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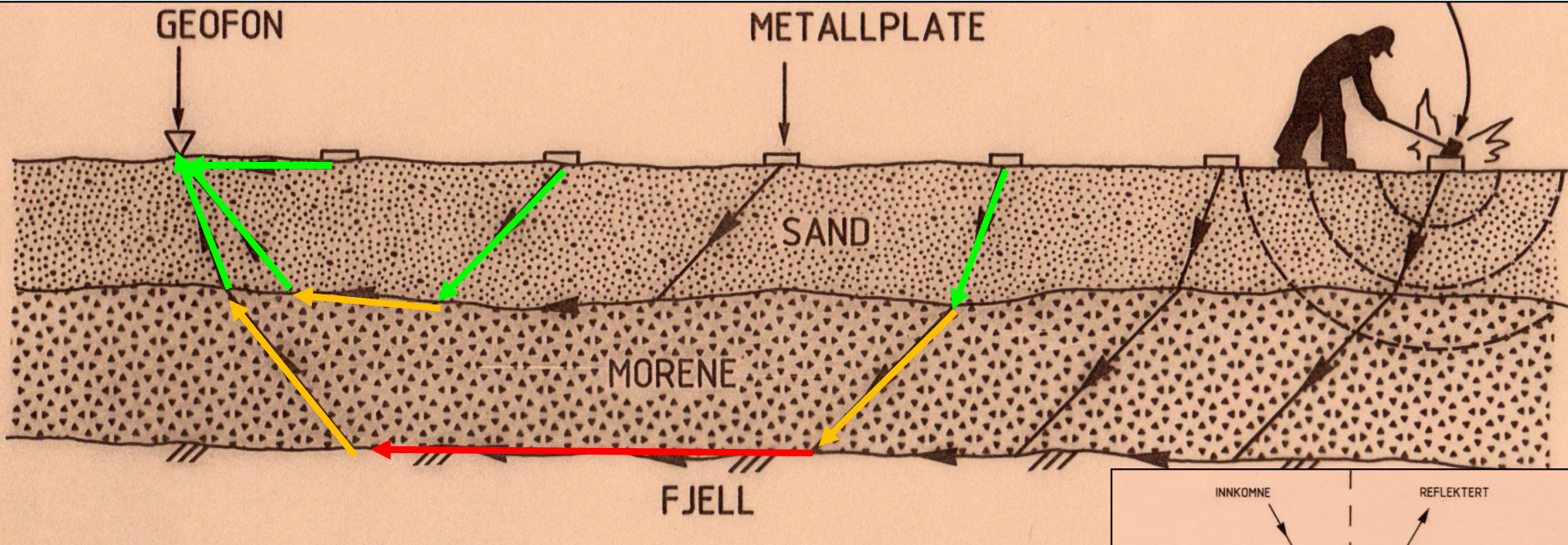
TEORETISK BAKGRUNN. KVALITET PÅ REFRAKSJONSSEISMISK TOMOGRAFI

Jan Steinar Rønning

Vårsleppet 2025, Oslo 6. mars 2025



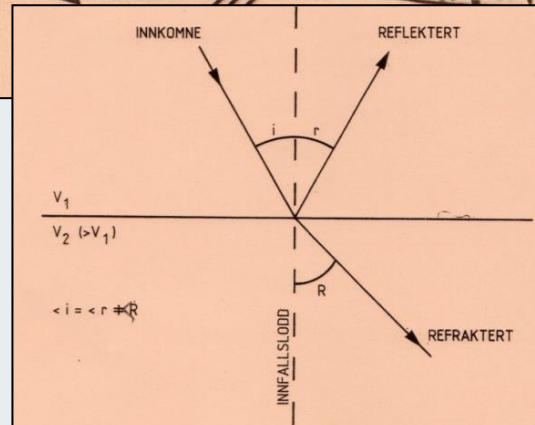
Teoretisk bakgrunn, tradisjonell lagdelt modell.



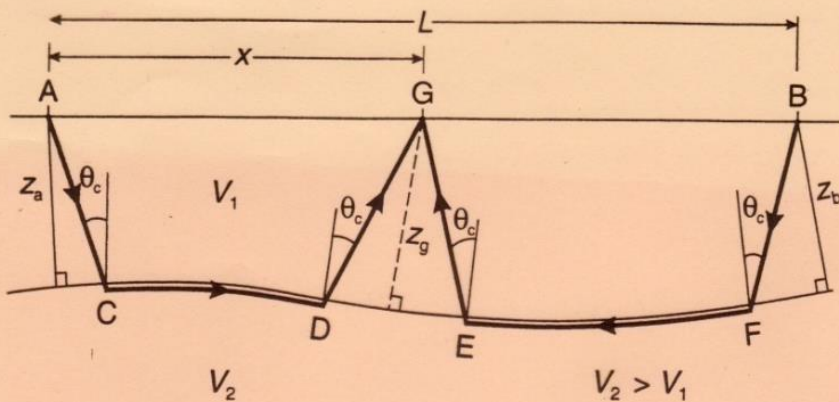
$V_1 < V_2 < V_3$
 $500 < 2000 < 5000 \text{ m/s}$

Snell's law:

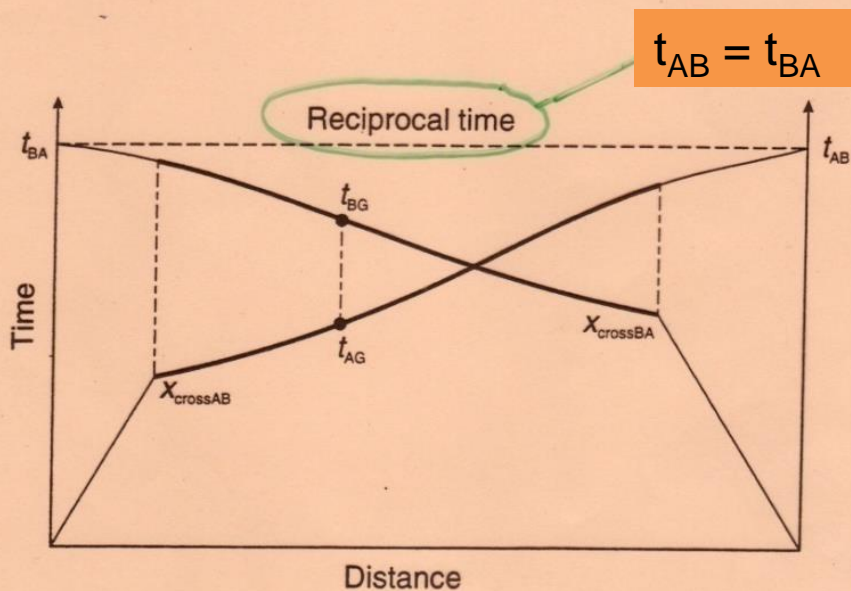
$$\frac{\sin i}{\sin R} = \frac{V_1}{V_2}$$



(A)



(B)



Hagedoorns +/- Method

Plus method finds depth at geophones **between shots!**

Minus method finds the velocity in layer 2.

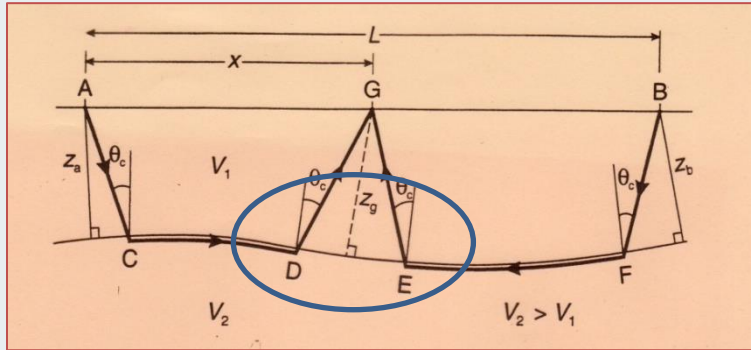
$$T^+ = t_{AG} + t_{BG} - t_{AB} = 2\delta t_g = 2z_g (\cos \theta_c) / V_1.$$

$$T^- = t_{AG} - t_{GB} = (2x - L) / V_2 + \delta t_a - \delta t_b.$$

Forutsetninger:

