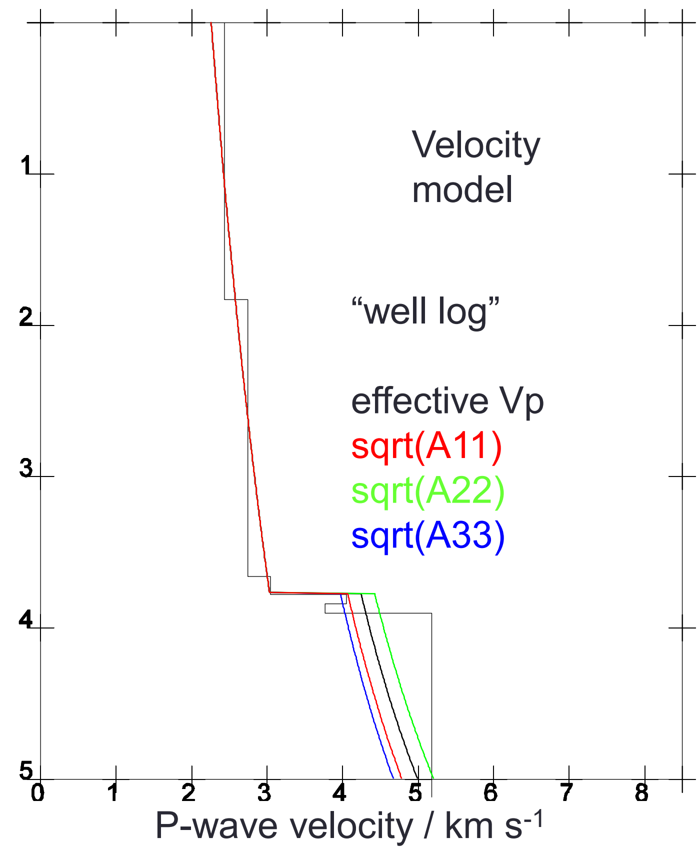




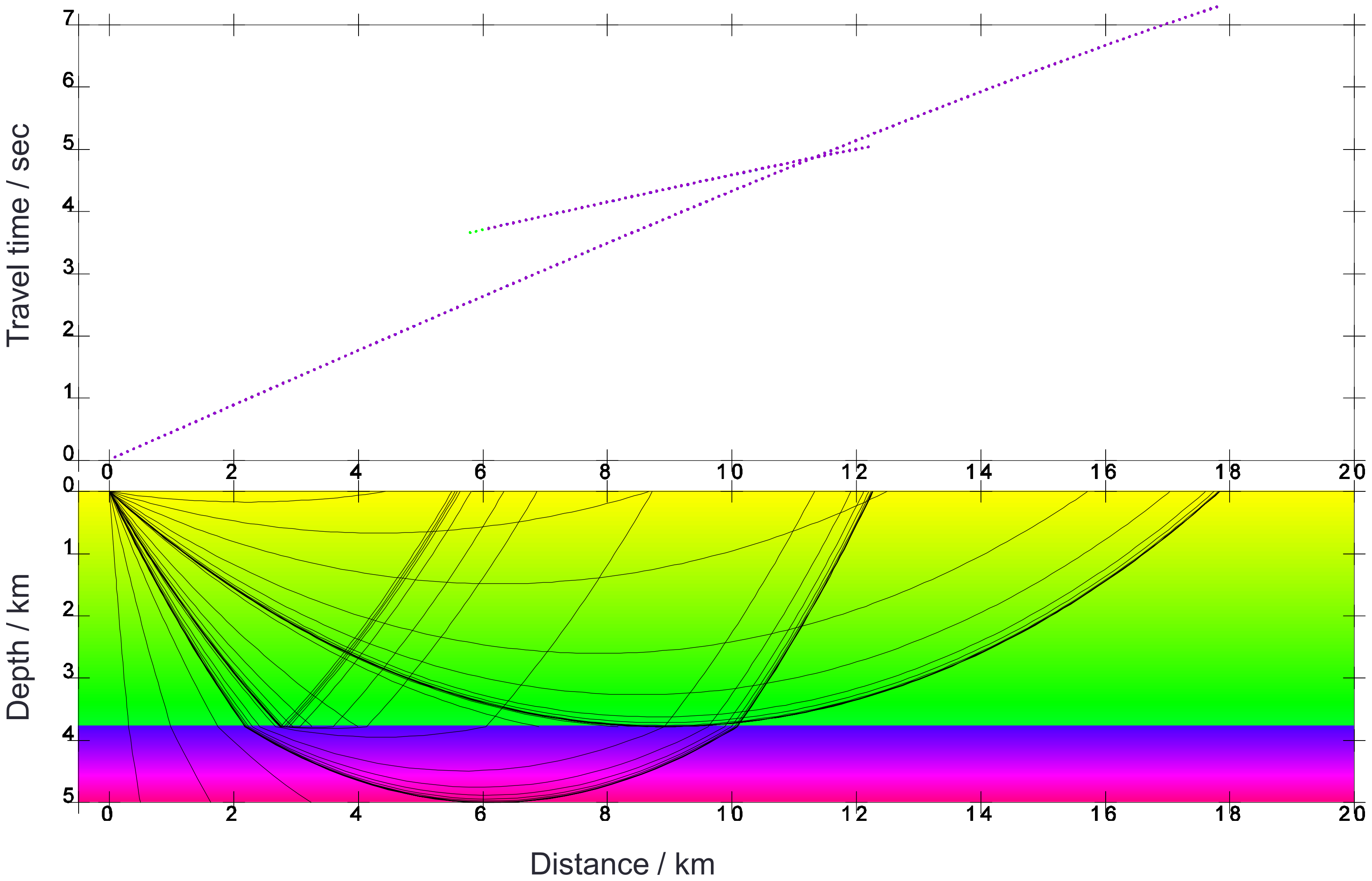
Anisotropic model 6 – lower layer VTI + cracks in the x2-x3 plane

max. vertical anisotropy about 10 %
(sqrt(A11)-sqrt(A33)) / sqrt(A11)
max. horizontal anisotropy about 8 %
(sqrt(A11)-sqrt(A22)) / sqrt(A11)

