Seismic velocity models based on wide-angle refraction and reflection profiles in Finland

Kolehmainen, Kauri Olavi

Institute of Seismology, University of Helsinki

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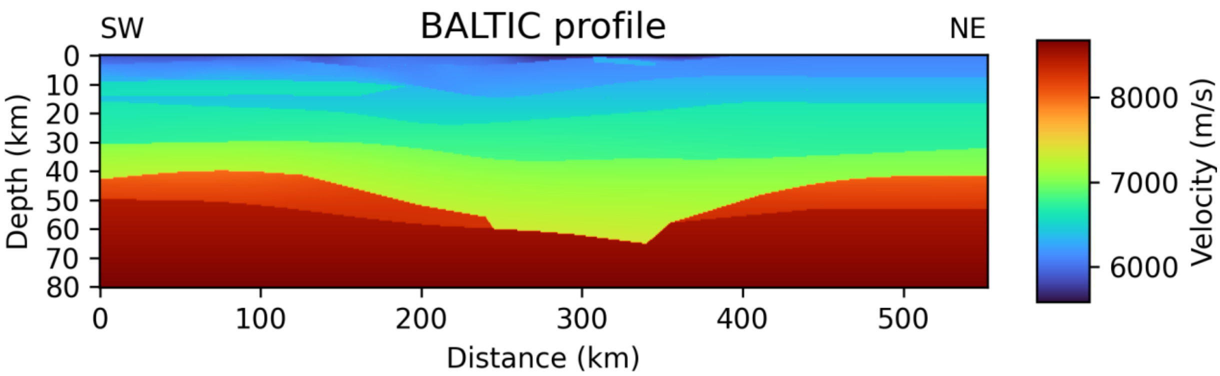

Helsinki 2022

Cover: Seismic velocity model of the BALTIC wide-angle refraction and reflection profile in Eastern Finland. Original model published by Luosto et al. (1990).

Kansi: Itä-Suomen BALTIC taittumis- ja heijastusluotausprofiilin seisminen nopeusmalli. Alkuperäisen mallin julkaisivat Luosto et al. (1990).

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Abstract

Seismic wide-angle refraction and reflection (WARR) surveys have been crucial in the study of the structure of the Fennoscandian shield. The valuable data and crustal seismic velocity models of major WARR studies from the 1980s to the present day have not been previously available to the public. In the work described in this report, the velocity models and wide-angle data were re-formatted to more accessible data formats and safely stored in the IDA Research Data Storage service for open access and data identification through Digital Object Identifiers. Data use is allowed under the Creative Commons By Attribution version 4.0 license. The data is also made available through the Hakku service of the Geological Survey of Finland. The velocity models are stored in a universal velocity point format in text files and wide-angle sections are stored in standard IBM SEG-Y format. A general description of WARR studies, available data and data use is given in this report.

Tiivistelmä

Laajakulmaiseen taittumis- ja heijastusluotaukseen perustuvat seismiset tutkimukset (WARR) ovat olleet keskeisessä roolissa Fennoskandian kilven rakenteellisessa tutkimuksessa. 1980-luvulta lähtien niissä on kerätty tieteellisesti arvokasta dataa sekä tuotettu seismisiä kuoren nopeusmalleja, jotka eivät ole aiemmin olleet julkisesti saatavilla. Tämän raportin kuvailemassa työssä vanhat nopeusmallit ja laajakulmasektiot muokattiin helpommin käytettäviin formaatteihin ja tallennettiin turvallisesti tutkimusdatan säilytyspalvelu IDAan. IDAssa tutkimusdata on avoimesti saatavilla ja tietokokonaisuuksille on IDAssa pysyvät DOI-tunnisteet. Säilötyn datan käyttö on määritelty Creative Commons By Attribution version 4.0 -lisenssillä. Sama data tulee myös saataville Geologian tutkimuskeskuksen Hakku-palveluun. Saatavilla olevat kaksiulotteiset nopeusmallit on tallennettu muotoon, jossa seisminen nopeus on määritetty koordinaattien pisteissä eri syvyyksillä tekstitiedostoissa. Laajakulmasektiot on tallennettu standard IBM SEG-Y -muotoisina. Tässä raportissa kuvaillaan taittumis- ja heijastusluotaustutkimuksia, saatavilla olevaa dataa sekä sen käyttöä.

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1. Introduction

Seismic wide-angle refraction and reflection (WARR) studies have been conducted in Finland from the 1960s to study the velocity structure of the Fennoscandian crust and upper mantle. Numerous significant discoveries concerning Fennoscandian lithosphere structure and evolution have been made through pioneering Finnish and joint international WARR projects in the 1980s and 1990s. WARR profiles such as SVEKA, BABEL, POLAR, BALTIC and FENNIA observed the unusually deep Moho and anomalous high velocity lower crust beneath Finland as well as features associated with ancient plate collisions (Luosto et al. 1984, Luosto et al. 1989, Luosto et al. 1990, BABEL Working Group 1993, Luosto et al. 1994, FENNIA Working Group 1998). Later WARR studies from the 2000s and 2010s, such as Kuusamo, HUKKA2007, KOKKY and SOFIC, continued by investigating local crustal velocity structures and developing more cost-effective WARR implementations (Uski et al. 2012, Tiira et al. 2014, Tiira et al. 2020, Tiira et al. 2022).

WARR seismic measurements are made by recording the seismic energy from a controlled seismic source, such as an explosion, using a large number of portable seismic instruments along a transect. Data from multiple shots recorded at different station positions are gathered to wide-angle seismic sections showing arrivals and travel times of refracted and reflected waves. These arrival times are affected by the medium through which the waves travel. The velocity structure of the medium can be modeled by inverting the observed travel times. The two-dimensional crustal velocity models presented in this report are constructed from the data by a trial-and-error ray tracing forward modeling method.