- Homogene lag
- Stor hastighetskontrast
- Lagenes dip $< 10^\circ$

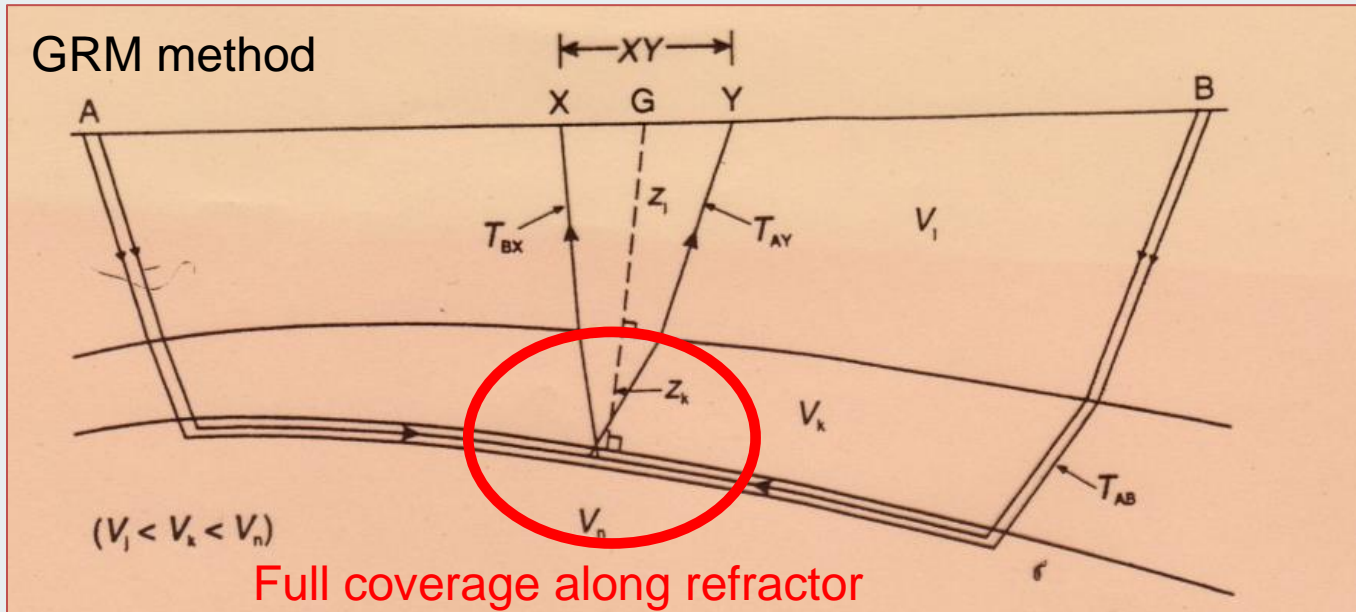
Hagedoorns +/- method

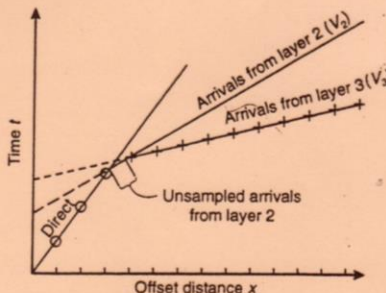
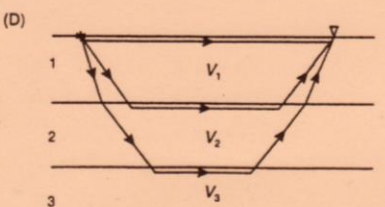
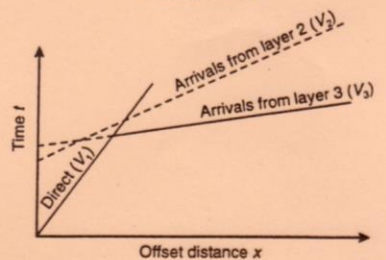
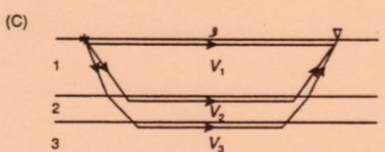
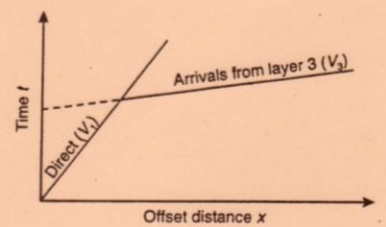
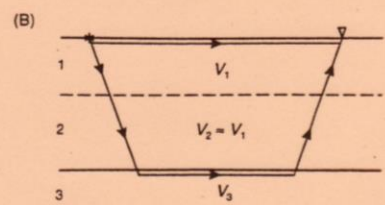
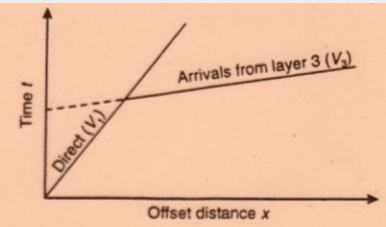
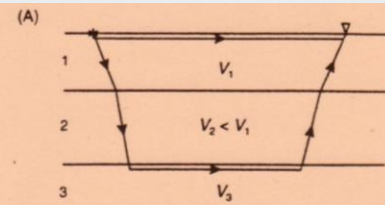


Generalised Reciprocal Method, GRM (Palmer 1980)

- more accurate interpretation

GRM method

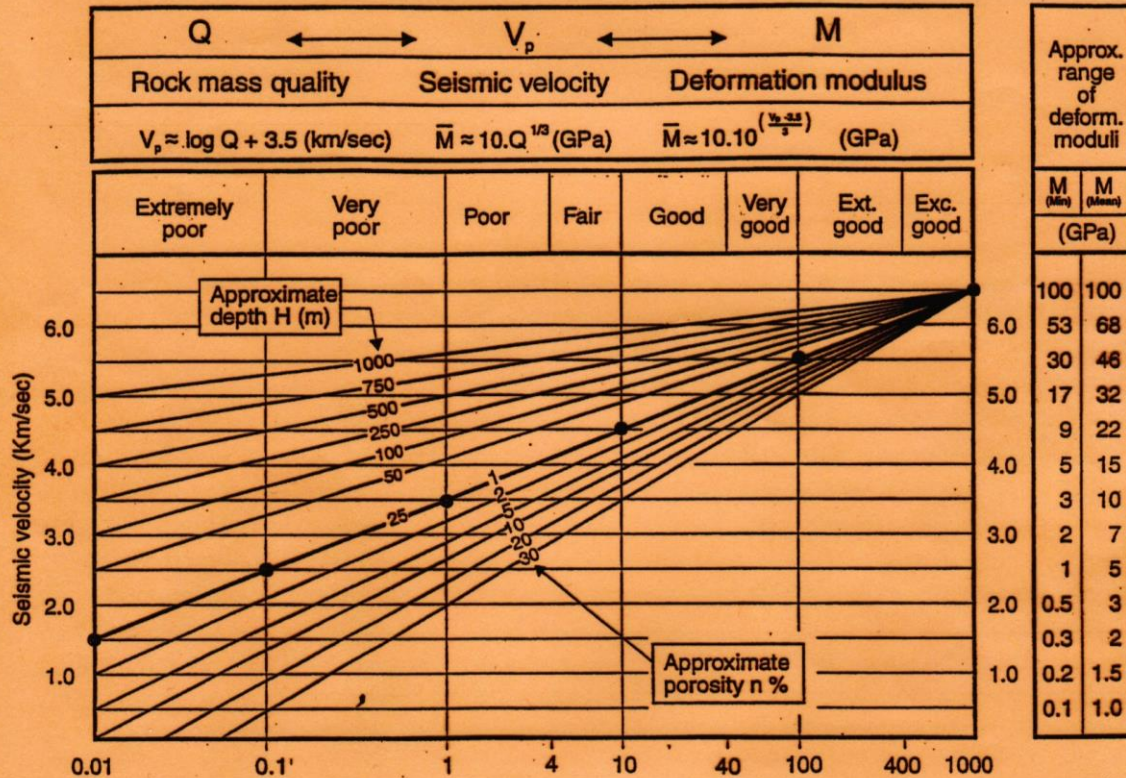




Error sources:

1. **Velocity inversion**
 $V_1 > V_2 < V_3$
2. **No velocity contrast**
 $V_1 = V_2$
3. **Blind zone**
 $V_1 < V_2 < V_3$
4. **Geofon spacing**

Interpretation of rock mass quality from Vp

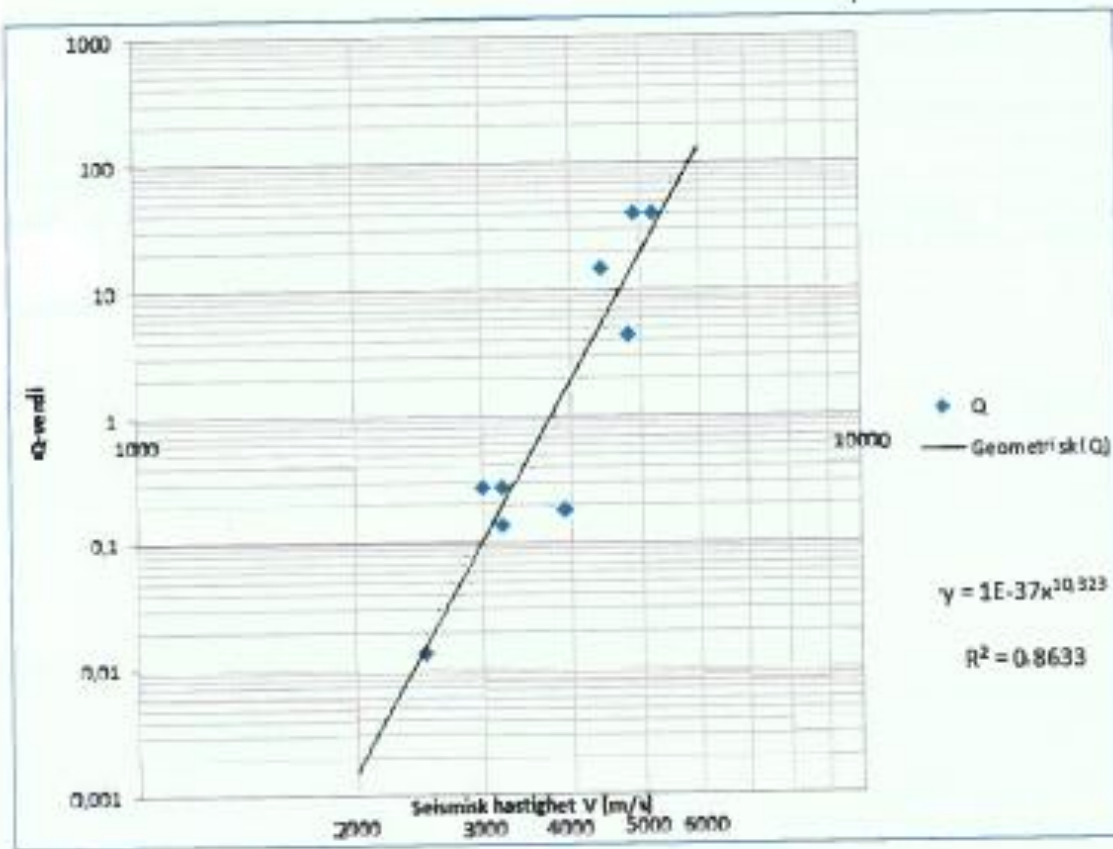


$$V_p = \lg Q + 3,5 \text{ (km/s)}$$

Barton 1995: ISRM
Congress Proceedings,
TOKYO, Also Barton 2007

$$Q_c = \left(\frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \right) \frac{\sigma_c}{100}$$

Correlation **Q-value** from drillcore logging and **Vp** from refraction seismics at same location.



Figur 12 Statistisk regresjon mellom Q-verdi og seismisk hastighet.

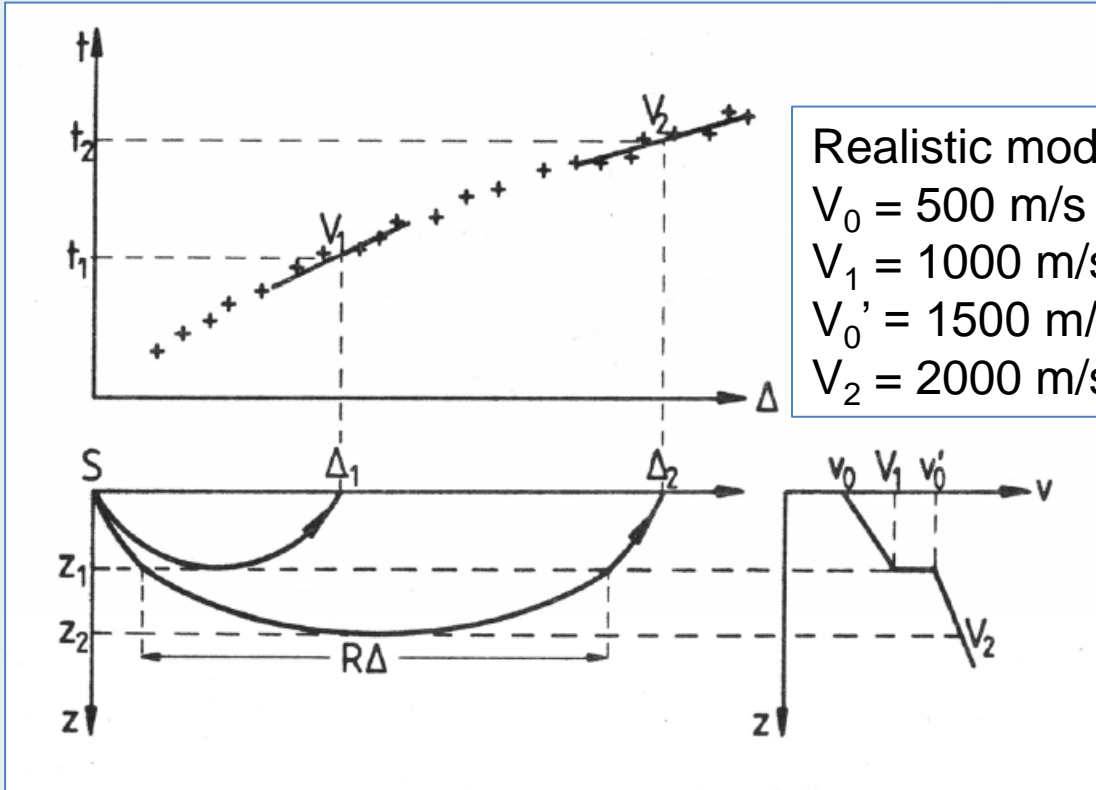
$$Q = 10^{-37} \cdot V^{10.923} \quad (1)$$

Gjelsnes, H.C. & Eidesen, J.M.
Bergmekanikkdagen 2013.
Data from the ROGFAST project.