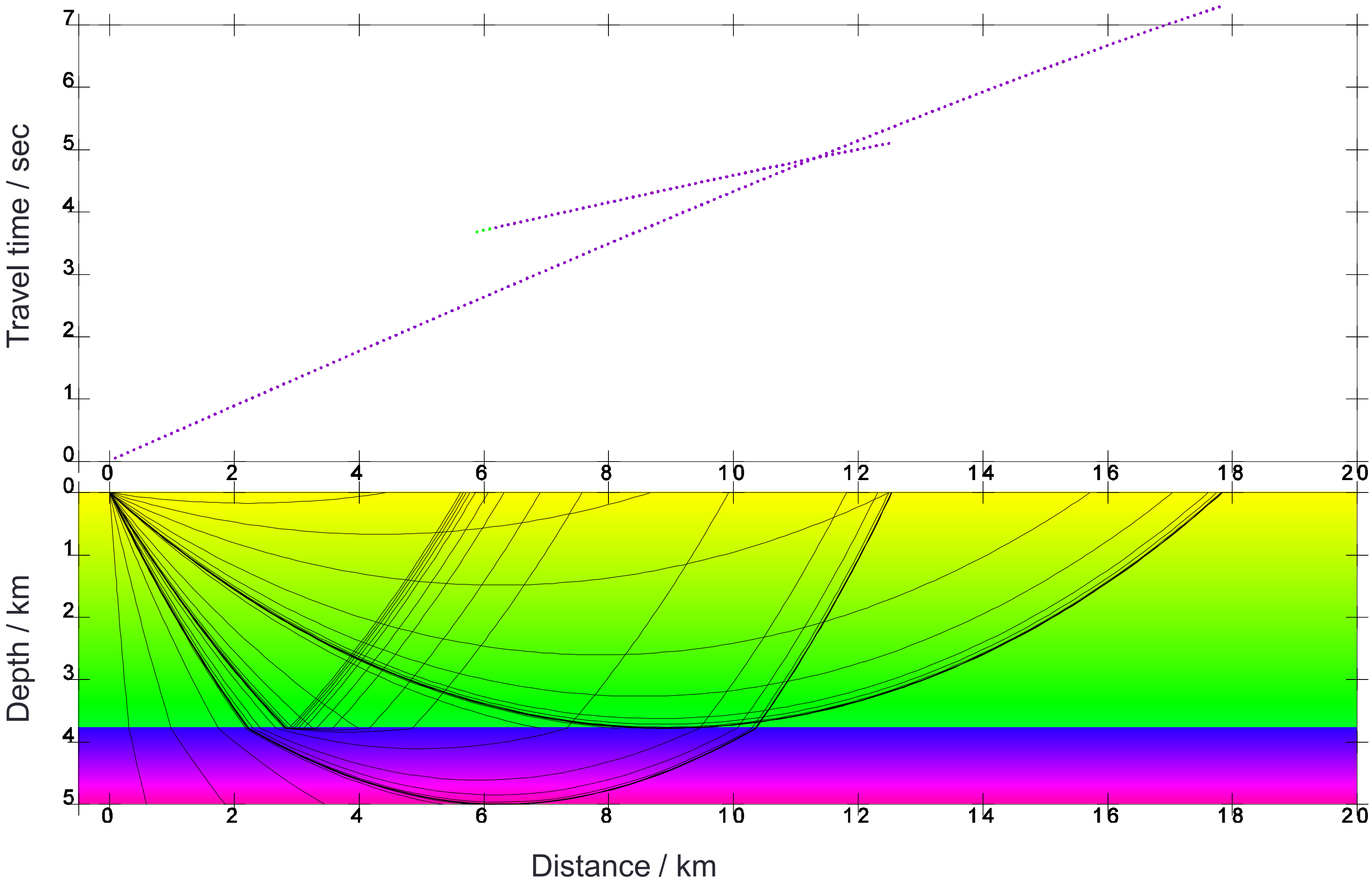




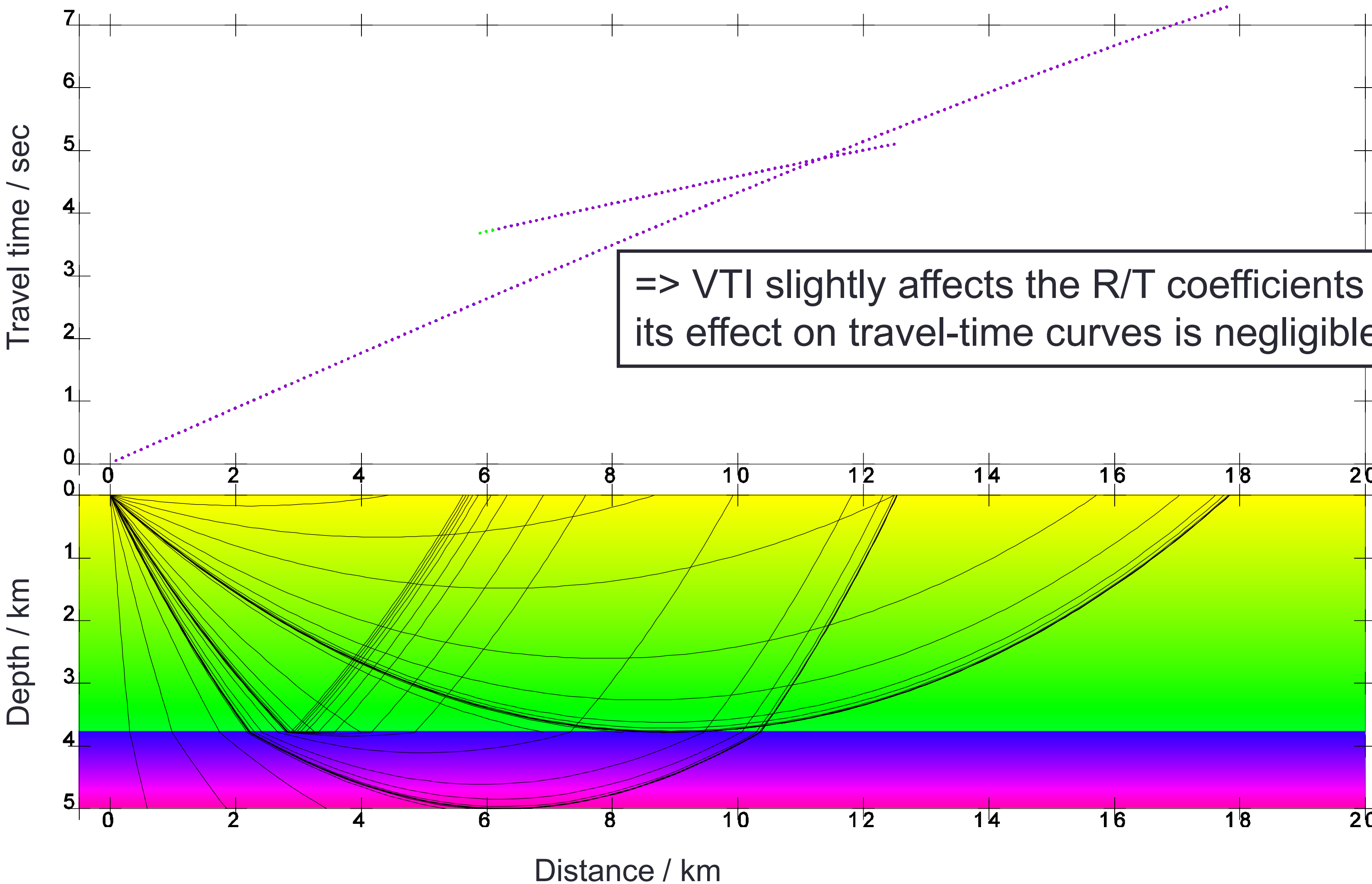
Isotropic model 2



Anisotropic model 5 – lower layer VTI

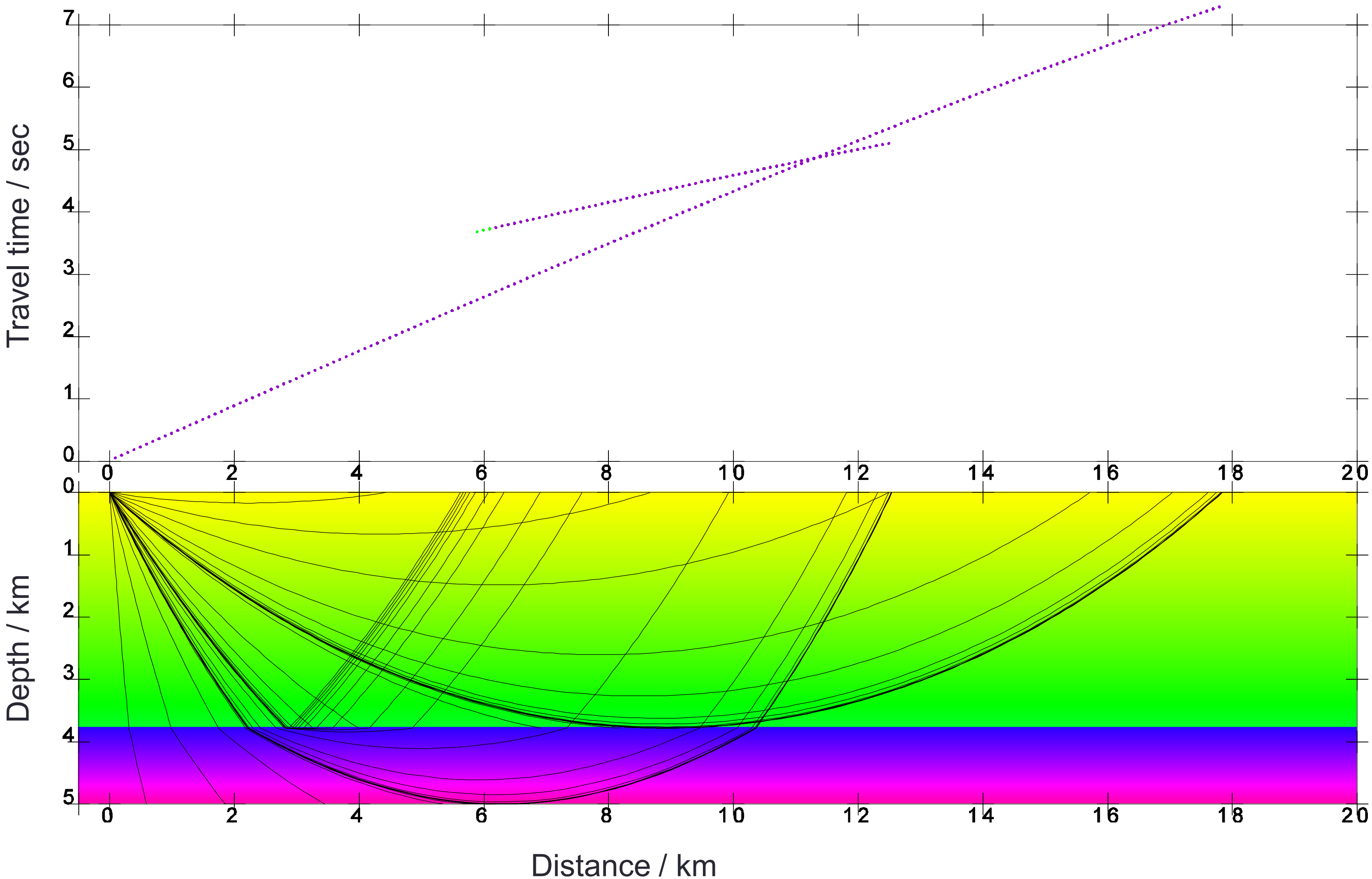


Anisotropic model 5 – lower layer VTI

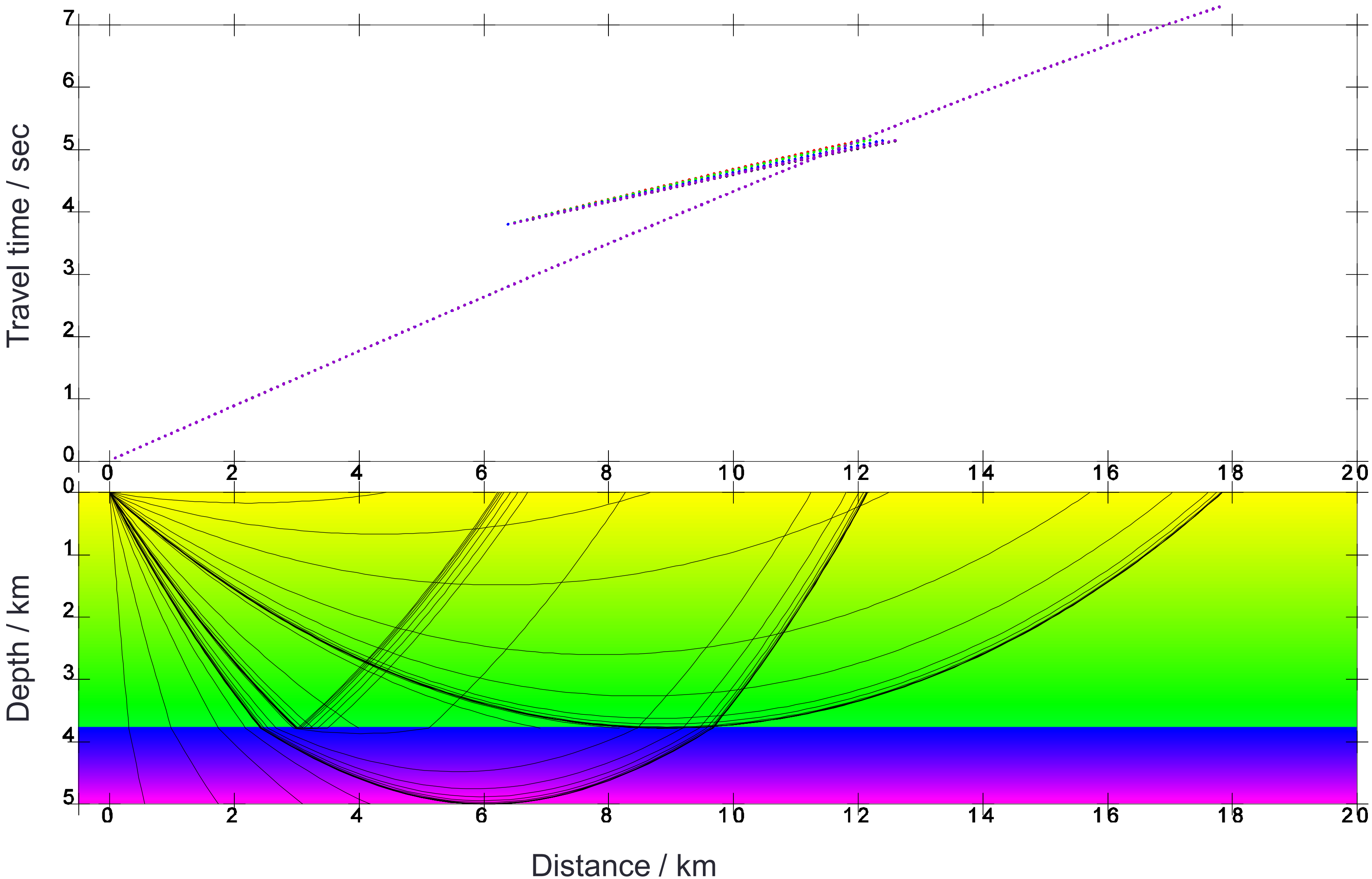


=> VTI slightly affects the R/T coefficients
its effect on travel-time curves is negligible