TOMOGRAPHIC INVERSION OF REFRACTION SEISMIC.



Gradual change in velocity towards depth, **DIVING WAVES**



Traveltime graph is curved

No crossover point

Impossible to read intercept time

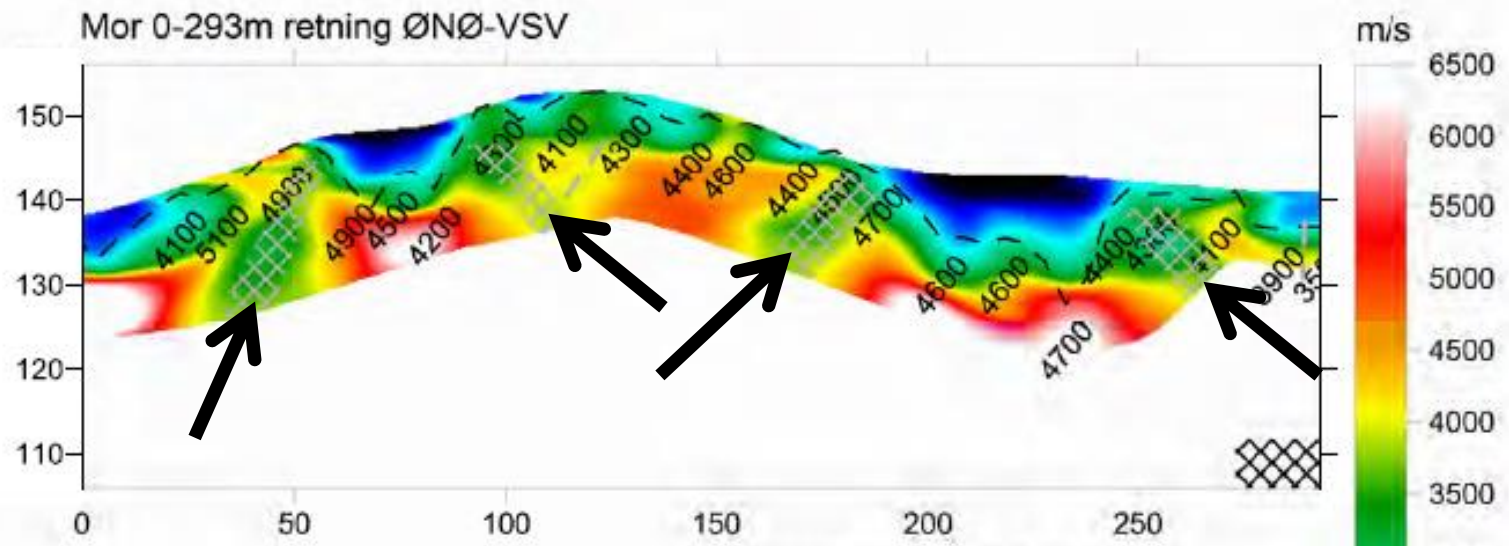
Standard methods for depth calculations is inappropriate.


Solution: Refraction seismic tomography with diving waves?


Several inversion programs available:

- **GeoGiga (Used by IMPAKT, Geophysix)**
- **SeisImager/2D (Geometrics)**
- **GeoCT-II**
- **Rayfract, used by NGU (and GeoPhysix and GeoVista)**
- **Others!**

Early example: Combined GRM and tomographic inversion. Dip interpretation??



- - - - - Tolket fjelloverflate fra refraksjonsseismisk 2-lagsmodell
 Tolket svakhetszone i 2-lagsmodell
 5000 Hastighet i fjelloverflate

 Tolket tomografi:
 Tolket svaghetszone
 - - - - - Tolket usikker svakhetszone

Colours: TOMOGRAPHY
 Black numbers: GRM

Fracture zones outcropping at bedrock heights!

De-MOTIVATION

Agreement:

GRM: 6500 m/s

Tomography: > 6000 m/s

Divergency:

GRM: 5600 m/s,.

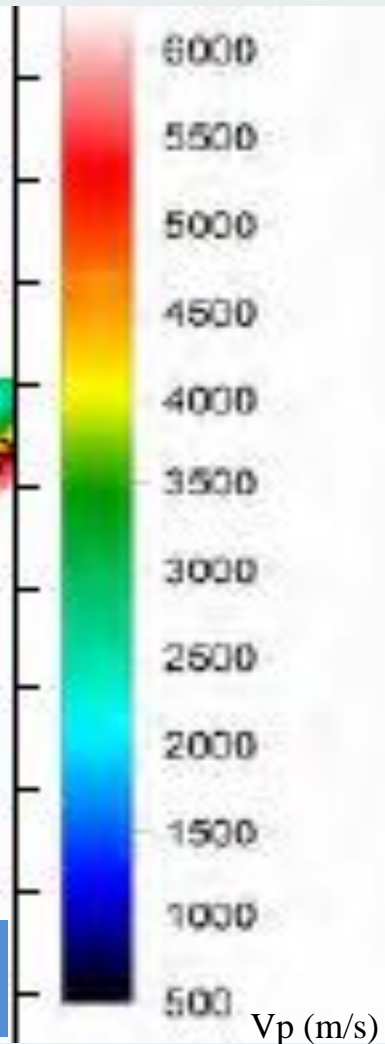
Very good rock quality!

Tomography: 2000 – 2500 m/s

Extremly bad rock quality!

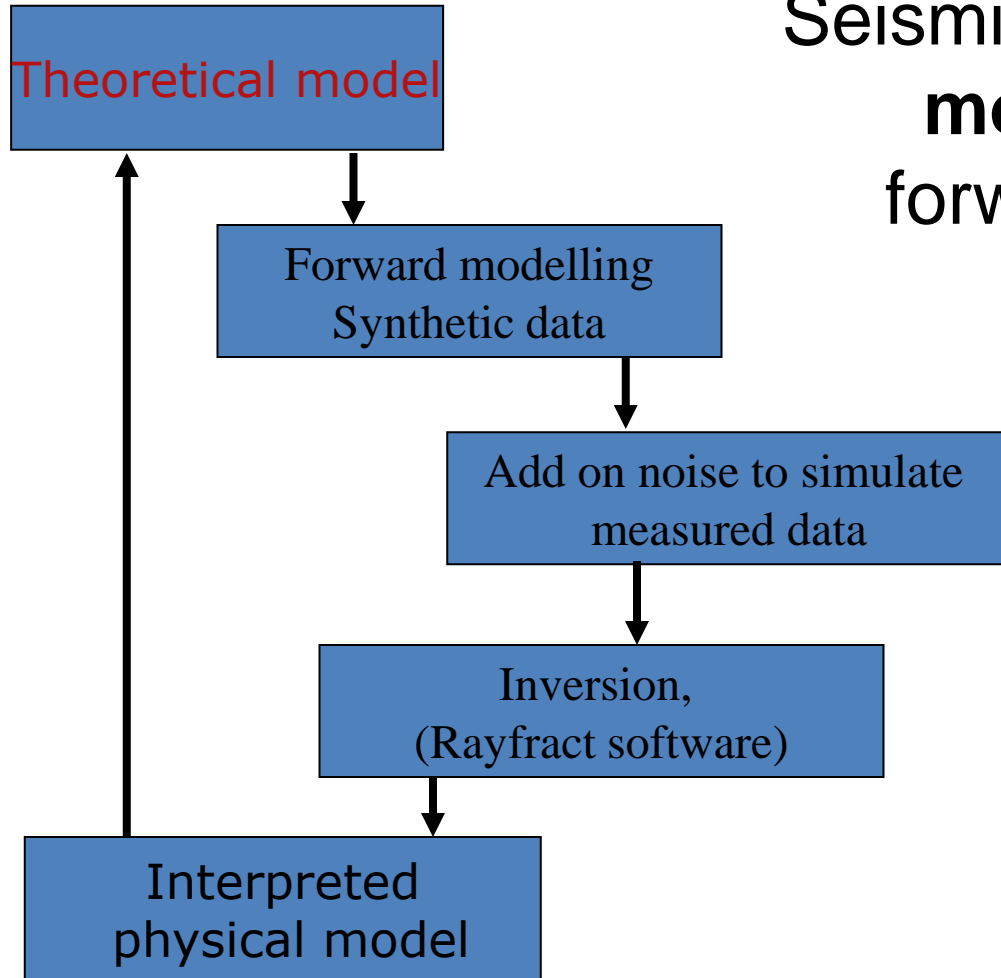
Colours: TOMOGRAPHY

Black numbers: GRM

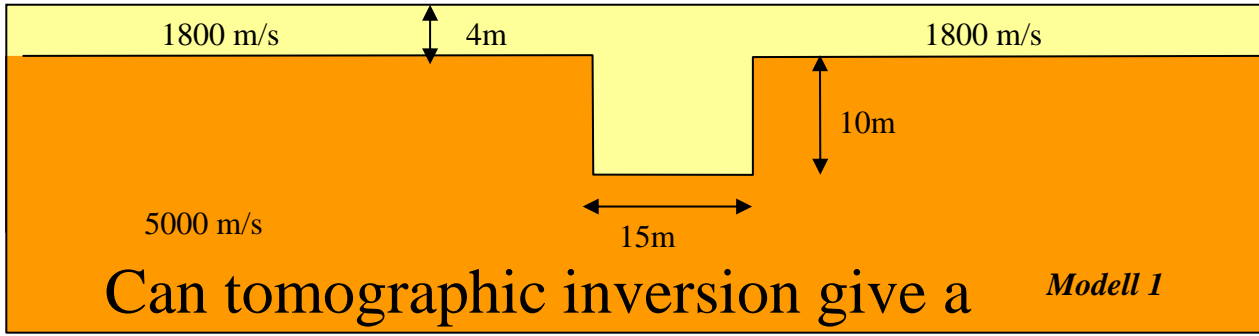


At NGU, we have performed seismic modelling to really understand how tomographic inversion of refraction seismic is working!