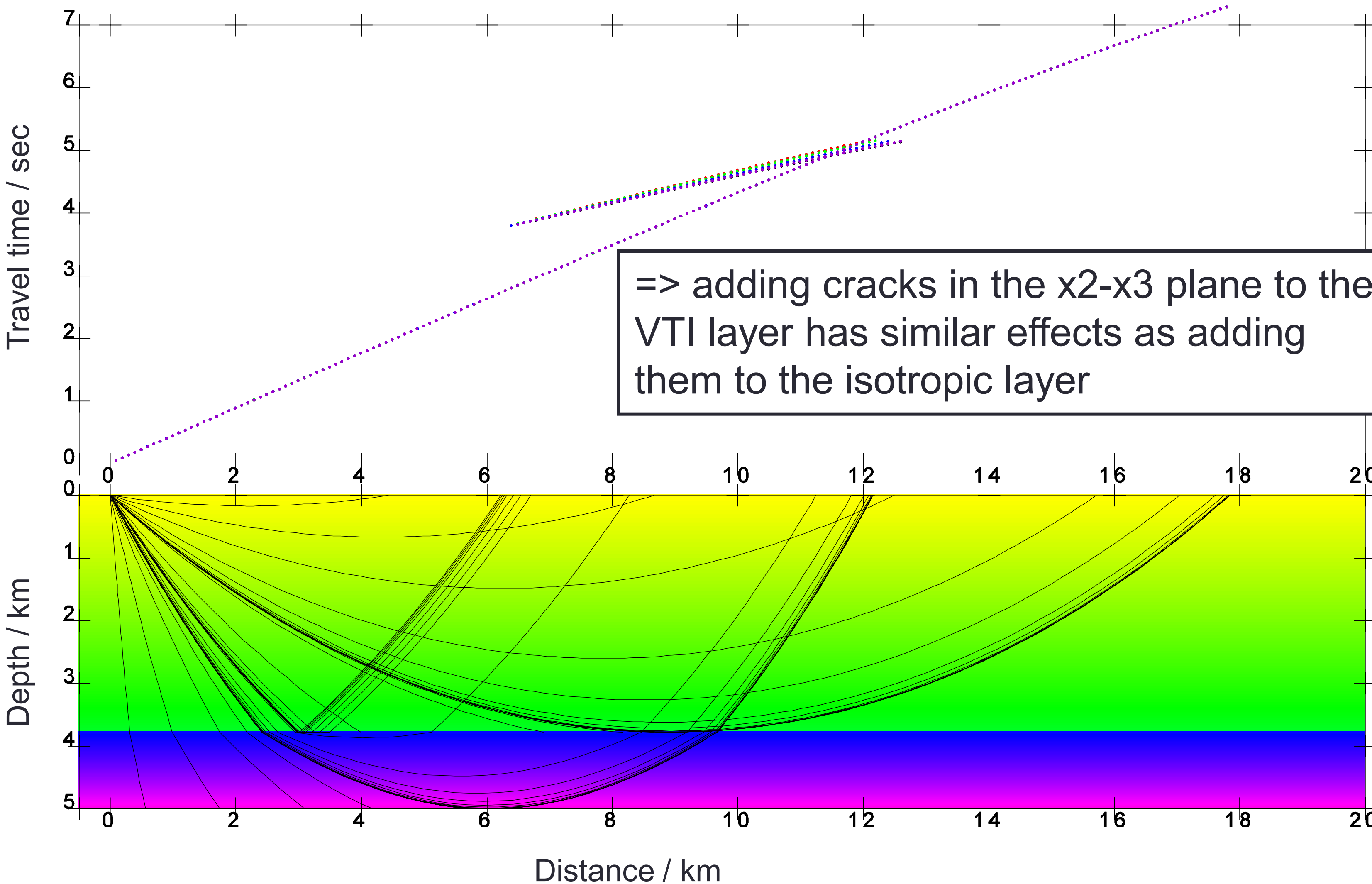
Anisotropic model 5 – lower layer VTI



Anisotropic model 6 – lower layer VTI + cracks in the x2-x3 plane

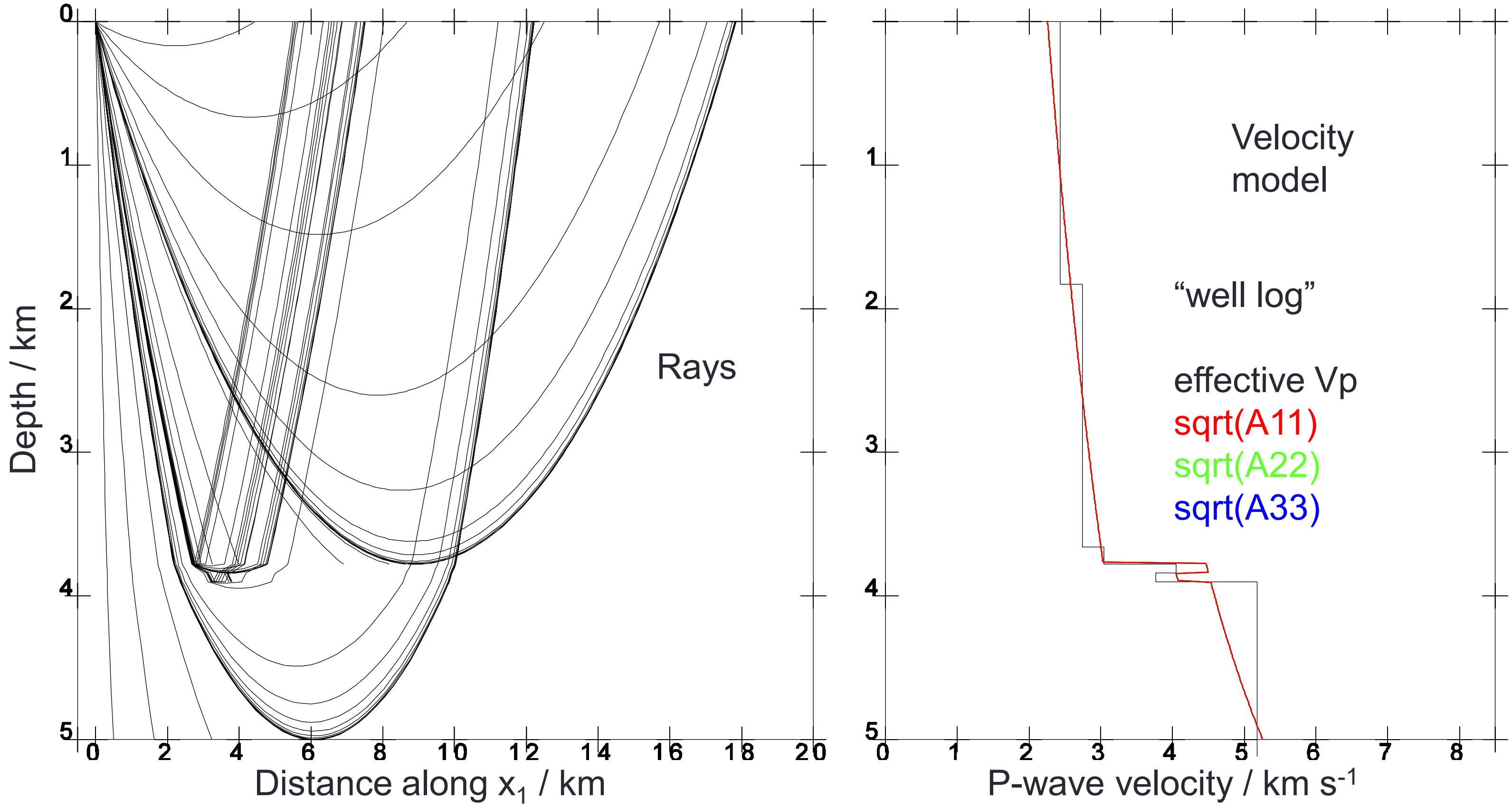


Anisotropic model 6 – lower layer VTI + cracks in the x2-x3 plane

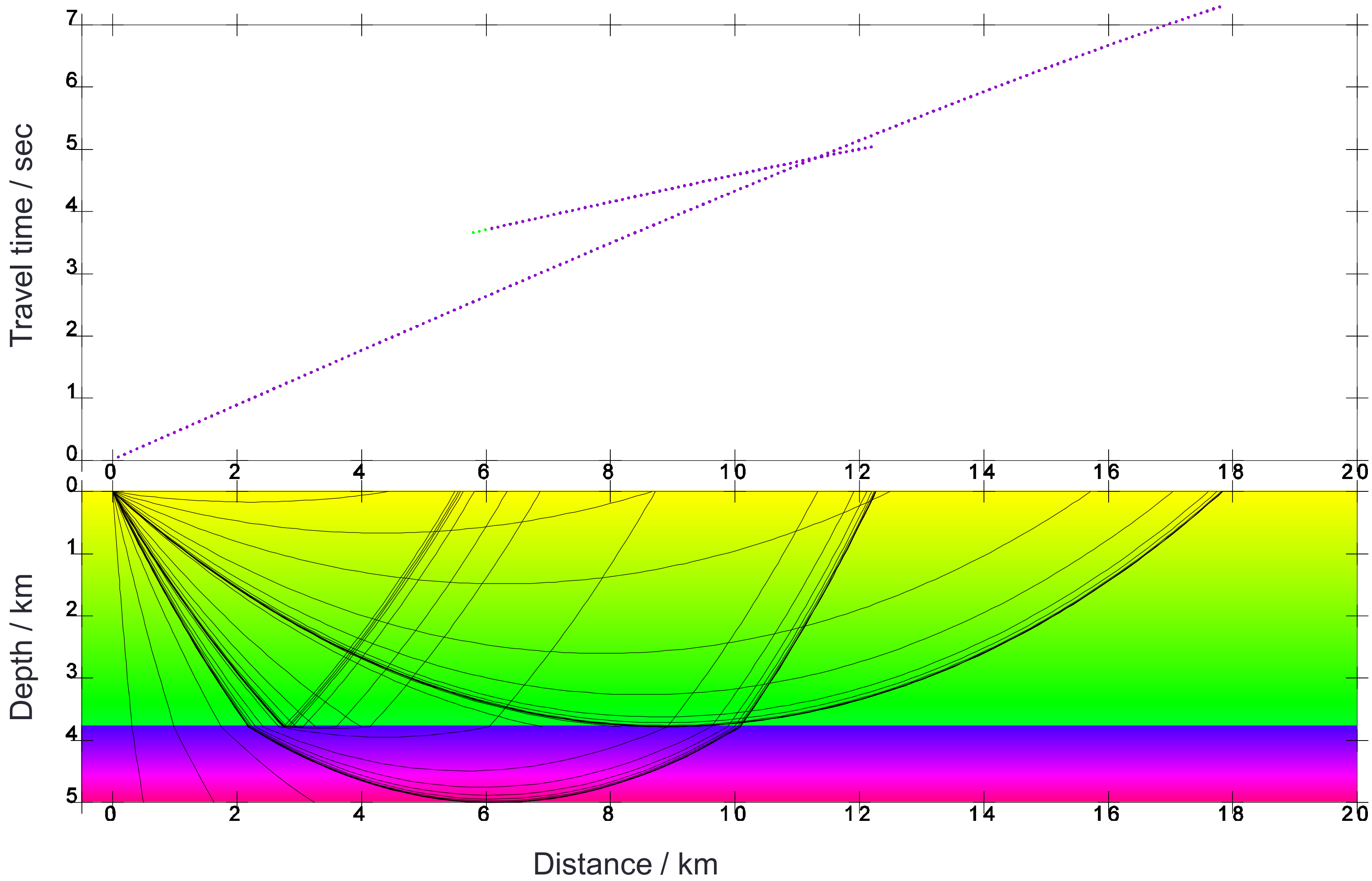


=> adding cracks in the x2-x3 plane to the VTI layer has similar effects as adding them to the isotropic layer