Seismic tomographic **modelling** using forward modelling and inversion.

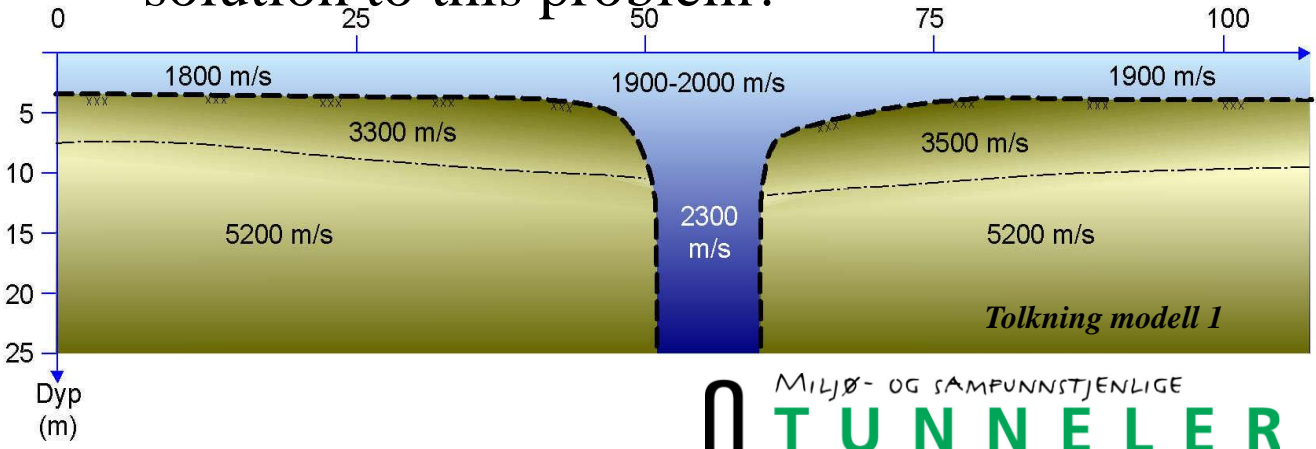


MOTIVATION: Blind test, traditional interpretation of synthetic data from a model (H. Westerdahl – O.C. Pedersen)



Synthetic data were calculated from this model.

Can tomographic inversion give a solution to this problem?



This is the interpretation from an expert. Fracture zone in bedrock, open towards the depth.

Ray-tracing and automatic wavefront inversion, 10 m deep depression, without and with till filling (Green material, $V = 2500$ m/s).

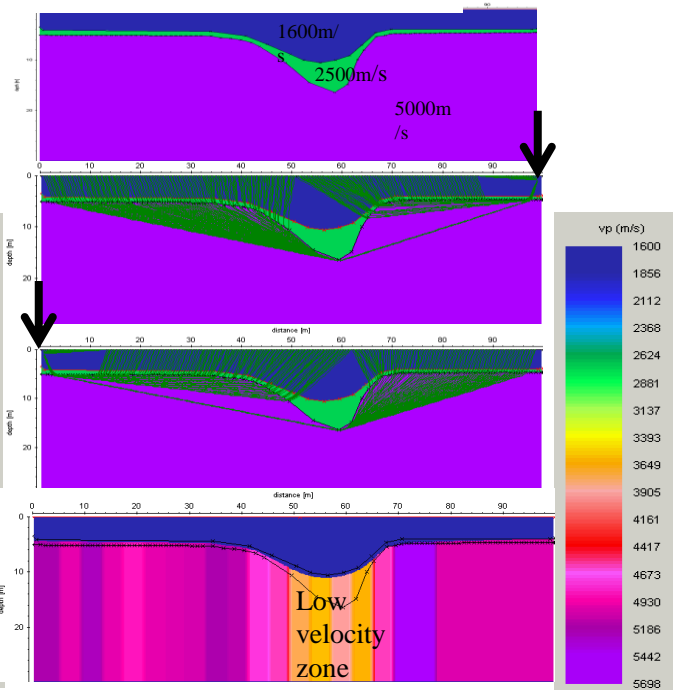
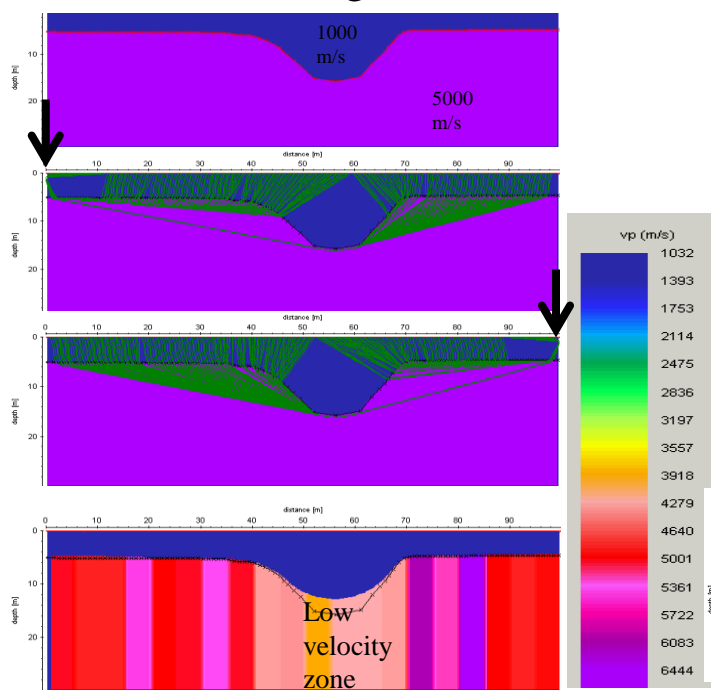
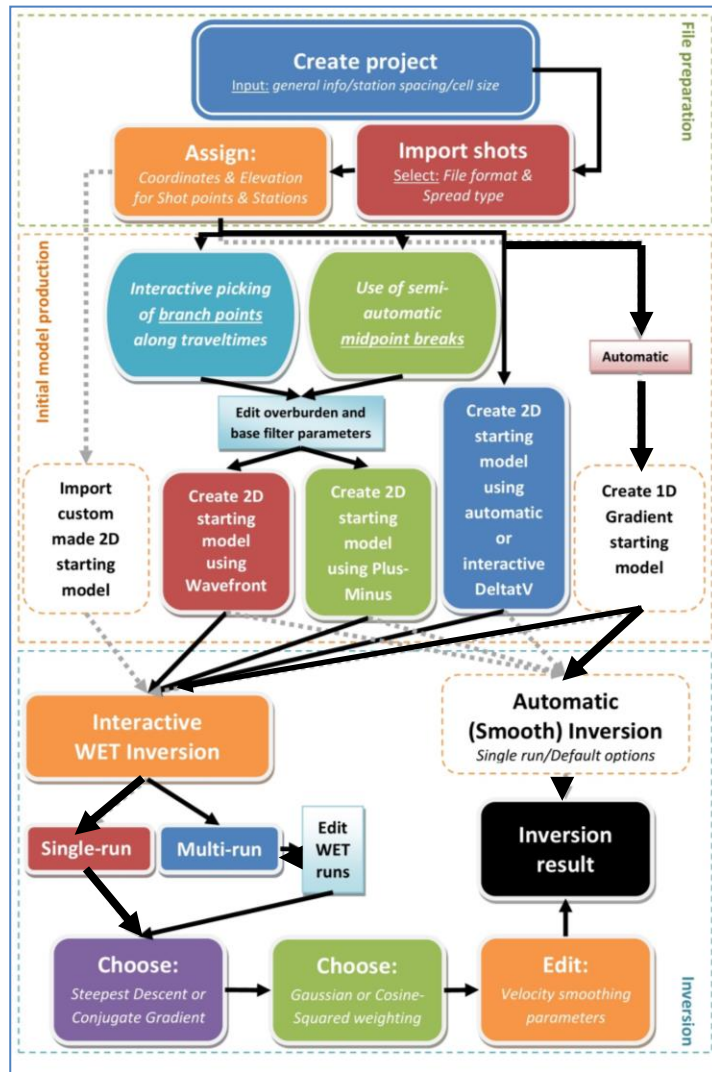


Figure 6: Model (top), raytracing from both sides (middle) and automatic waveform inversion

Figure 7: Model (top), raytracing from both sides (middle) and automatic waveform inversion (bottom).

↓ Shot position



Tomographic inversion and modelling.

Resent inversion and modelling work using **Rayfract software**.

Procedure in three steps:

1. Data preparation (sorting data)
2. Generating a starting model, 5 methods
3. Inversion process

WET = Wave Eikonal Traveltime

Options used by NGU

Cooperation between:



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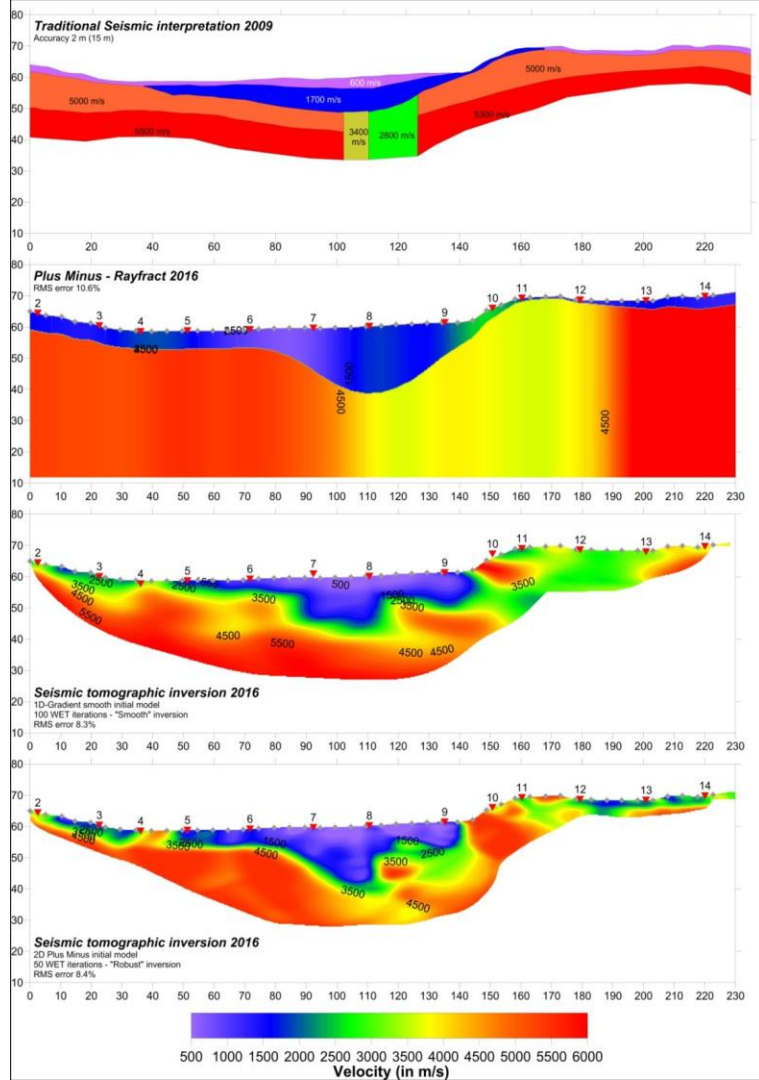


18

58

Inversion of **real** refraction seismic data for fracture zone detection, Ringveg vest, Bergen (Wåle GeoPhysics).

1. **Traditional Hagedoorn** interpretation (Morgan Wåle, GeoPhysix)
2. **Automatic Hagedoorn** interpretation using Rayfract software
3. **Tomographic inversion** using Rayfract software, **1D** starting model
4. **Tomographic inversion** Rayfract software, **2D** starting model (Hagedoorns +/-)



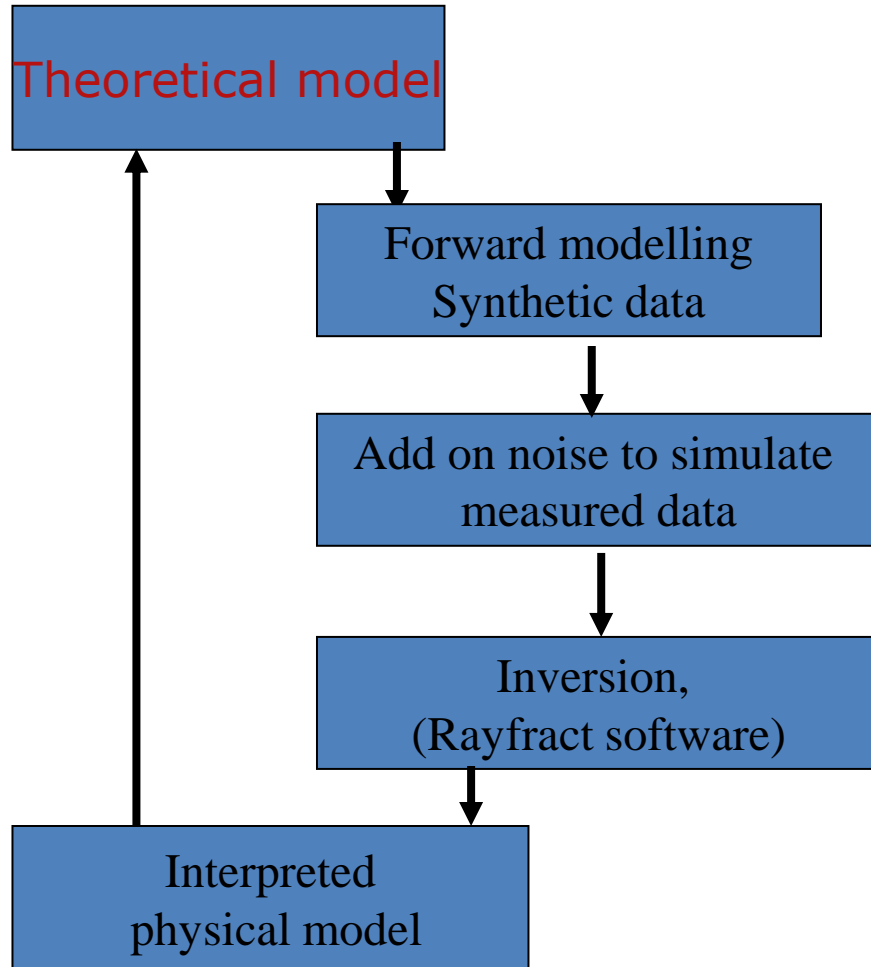
Results were promising, and we decided to do modelling work.



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Seismic tomographic **modelling** using forward modelling and inversion.



Inversion of synthetic data!

Refraction seismic tomography modelling.

All done using Rayfract software, early version.

1. Velocity contrast. Single run ✓
2. Velocity contrast. Multi run ✓ ✓
3. Fracture zone width. Multi run ✓ ✓
4. Depth extent. Multi run ✓
5. Fracture zone dip. Multi run ?



TOLKING: DYP TIL BERG

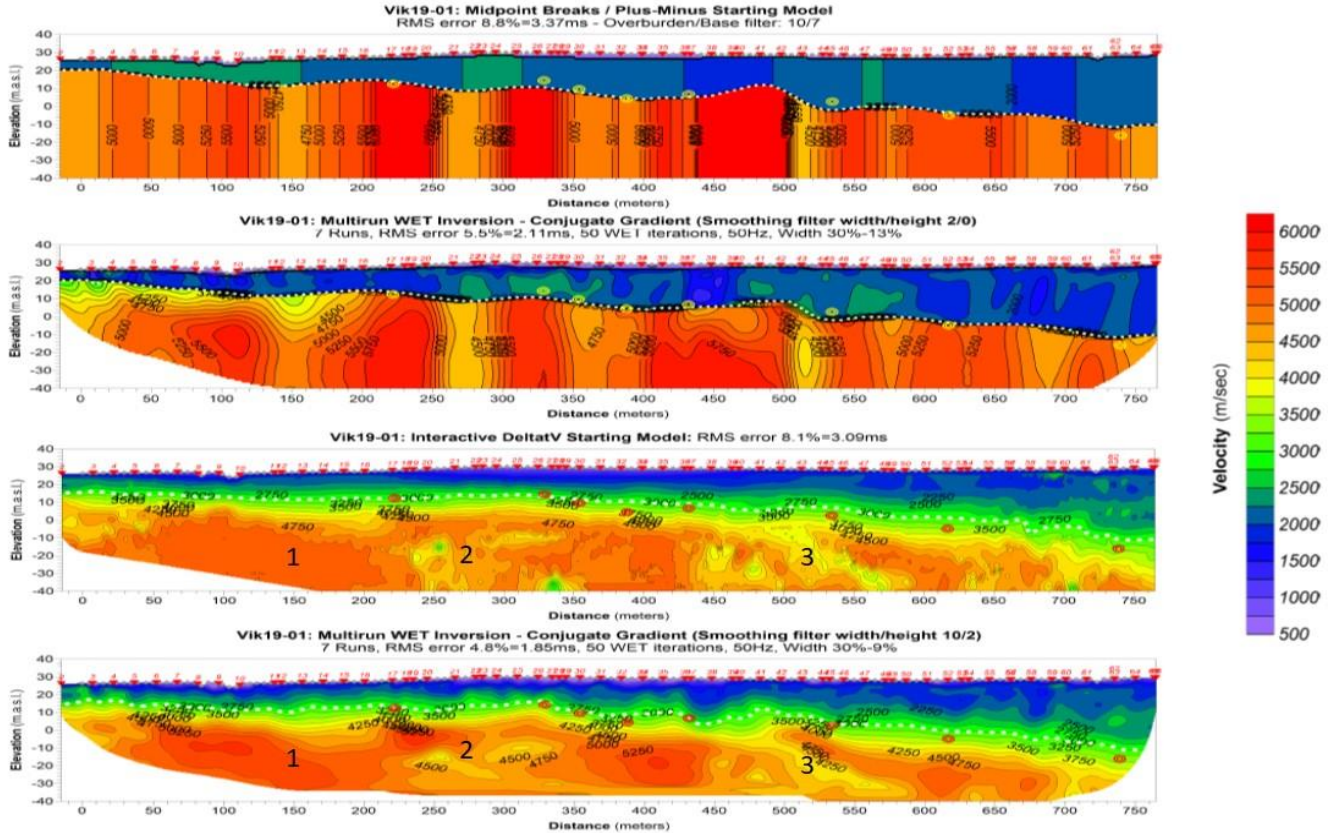
Data fra Kryssing av Romsdalsfjorden, Vik på sørsida av fjorden

- 3 refraksjonsseismiske profiler
- 15 boringer, alle < 4 m fra seismikktolking

Inversjon av syntetiske data (Blindsone-problem).

REFRAKSJONSSEISMIKK, Vik 19-01, fra IMPAKT

Tolking av dyp til berg. Tolking av svakhetssoner i berg



Alternative NGU-tolkinger (Rayfract):

1. Hagedoorns
2. Tomografi med Hagedorn start
3. DeltatV start
4. Tomografi med DeltatV start

NB: Fracture zone 3



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White dotted line: $V_p = 3000$ m/s

REFRAKSJONSSEISMIKK, Tolking av dyp til berg, NGU-Hagedoorns.

Linje	Bore-hull	Avstand til boring (m)	Dyp til berg, boring (m)	Dyp til berg Hagedoorn (m)	Hagedoorn / Boring (%)	Dyp til berg, beste Tomo (m)	Beste Hagedoorn Tomo / Boring (%)
Vik19-01	415	1,69	15,9	14,4	91	13,7	86
Vik19-01	411	0,13	15,4	18,9	123	16,7	108
Vik19-01	410	1,47	20	21,8	109	20,4	102
Vik19-01	409	2,74	24,8	24,4	98	23,1	93
Vik19-01	363	2,53	22,3	24,2	109	24,2	109
Vik19-01	406	3,75	26	30,8	118	28	108
Vik19-01	405	2,41	33,2	31,5	95	29,7	89
Vik19-01	403	0,71	45,3	40,3	89	38,8	86
Vik19-02	414	0,41	19,8	19,7	99	19,4	98
Vik19-02	413	1,87	20,0	19,0	95	19,0	95
Vik19-02	412	0,85	25,9	24,1	93	24,1	93
Vik19-02	404	0,66	43,7	44,6	102	43,8	100
Vik19-04	408	1,06	20,4	21,1	103	21,3	104
Vik19-04	407	0,86	20,9	23,6	113	23,6	113
Vik19-04	401	2,47	55,6	52,4	94	51,6	93
SNITT		1,6			102		98
SDEV		1,0			10,3		8,6

I gjennomsnitt er tolket dyp til berg meget god for begge metoder!

Individuelle tolkinger kan avvike opp mot $\pm 15\%$!