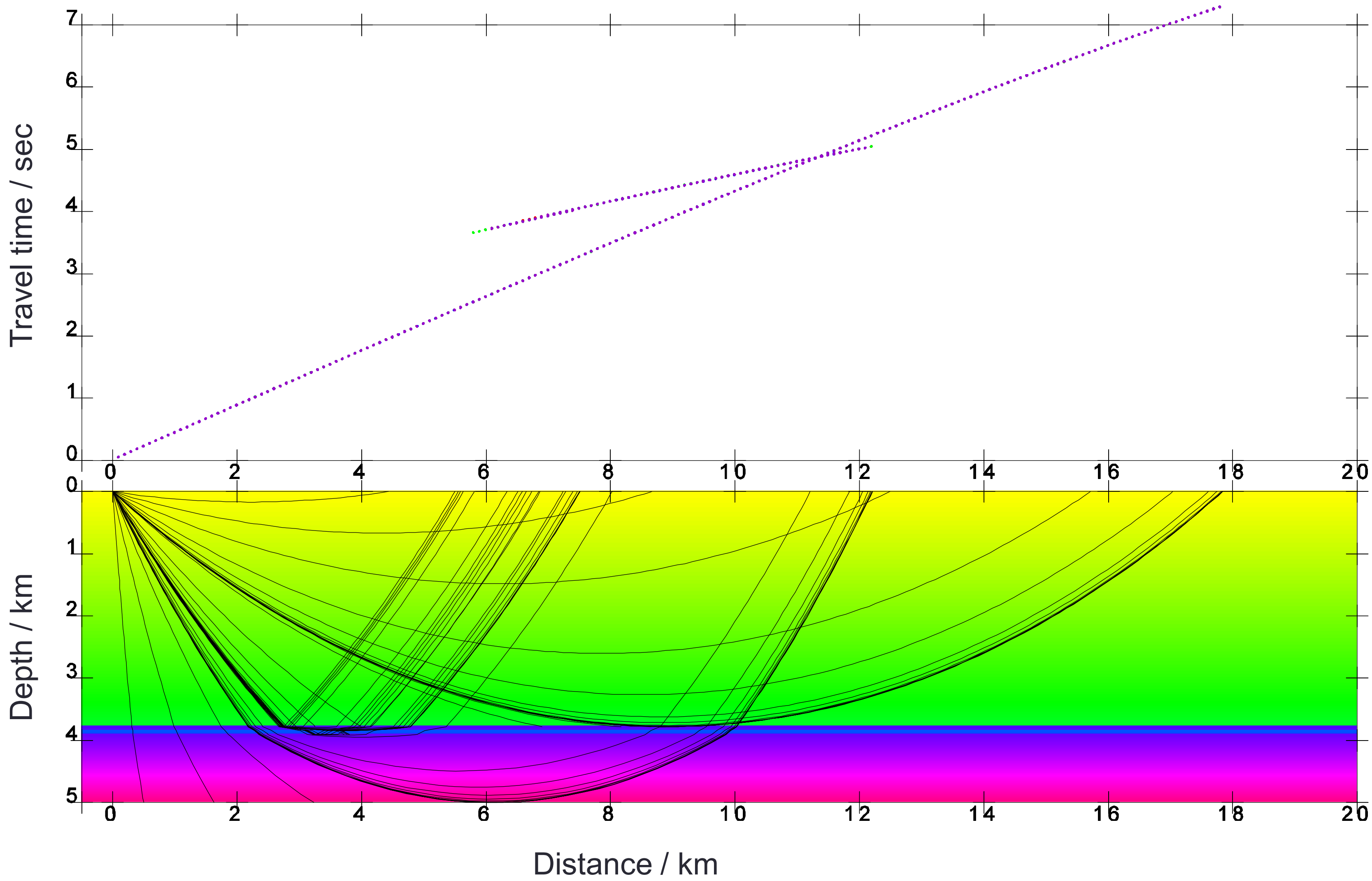
Isotropic model 3 – thin low velocity channel



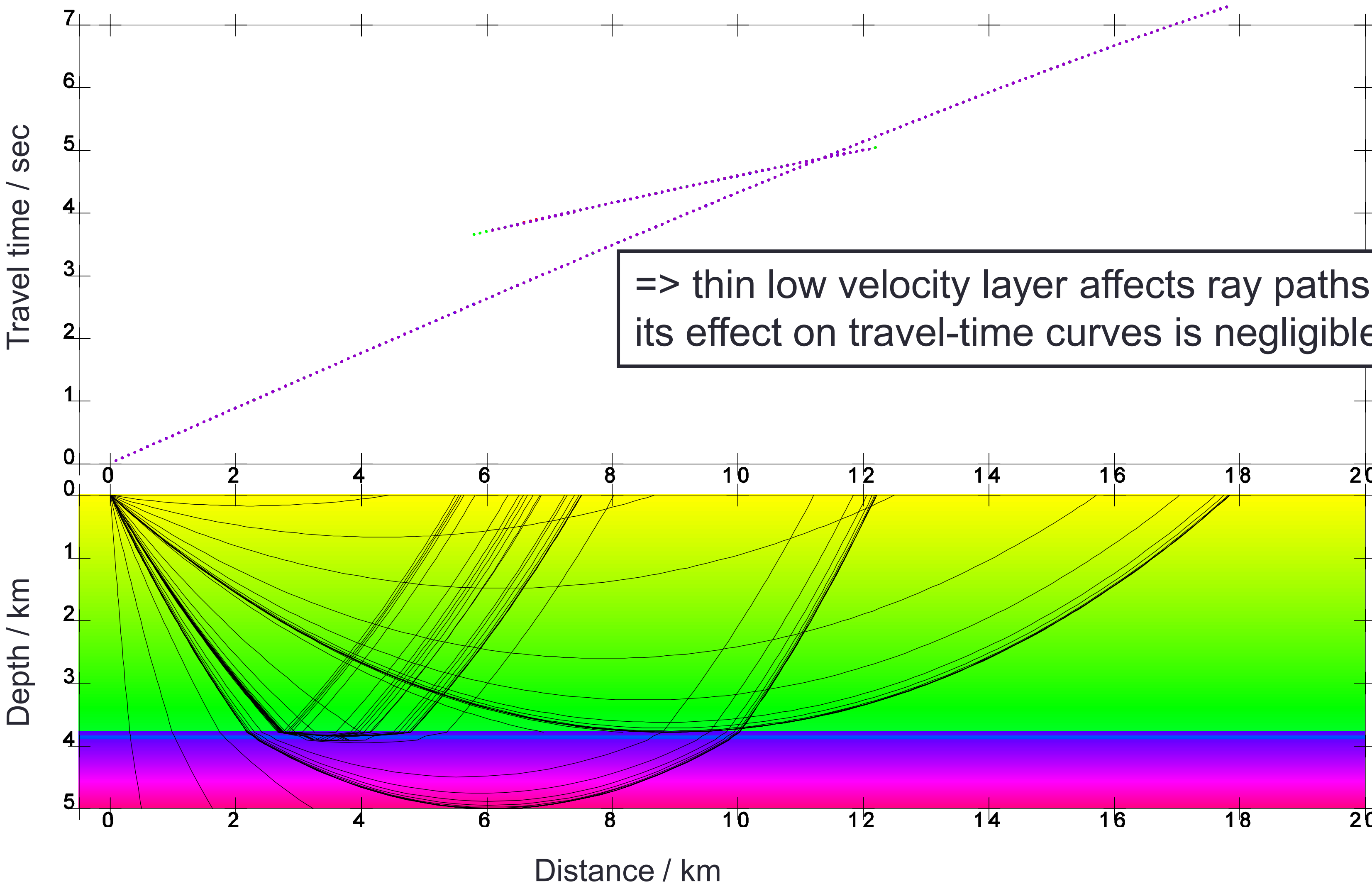
Isotropic model 2



Isotropic model 3 – thin low velocity channel

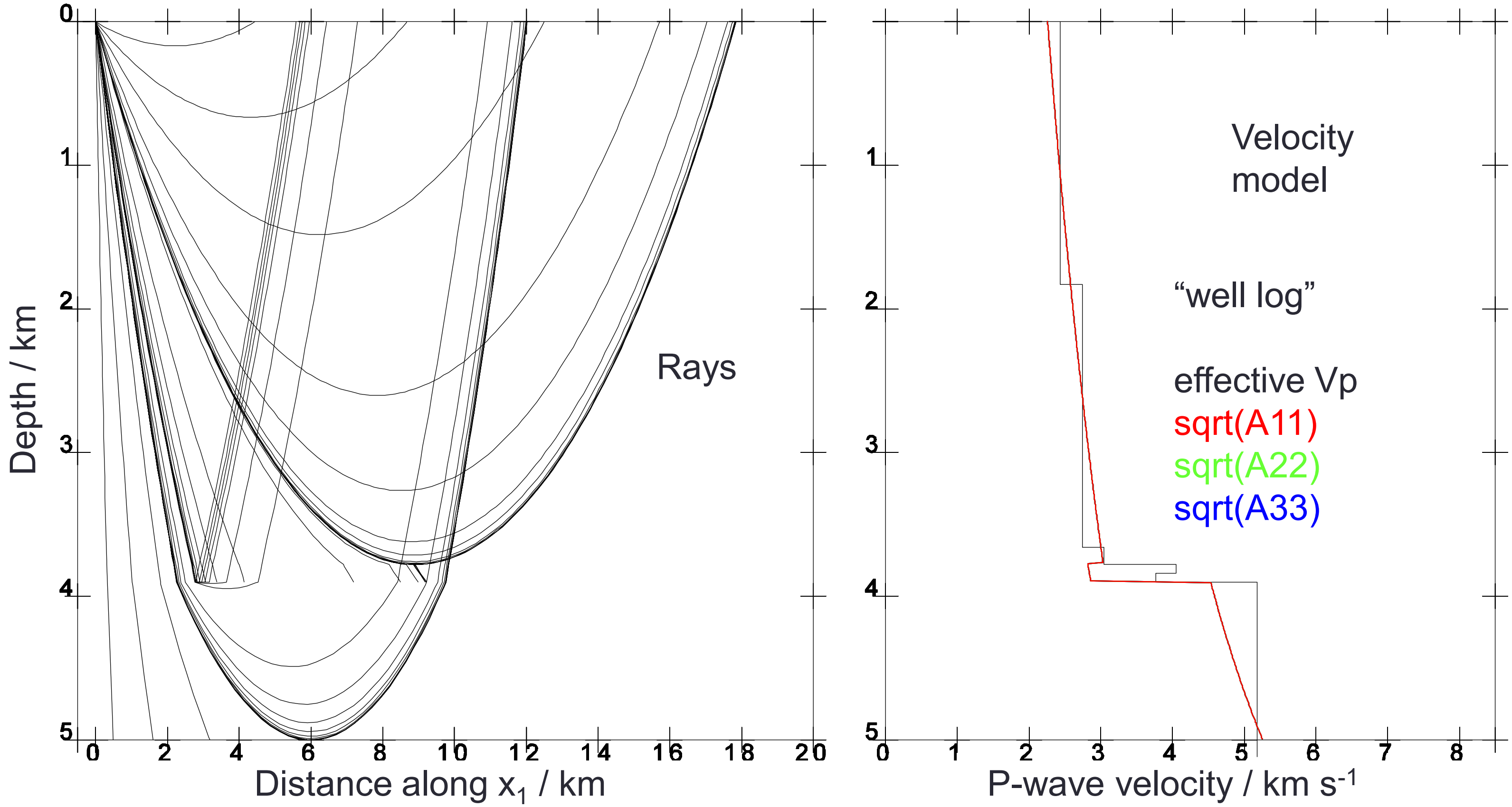


Isotropic model 3 – thin low velocity channel

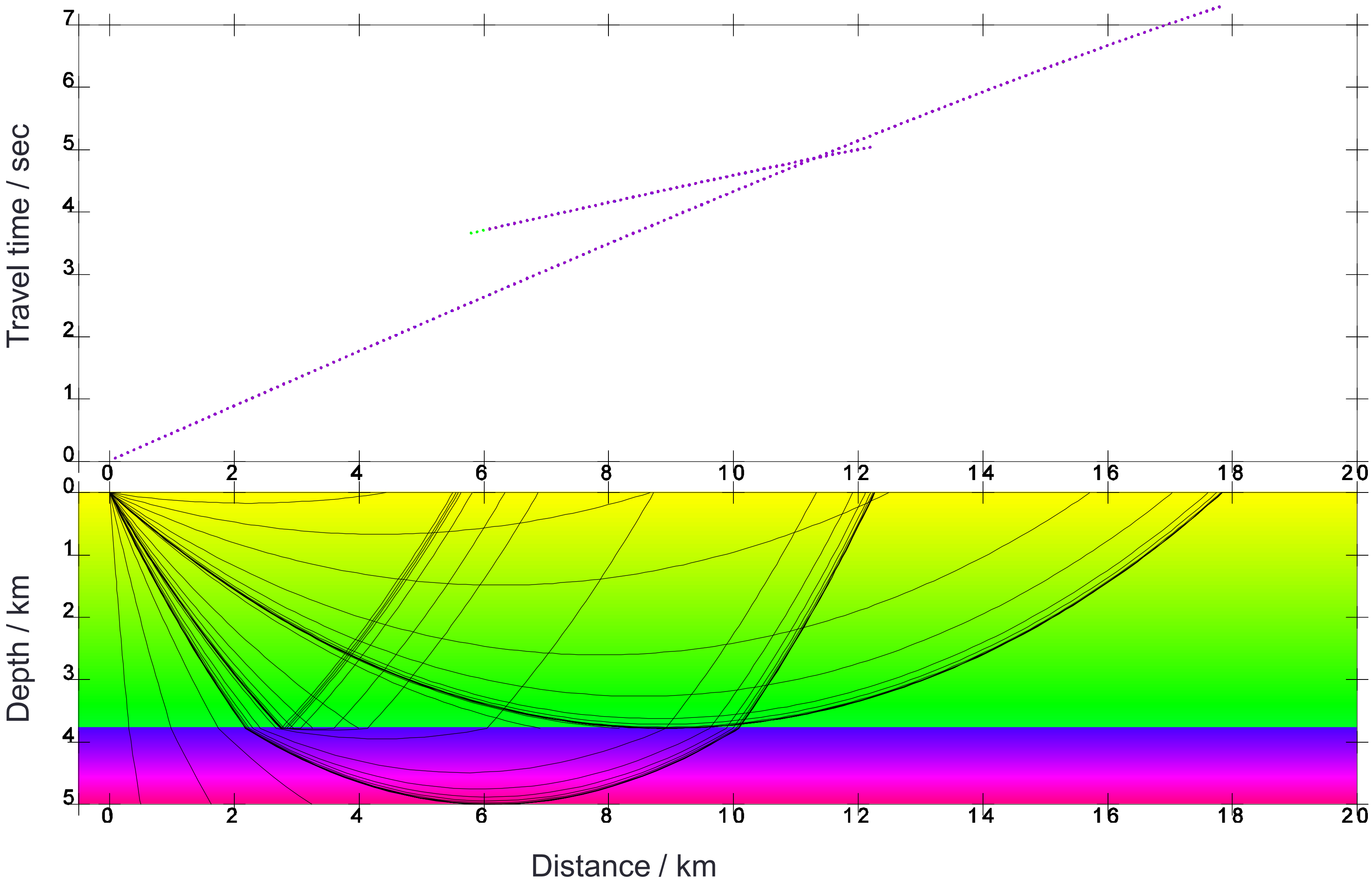


=> thin low velocity layer affects ray paths, its effect on travel-time curves is negligible

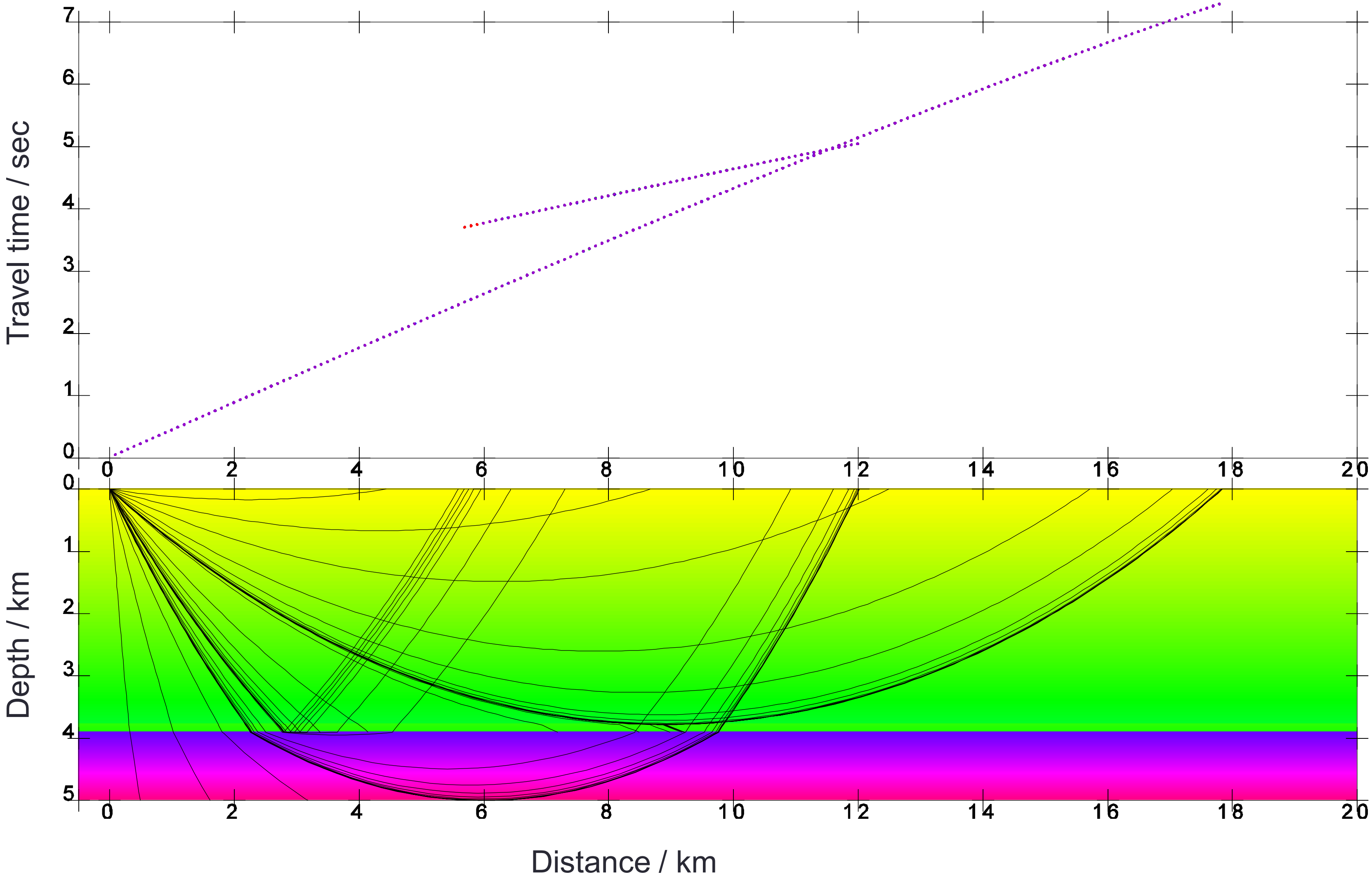
Isotropic model 4 – thin layer of a very low velocity