Tomografisk inversjon kan forbedre tolkingene! **Modellen stemmer!**



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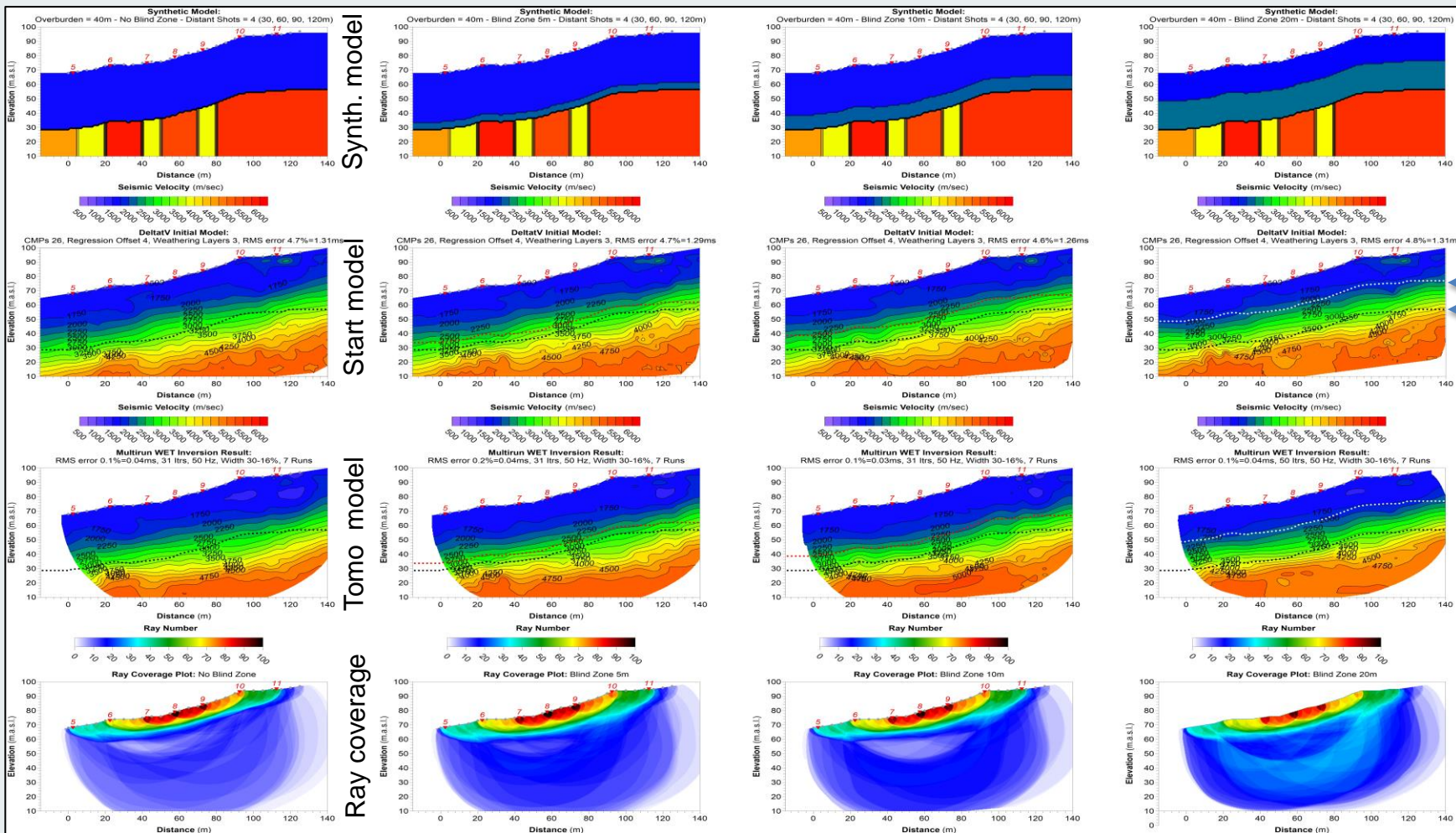
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REFRAKSJONSSEISMIKK, Tolking av dyp til berg, DeltatV-metoden.

Linje	Borehull	Avstand til boring (m)	Boring Dyp til berg (m)	DeltatV Startmodell (m)	DeltatV Startmodell / Boring (%)	DeltatV Tomo (m)	DeltatV Tomo / Boring (%)
Vik19-01	415	1,69	15,9	15,6	98	15,3	96
Vik19-01	411	0,13	15,4	16,4	106	13,1	85
Vik19-01	410	1,47	20,0	17,6	88	18,3	92
Vik19-01	409	2,74	24,8	18,4	74	20,3	82
Vik19-01	363	2,53	22,3	19,9	89	22,8	102
Vik19-01	406	3,75	26,0	21,3	82	25,0	96
Vik19-01	405	2,41	33,2	26,7	80	29,0	87
Vik19-01	403	0,71	45,3	39,7	88	39,7	88
Vik19-02	414	0,41	19,8	15,9	80	20,9	105
Vik19-02	413	1,87	20,0	20,2	101	19,0	95
Vik19-02	412	0,85	25,9	26,1	107	28,2	108
Vik19-02	404	0,66	43,7	34,1	78	35,9	82
Vik19-04	408	1,06	20,4	19,5	96	22,3	109
Vik19-04	407	0,86	20,9	19,4	93	19,9	95
Vik19-04	401	2,47	55,6	38,8	70	42,3	76
Snitt		1,6			89		93
SDEV		1,0			11		10

DeltatV-metoden viser ikke bedre tolkinger enn Hagedoorns metode!
 Resultatet kan forbedres ved å velge annen indikasjon for dyp til berg!

Modelling of complex model and hidden layer. Blind zone: 0, 5, 10 and 20 m. DeltatV.



1600 m/s
2100 m/s
3800 m/s
4000 m/s
5000 m/s

1600 m/s
2100 m/s
5000 m/s

No indication of fracture zones!

Where to find bedrock in gradient velocity model in case of “Blind zone”?
 DeltaTV method (1D velocity gradient starting model).

Dataset	Blind zone thickness (m)	Method	Isoline Min- (m/s)	Max (m/s)	Average Isoline (m/s)	SDEV Isoline (m/s)
F1	0	Starting model	2750 - 3500		3083	214
F1	0	Tomographic inv.	2600 - 3500		3050	288
F2	5	Starting model	2750 - 3600		3200	276
F2	5	Tomographic inv.	2750 - 3500		3263	318
F3	10	Starting model	3000 - 3750		3390	253
F3	10	Tomographic inv.	2800 - 3750		3288	300
F4	20	Starting model	3000 - 4200		3528	347
F4	20	Tomographic inv.	3050 - 4000		3575	330
Average					3297	291

Need some other information to decide which velocity contour that is best to indicate bedrock, and still, it might be some variations.

TOLKING: SVAKHETSSONER I BERG

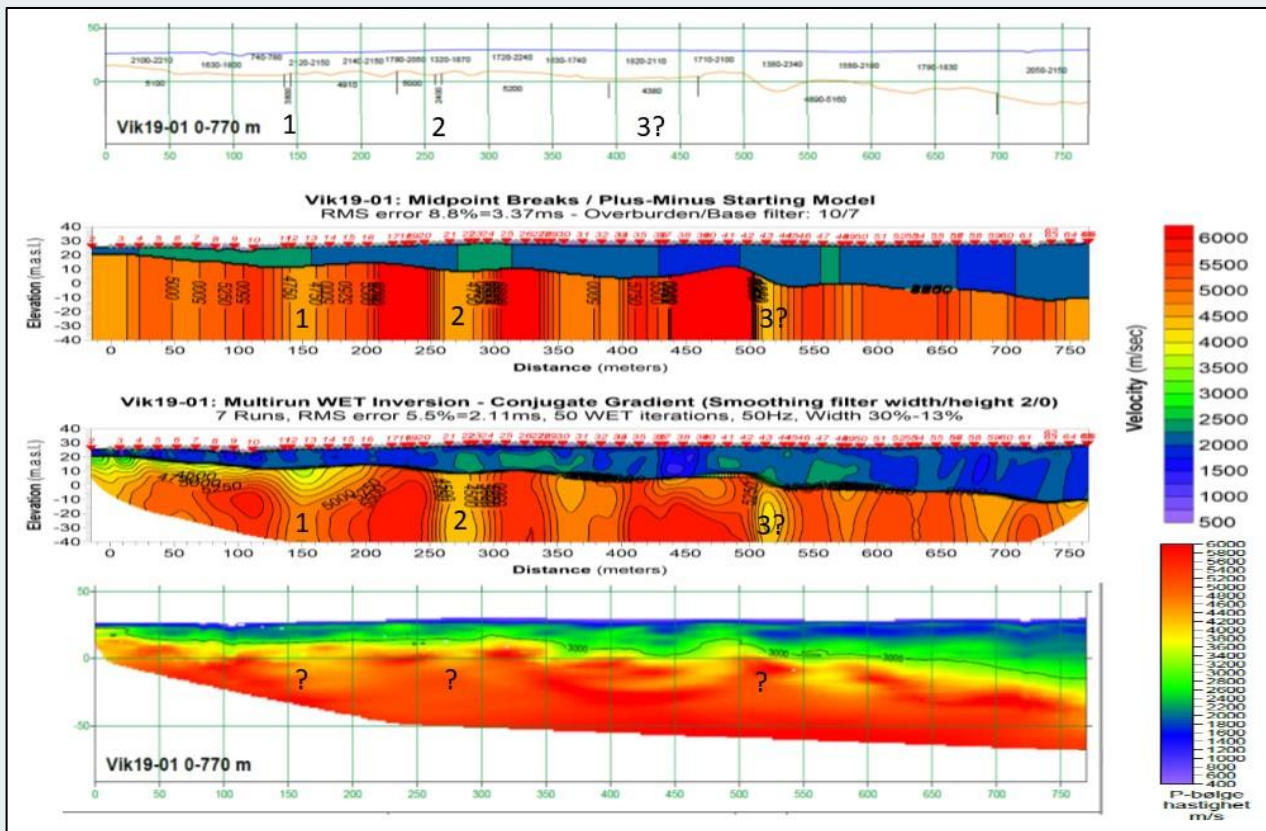
Data fra Kryssing av Romsdalsfjorden (IMPAKT)

Modelling og synthetic data

Data from Knappetunnelen in Bergen (GeoPhysix)



REFRAKSJONSSEISMIKK, Tolking av svakhetssoner i berg



Fire tolkingsmetoder er testet:

- Tradisjonelle tolkinger IMPAKT
- Auto. Hagedoorn 2D NGU, Rayfract
- Tomografisk inversjon NGU, Rayfract
- Tomografisk inversjon IMPAKT, Geogiga, 1D

REFRAKSJONSSEISMIKK, Tolking av svakhetssoner i berg



Statens vegvesen

Antall soner (Totalt 23 langs flere profiler, totalt 4800 m)

Bergmasseklasse	Hastighet (m/s)	Karakteristikk	Impakt Tradisjonell lagdelt	NGU Hagedoorn Middell	NGU Hagedoorn Minimum	NGU Tomo Middell	NGU Tomo Minimum
C	5000 - 4600	Middels bergmassekvalitet	3	1	1	2	2
D	4600 - 4000	Dårlig bergmassekvalitet	7	18	18	12	11
E	4000 - 3000	Svært dårlig bergmassekvalitet	11	3	3	6	7
F	3000 - 2000	Ekstremt dårlig bergmassekvalitet	1	0	0	0	0
G	< 2000	Eksepsjonelt dårlig bergmassekvalitet	0	0	0	0	0
Utelatt			1	1	1	3	3
Sum			23	23	23	23	23

Tilnærmet samme antall soner i bergmasseklassene D og E!