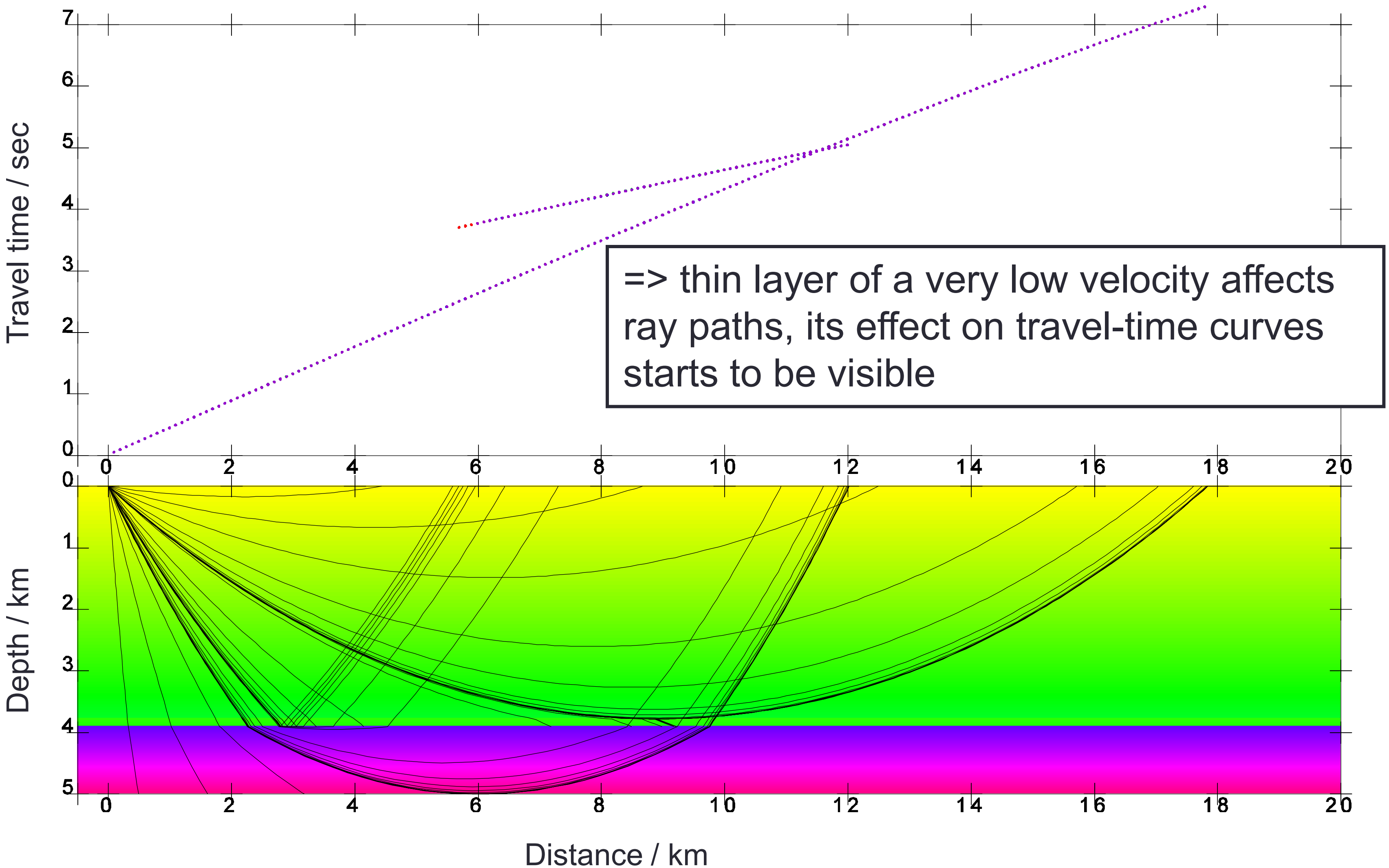
Isotropic model 2



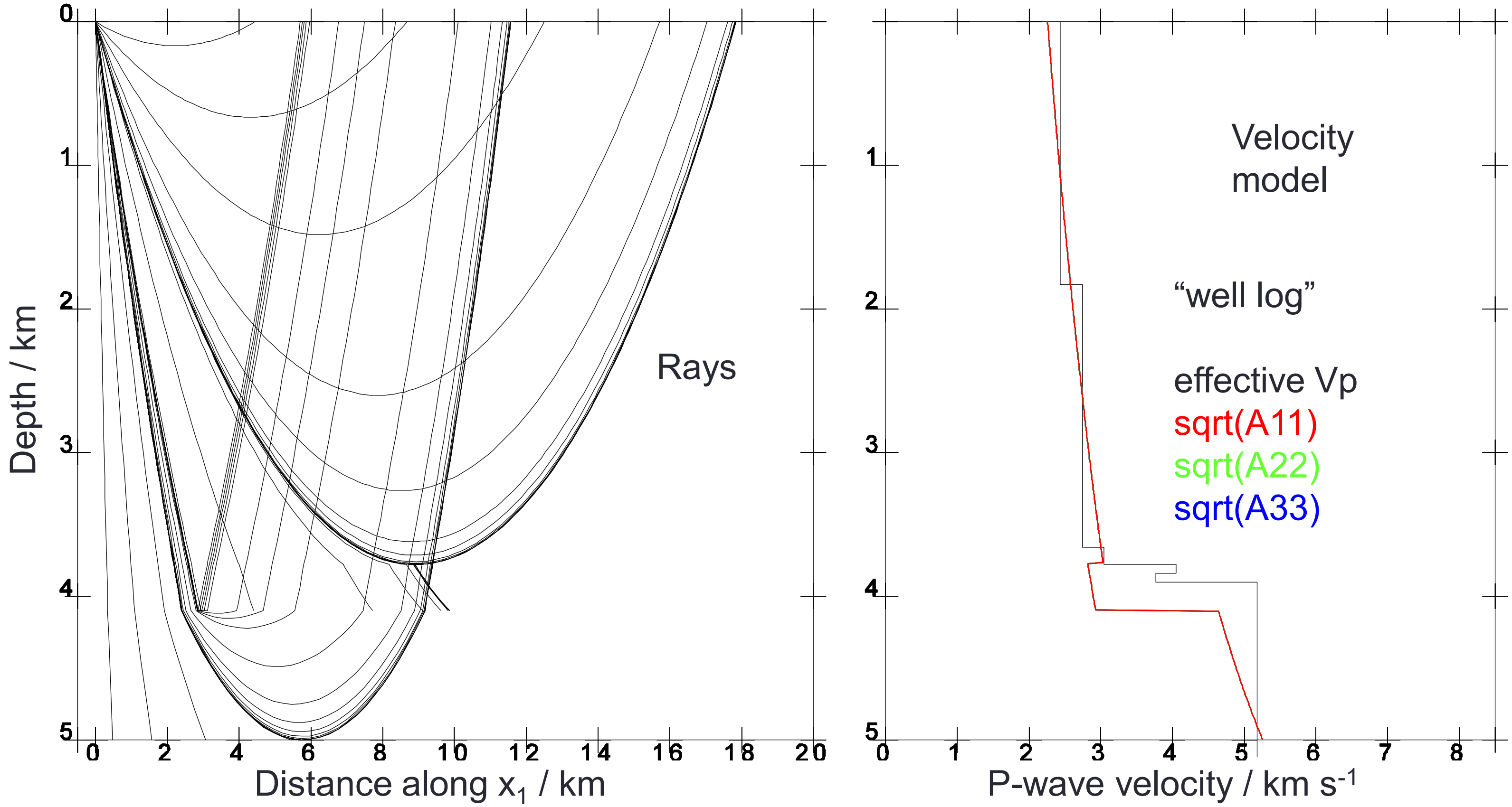
Isotropic model 4 – thin layer of a very low velocity



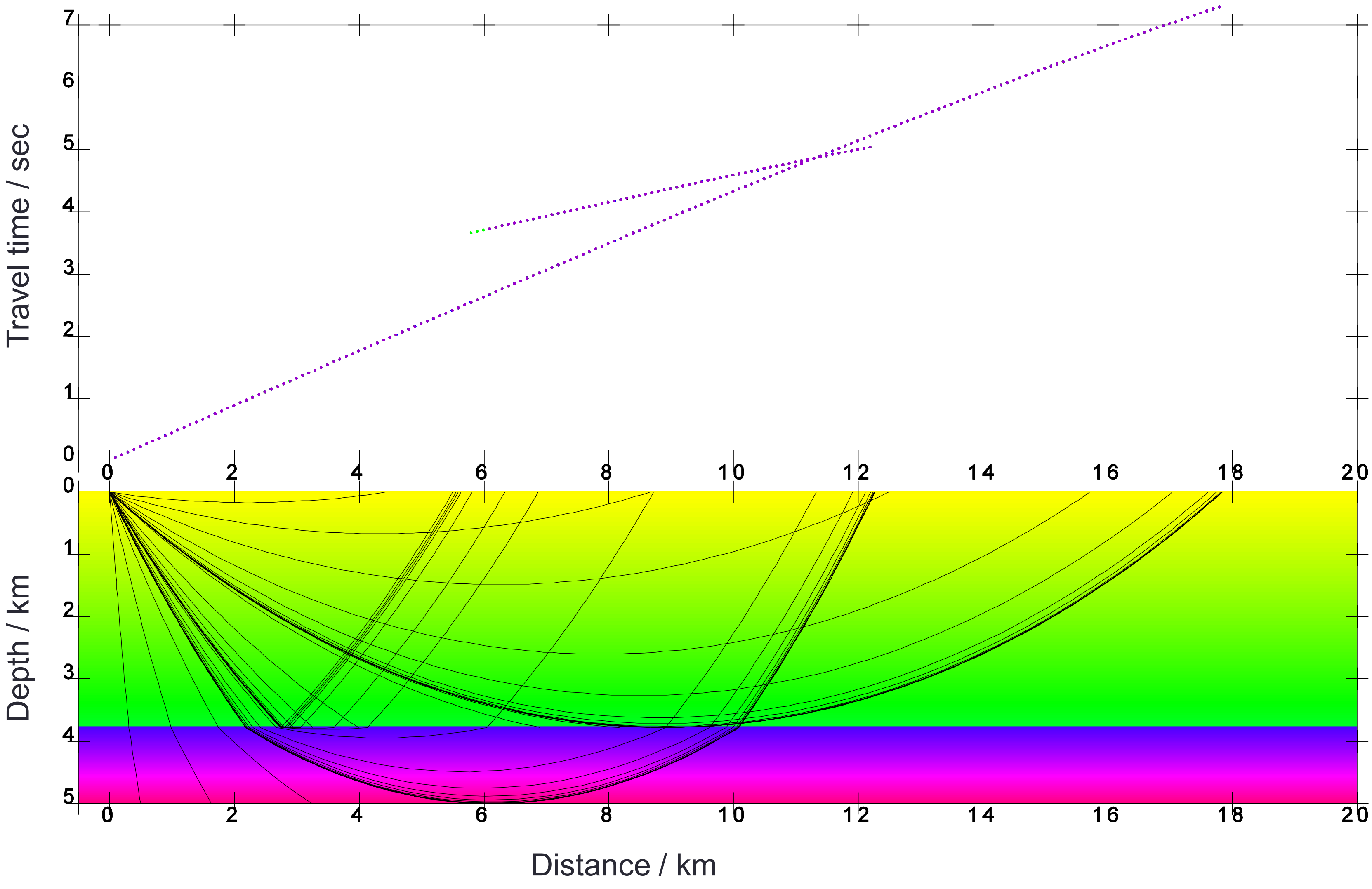
Isotropic model 4 – thin layer of a very low velocity



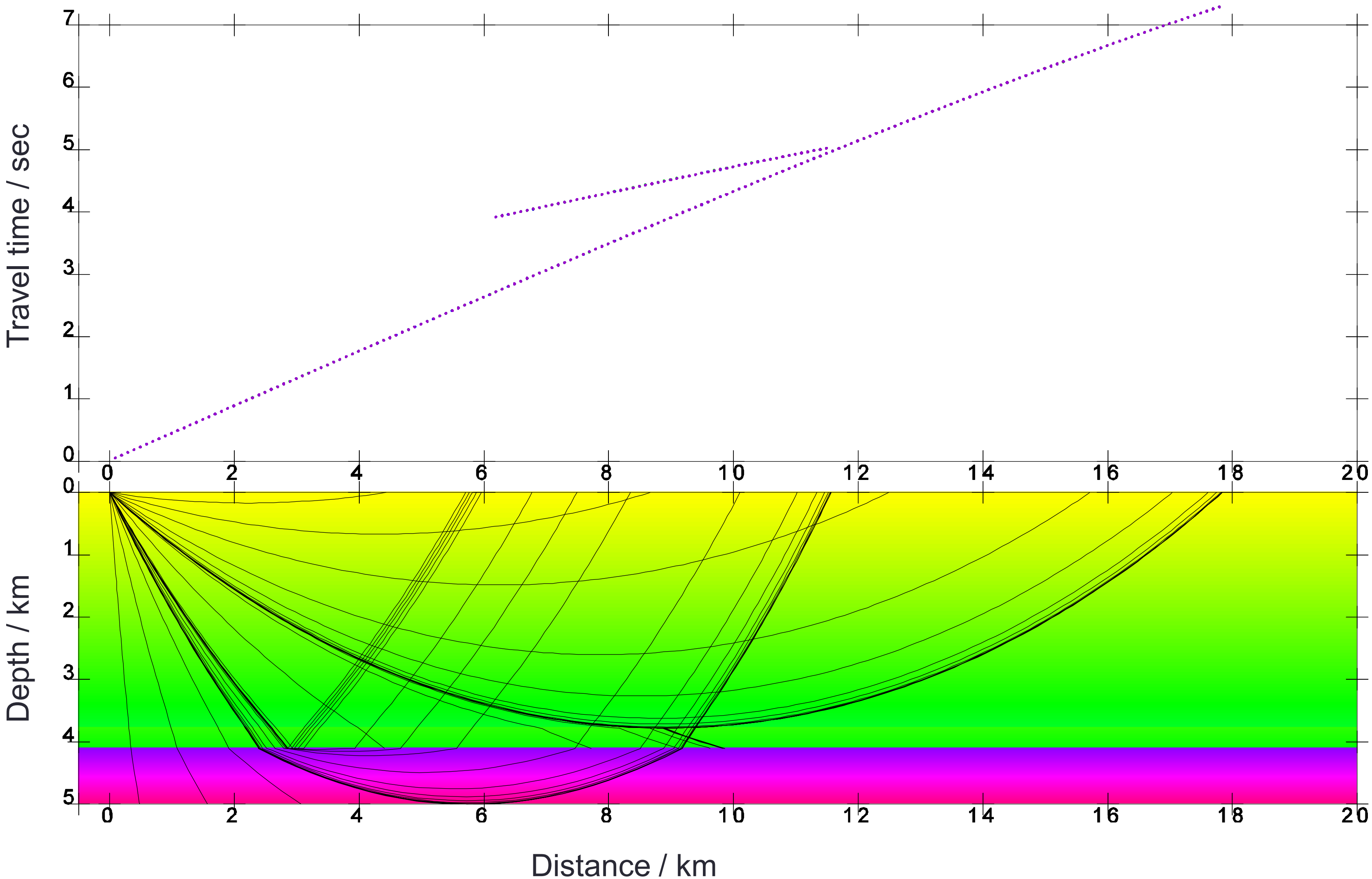
Isotropic model 5 – thicker layer of a very low velocity