Fordeling på bergmasseklasser varierer!

Automatiske tolkinger indikerer noe bedre bergmassekvalitet!

Best samsvar med tradisjonelle tolkinger ved tomografisk inversjon og minimumshastighet i sonen.

Tilsvarende resultater ved å se på sonebredden!



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REFRAKSJONSSEISMIKK, Tolking av svakhetssoner i berg



Statens vegvesen

Sonebredde (Samme profilene 4800 m, samme 23 sonene).

Berg-masse-klasse	Hastighet (m/s)	Karakteristikk	Impakt Tradisjonell lagdelt (m) / Andel (%)	NGU Hagedoorn Middel (m) / Andel (%)	NGU Hagedoorn Minimum (m) / Andel (%)	NGU Tomo Middel (m) / Andel (%)	NGU Tomo Minimum (m) / Andel (%)
C	5000 - 4600	Middels bergmassekvalitet	160 / 12,5	20 / 1,5	20 / 1,5	40 / 3,6	40 / 3,6
D	4600 - 4000	Dårlig bergmassekvalitet	640 / 50,0	865 / 68,0	825 / 65,0	710 / 64,3	510 / 46,2
E	4000 - 3000	Svært dårlig BMK	480 / 37,5	390 / 30,5	430 / 33,5	355 / 32,1	555 / 50,2
F	3000 - 2000	Ekstremt dårlig BMK	5 / 0,1	0 / 0	0 / 0	0 / 0	0 / 0
G	< 2000	Eksepsjonelt dårlig BMK	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
SUM (m)			1280	1275	1275	1105	1105
SUM (m)	4600 - 2000	Bergklasse D, E og F	1120	1255	1255	1065	1065

Tilnærmet samme total bredde i bergmasseklassene D, E og F!

Fordeling på bergmasseklasser varierer!

Automatiske tolkinger indikerer noe bedre bergmassekvalitet!

Metoden som benytter minimumshastighet passer best med tradisjonell tolking!



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Modelling of complex model with low velocity zones extending to different depth (150 – 5 -10 and 20 m).

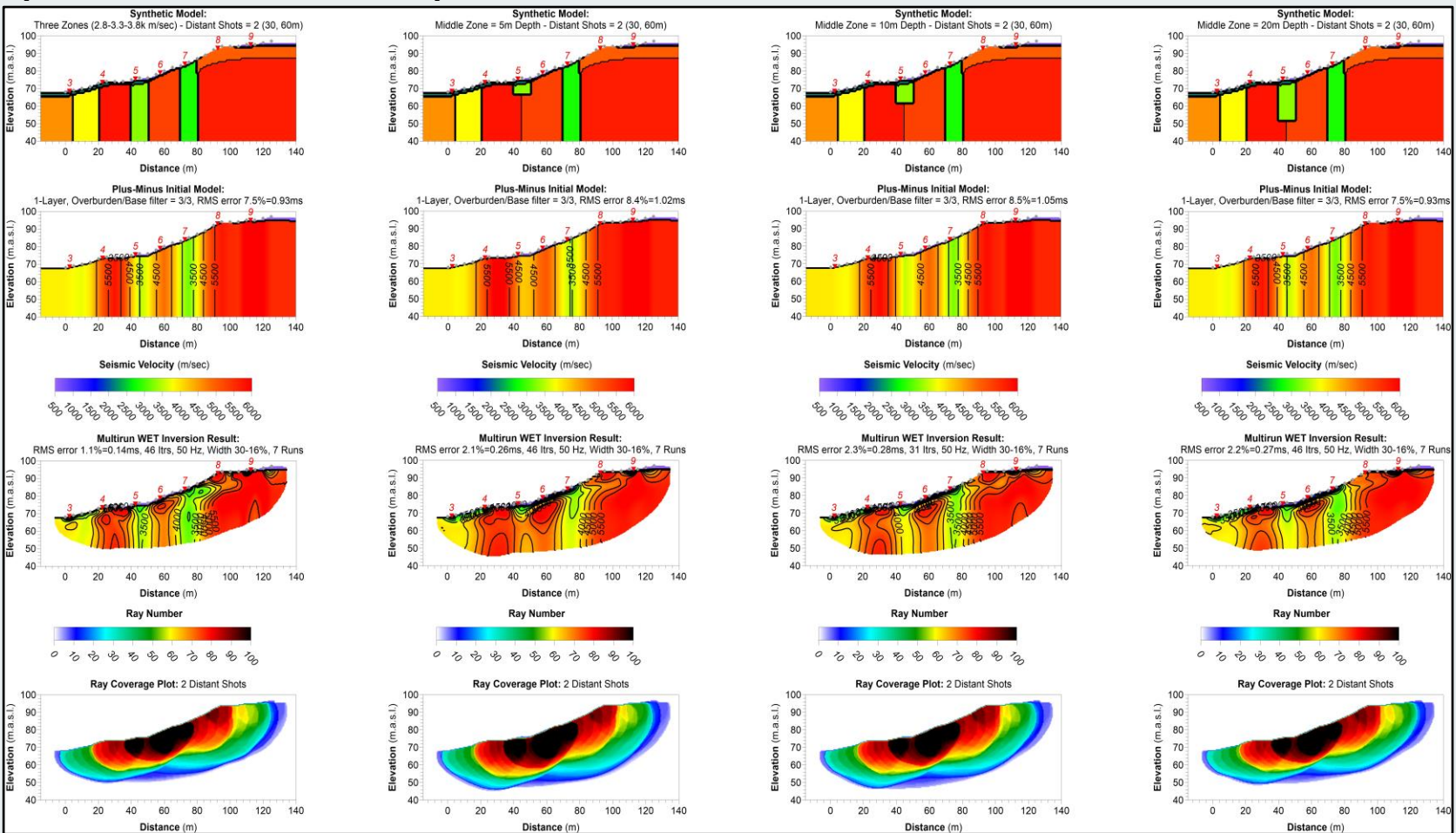
False fracture zone can partly be processed away!

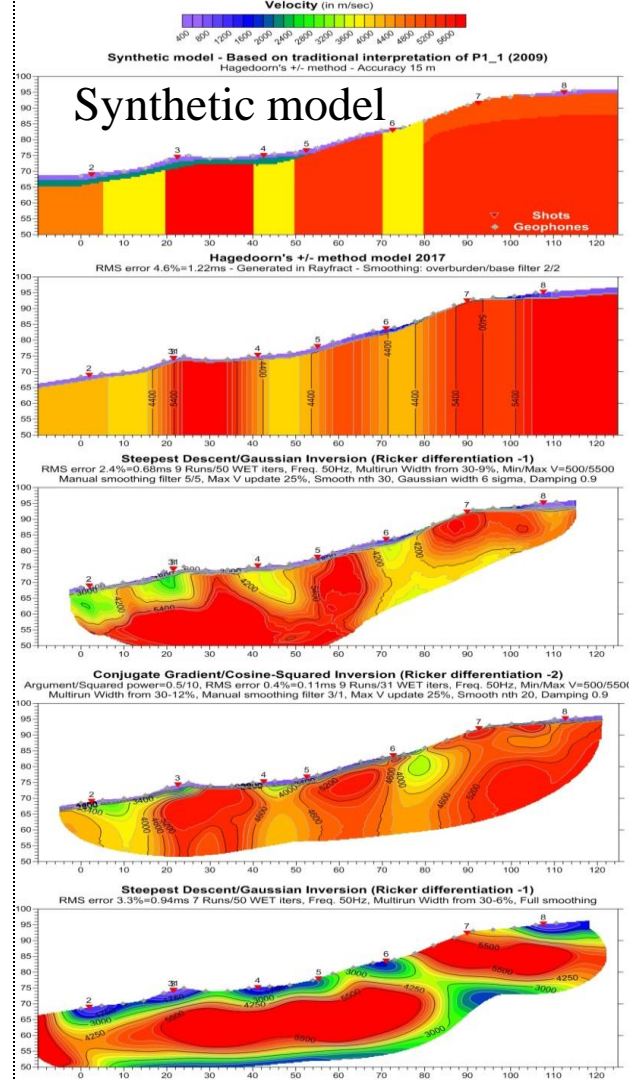
Synth.
Model

Hage-
doorn
+/-

Tomo-
inv. Best
method

Ray cov.





Tomographic inversion, modelling of synthetic data.

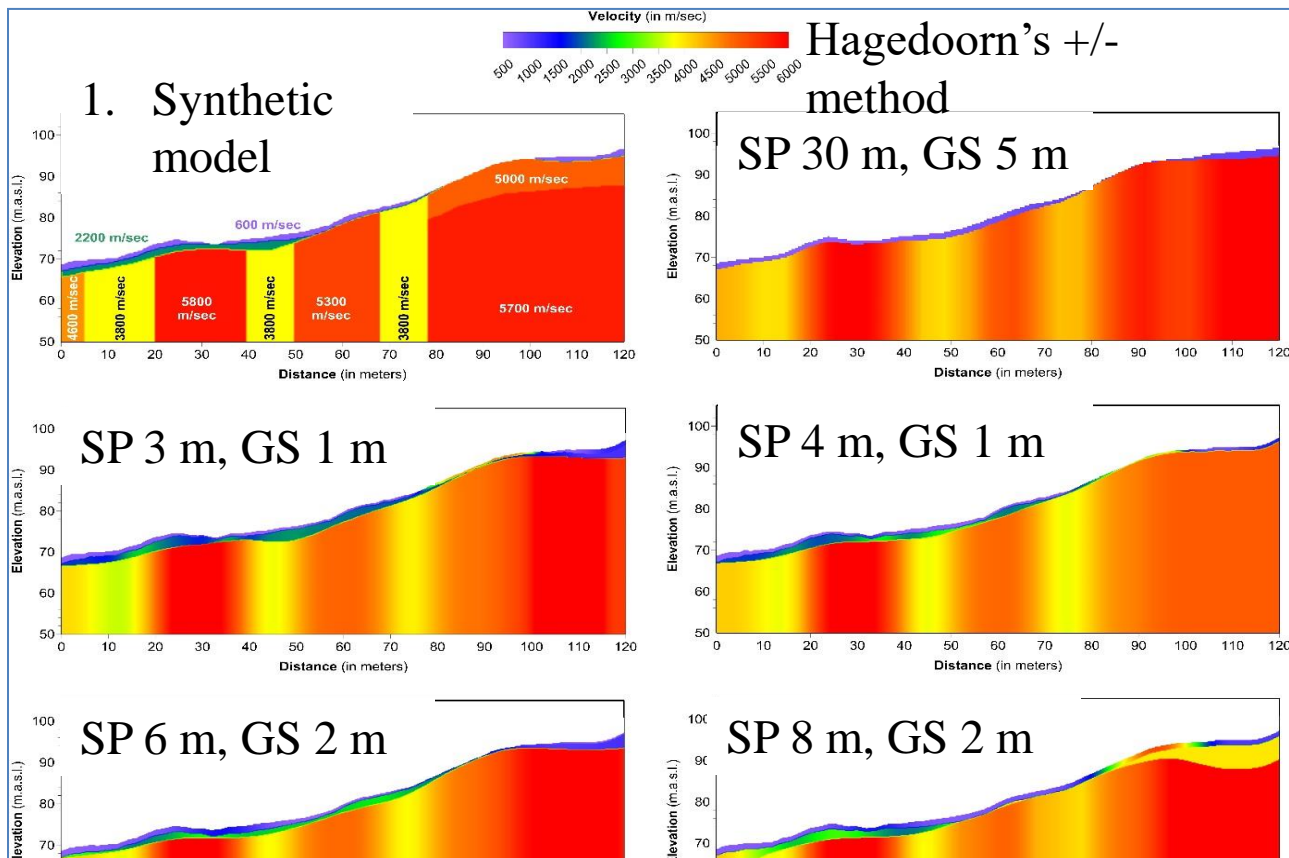
Inversion of synthetic data from a complex model.