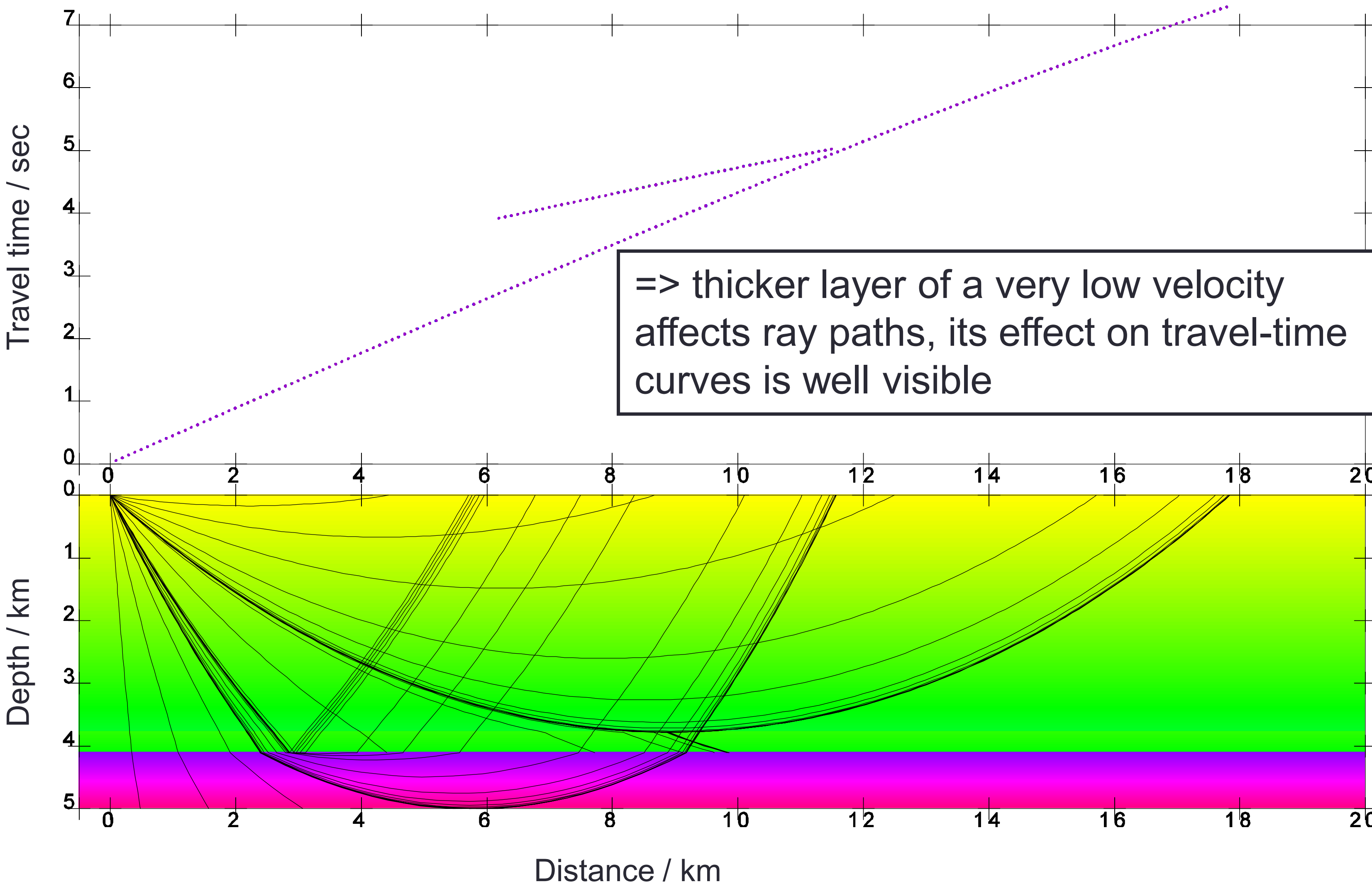
Isotropic model 2



Isotropic model 5 – thicker layer of a very low velocity

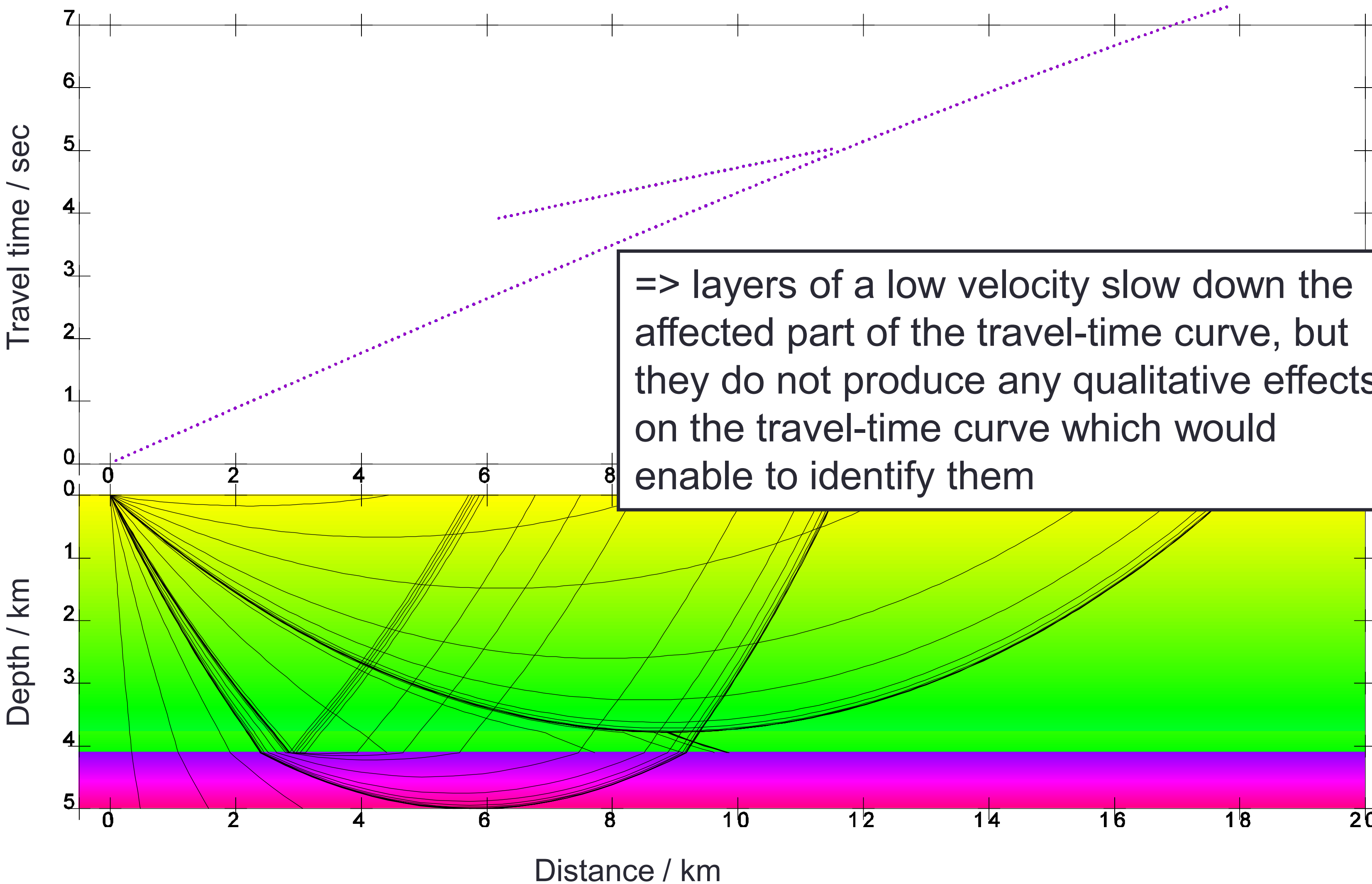


Isotropic model 5 – thicker layer of a very low velocity



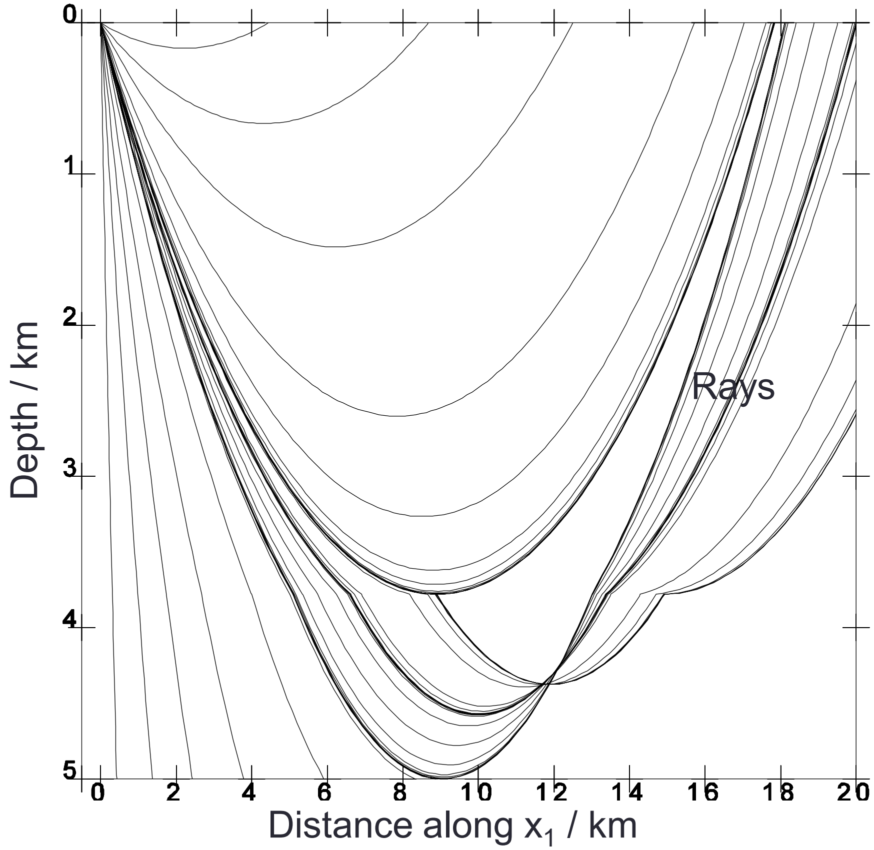
=> thicker layer of a very low velocity affects ray paths, its effect on travel-time curves is well visible