From top to bottom:

1. **Synthetic model** based on traditional interpretation of Profile P1_1 Knappe (Wåle, GeoPhysix).
2. **2D plus-minus method** model as constructed in Rayfract® and **used as starting model** in the tomographic inversion
3. Inversion result using the **Steepest Descent/Gaussian scheme**
4. Inversion result using the **Conjugate Gradient/Cosine-Squared scheme**
5. Inversion result using the **Steepest Descent/Gaussian scheme with full smoothing (No. 3 with max smoothing).**

Important to do the inversion correctly.
Latest inverted model is misleading,
Hagedoorns +/- gives the best result.

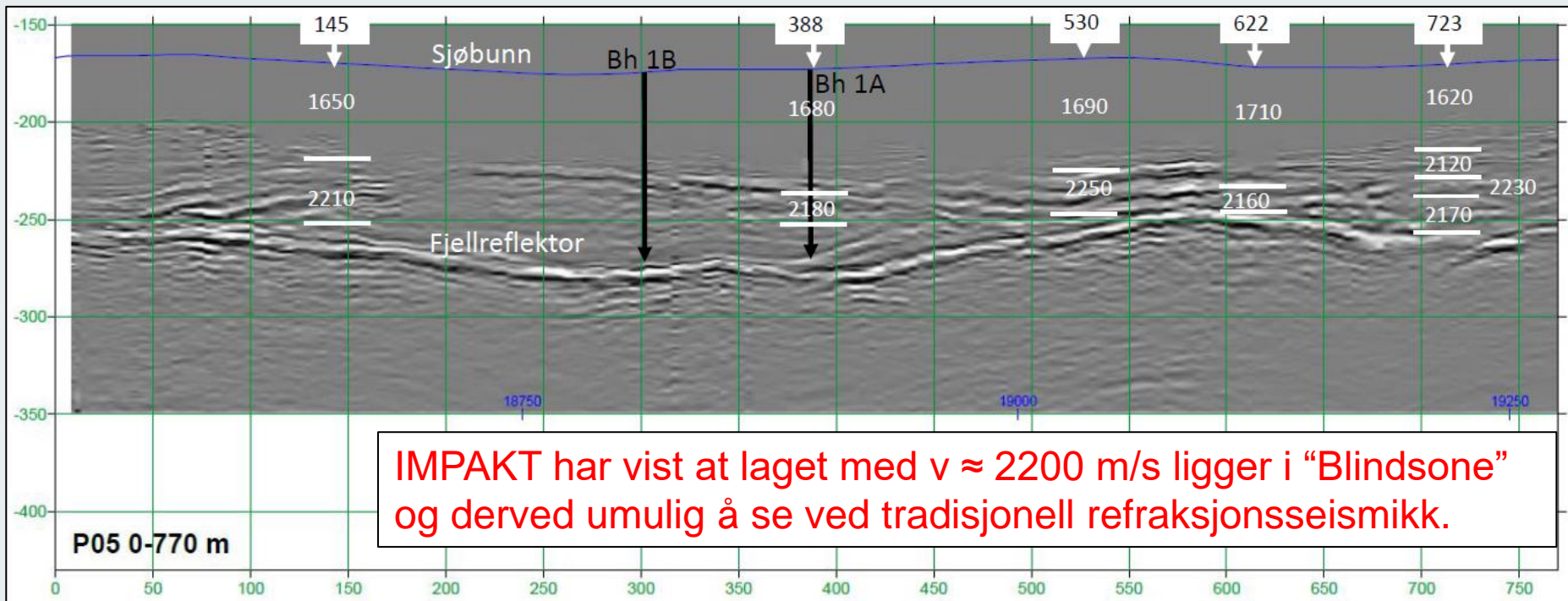
Shotpoint (SP) and geophone spacing (GS)



With Hagedoorn's method, more shots and shorter spacing **do not give significant better results!**

REFLEKSJONSSEISMIKK, fra IMPAKT. Tolking av dyp til berg.

Hastigheter i løsmasser.



Refraksjonsseismiske data kan inneholde gode refleksjoner!

Refleksjonsseismikk viser klare hastighetsvariasjoner i løsmassene!

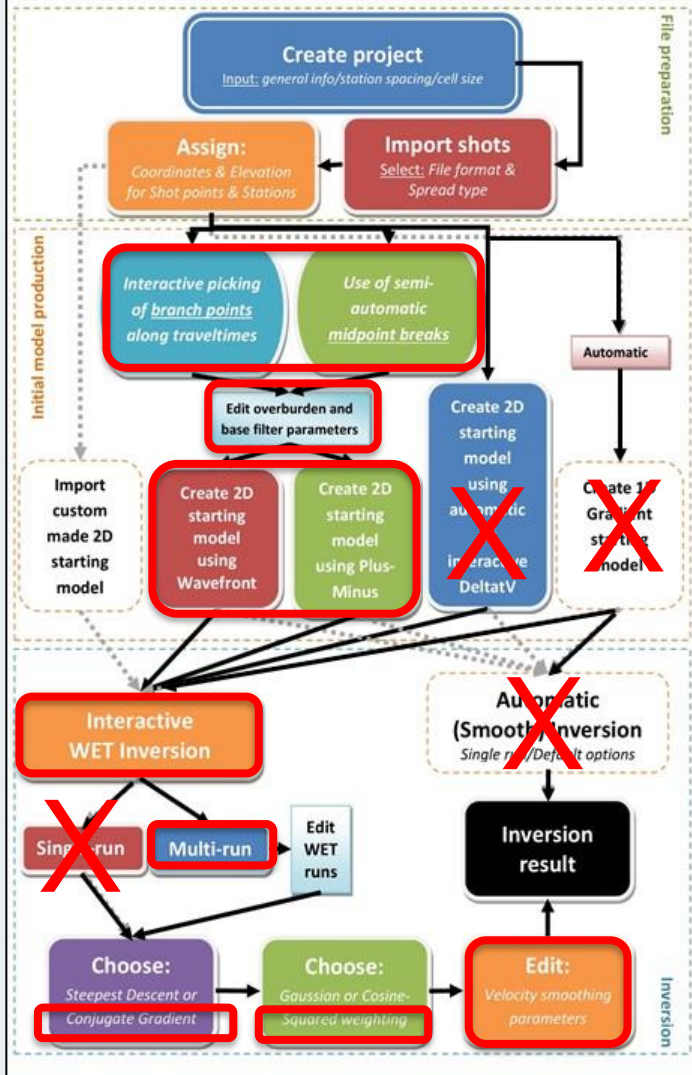
Refleksjonsseismikk viser relativt gode dybder til berg!

REFLEKSJONSSEISMIKK, fra FUGRO. Tolking av dyp til berg i sjøen.

Borehull	Dyp til berg fra boring (m)	Dyp til berg FUGRO 1600 m/s (m)	Avvik i % FUGROs 1600 m/s	Dyp til berg IMPAKTs hastigheter (m)	Avvik i % IMPAKTs hastigheter
Nord for Tautra					
P-Bh-0c	103,5	93,1	90	109,2	106
C-Bh-0c	103,5	92,7	90	108,7	105
C-Bh-0c-a	103,5	92,3	89	108,1	105
P-Bh-0d	90 - 91	80,4	89	89,3	99
C-Bh-0e	98 - 99	86,8	88	106,0	108
Bh-1a	94,5-95,6	87,9	92	98,6	103
Bh-1B	96	86,5	90	99,3	103
Sør for Tautra					
Bh-2	37 – 39	-	-	-	-
Bh-2b	9 – 9,5	4,6	50	6,0	65
Bh-3b	77,2–77,7	59,3	77	78,5	101
P-Bh-3e	56,5–57,5	-	-	-	-
Gjennomsnitt*			88,1		103,8
SDEV			4,6		2,9



Refleksjonsseismikk gir gode tolkinger av dyp til berg ved riktig hastighetsprofil!



File preparation

Data editing

Start modell

Rayfract inversion software

Intelligent Resources Inc. Vancouver, Canada
 Benyttet av NGU, GeoPhysix og GeoVista (Geomap).

Black arrows: Tested by NGU

Assumed best procedure based on own experience.

UTARBEIDELSE AV TO VEILEDERE

Vegdirektoratet
Vegavdelingen
Tunnel og betong
28.02.2018



Statens vegvesen



Kartlegging av svakhetssoner i berg med 2D resistivitet

Veiledning

STATENS VEGVESENS RAPPORTER

Nr. 305

Myndighet og regelverk
Konstruksjoner
Konstruksjonsteknikk
30.09.2021



Statens vegvesen



Seismiske målemetoder

Veiledning

STATENS VEGVESENS RAPPORTER

Nr. 733

Begge veilederne ligger som vedlegg i sluttrapport til Vegdirektoratet og på NGUs og SVVs nettsider!.



NORGES
GEOLOGISKE
UNDERSØKELSE
- NGU -

Relevant litteratur:

- NGU Rapport 2017.025: Første fase med modellering
- NGU Rapport 2018.015: Andre fase med modellering
- NGU Rapport 2020.040: Reelle data fra Kryssing av Romsdalen
- NGU Rapport 2020.044: Advanced tomographic modelling
- NGU Rapport 2021.032: Sluttrapport ForForUT, mange metoder

Irrelevant litteratur (metodebeskrivelser):

- NGU Rapport 2022.002: Georadar (125 sider)
- NGU Rapport 2022.016: Elektriske metoder (219 sider)
- NGU Rapport 2024.033: Elektromagnetiske metoder (217 sider)
- **NGU Rapport 202?.???: Seismiske metoder ???**

Takk for oppmerksomheten!