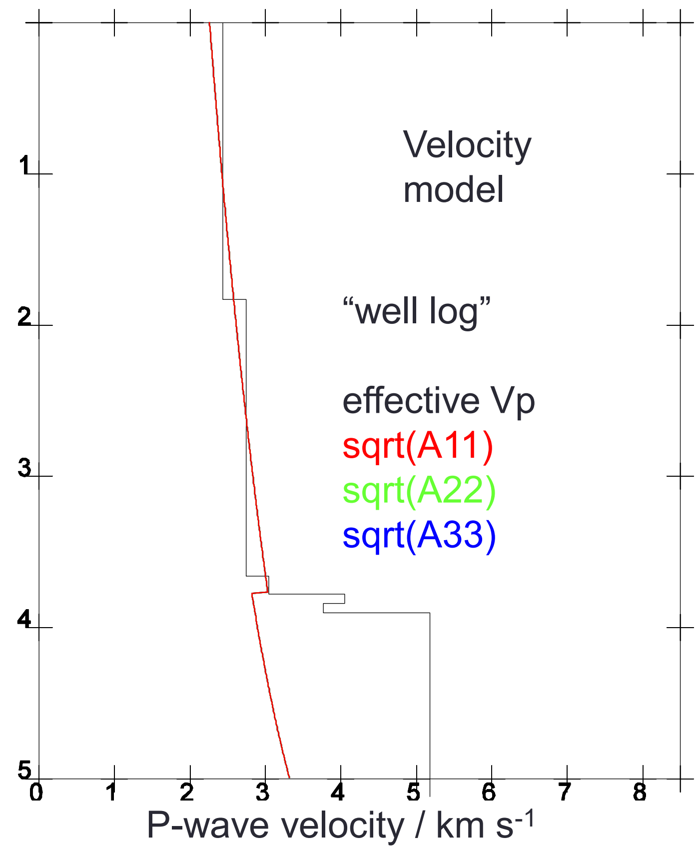
Isotropic model 5 – thicker layer of a very low velocity



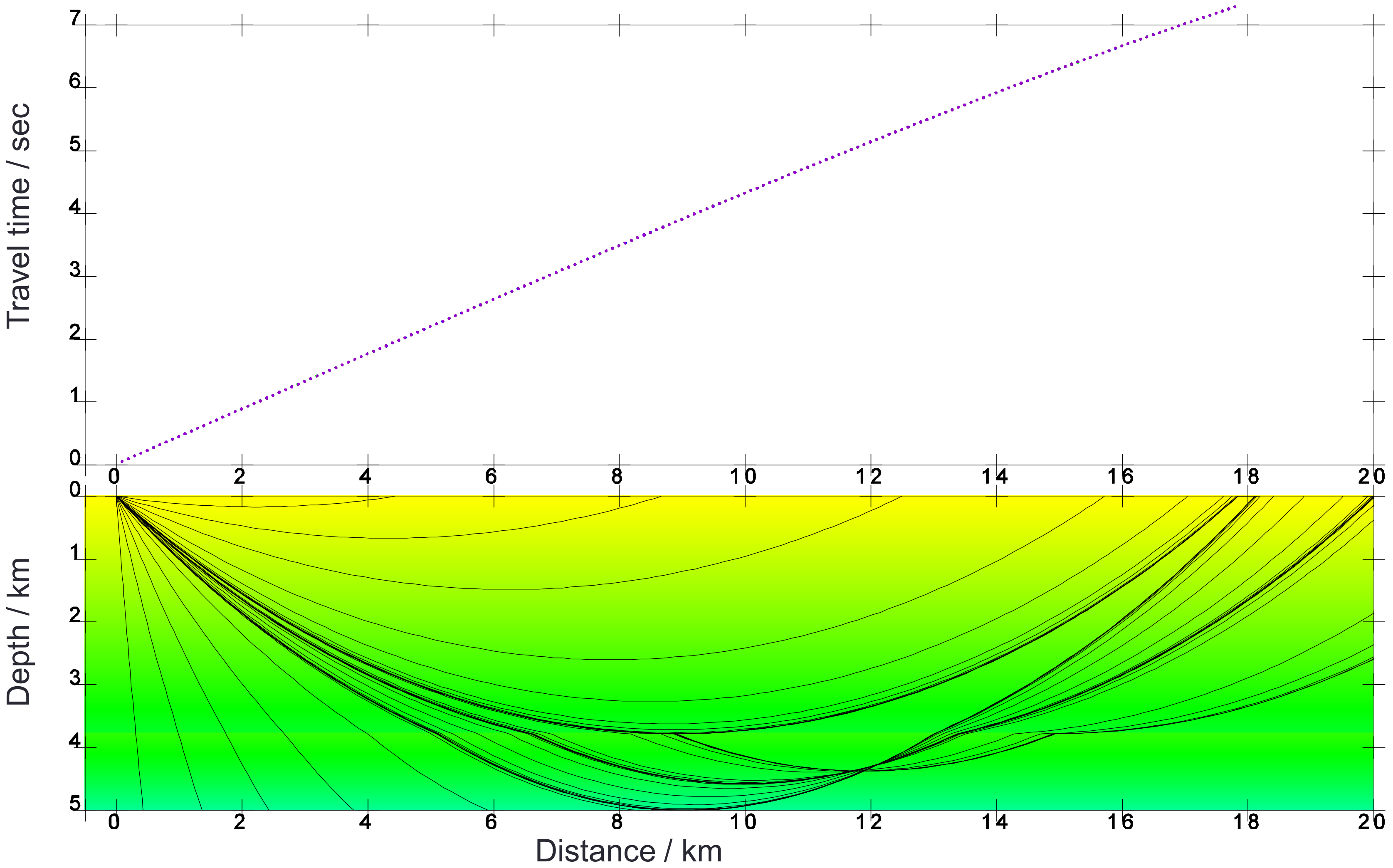
=> layers of a low velocity slow down the affected part of the travel-time curve, but they do not produce any qualitative effects on the travel-time curve which would enable to identify them

Isotropic model 6 – low velocity halfspace

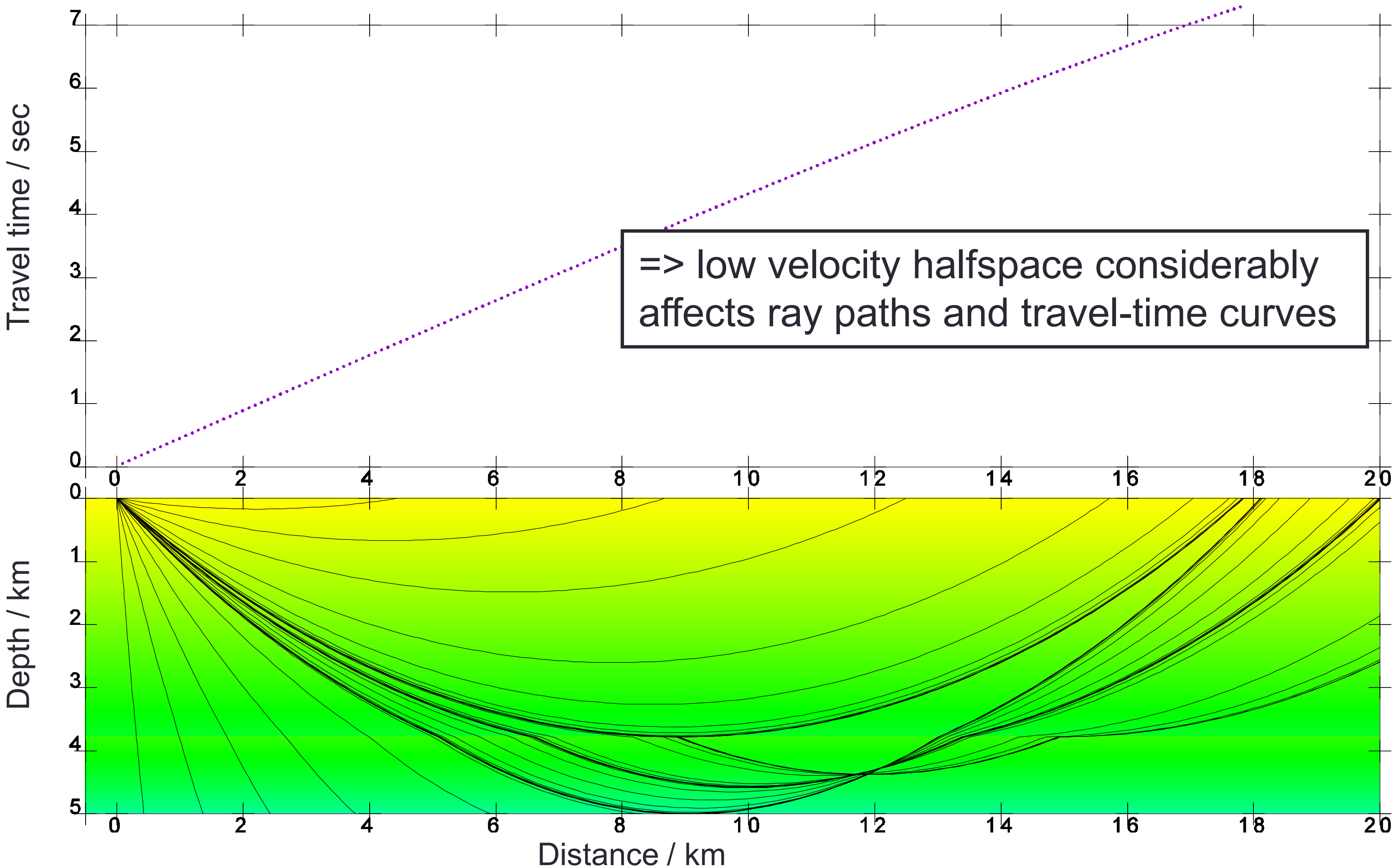




Isotropic model 6 – low velocity halfspace



Isotropic model 6 – low velocity halfspace



Conclusions

- In the models considered in this study, the effects of the vertical cracks on the P-wave travel-time curves start to be visible from the anisotropy of 7.5%.

- The vertical cracks slow down the rays propagating perpendicularly to the cracks, while their influence on the rays propagating parallel to the cracks is negligible. This effect appears similarly either when we introduce vertical cracks to the isotropic layer, or when we introduce them to the VTI layer.

- Structural interface declined away from the source in the isotropic model has similar effects on the travel-time curves as the vertical cracks, while the interface inclined towards the source has opposite effects. Effects of dipping interface and of vertical cracks sum up.

- Low-velocity channels slow down the affected part of the travel-time curve, but do not produce any qualitative effects which would enable to identify them from the travel-time curves.

Acknowledgments

I am grateful to Leo Eisner who motivated me to perform this study and came with many ideas regarding which models should be investigated.

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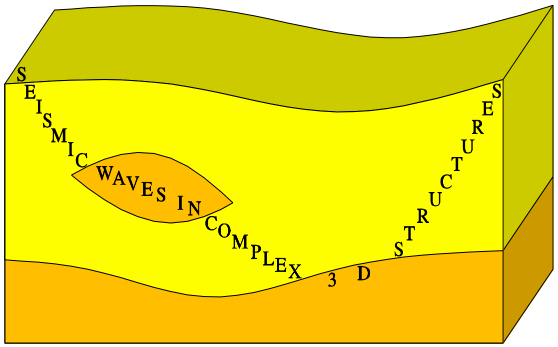

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