The aim of this work is to make valuable Finnish WARR study data previously stored by the Institute of Seismology, University of Helsinki more accessible for the scientific community. The presented Finnish crustal velocity models and seismic wide-angle sections are stored in the Research Data Storage Service IDA operated by CSC (IT Center for Science) governed by the Ministry of Education and Culture of Finland. The same data will also be stored in the Hakku service (https://hakku.gtk.fi/) of Geological Survey of Finland. The stored data can be openly accessed and cited through the IDA service. The models and data as well as their acquisition and usage are described in this report.

2. Wide-angle refraction and reflection

2.1. Survey method

The wide-angle refraction and reflection (WARR, also often referred to as deep seismic sounding, DSS) method is based on seismic ray theory. Seismic rays propagating away from a point-like seismic source are refracted at interfaces defined by velocity contrasts. Due to the generally increasing seismic velocity with depth, the downgoing rays from a surface source eventually return to the surface at distances determined by the velocity structure and takeoff angle of the ray from the source. These surfacing rays can be recorded on seismic instruments placed on the surface in a linear geometry from the seismic source (Figure 1). The recordings from multiple seismic stations can be placed alongside each other to produce a wide-angle seismic section which can be used to infer the velocity structure beneath the transect.

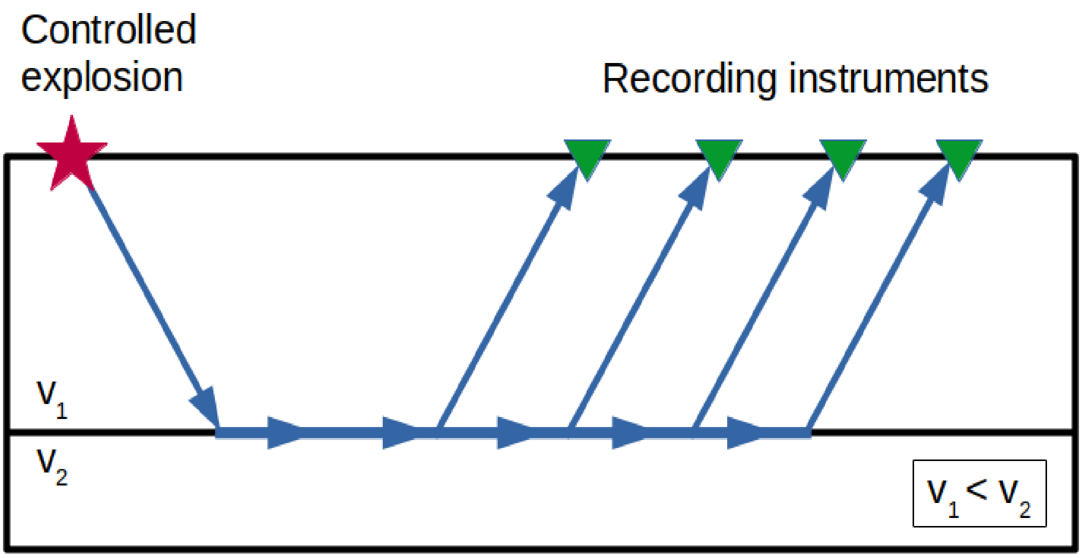

Figure 1. *Simple illustration of a wide-angle refraction and reflection survey. Seismic waves propagating from a surface explosion source are refracted at an interface of changing seismic velocity. Refraction at the critical angle of incidence produces a head wave recorded by seismic stations on the surface.*

Kuva 1. *Yksinkertaistettu kaavakuva laajakulmaisesta taittumis- ja heijastusluotauksesta. Pinnalla tehty räjäytys synnyttää seismisiä aaltoja, jotka taittuvat kohdatessaan eri seismisen nopeuden määräämän rajapinnan. Taittuminen kokonaisheijastuksen rajakulmassa synnyttää uuden aallon Huygensin periaatteen mukaisesti. Uusi aalto rekisteröidään pinnan seismisillä asemilla.*

A conventional WARR survey is conducted by placing multiple dozens of portable seismic stations along a relatively straight survey line and using them to record controlled explosions with an exact position and detonation time (configuration in Figure 1). Multiple shots at different positions are recorded by moving seismic stations along the transect to achieve better ray coverage in the studied structure. Typical spacings between shots are 60-80 km and station spacings 2-3 km (Luosto 1997). Additionally, other configurations of shots and stations have been used to accommodate for other equipment or reduce costs. The marine WARR survey of the BABEL project (BABEL Working Group 1993) used a large number of sources recorded by single stations to produce wide-angle sections similar to those of conventional surveys. The sources were air gun shots from a moving ship recorded on land stations. The similar effect of a conventional WARR survey was achieved by moving the source relative to the station between the shots.

Conventional WARR surveys require a large number of recording stations to be placed by personnel along with a controlled explosive source. To reduce the costs, pre-existing station networks or networks meant for other purposes may be used for recording and industrial blasts or natural earthquakes as seismic sources. Temporary SVEKALAPKO and Kuusamo station networks were successfully used to record industrial and natural sources in SVEKALAPKO (Yliniemi 2004) and Kuusamo (Uski et al. 2012) WARR studies. The use of station networks, however, reduced the modeling resolution as the station numbers were low. Industrial and military sources were also used in HUKKA 2007 (Tiira et al. 2014), KOKKY (Tiira et al. 2020) and SOFIC (Tiira et al. 2022) demonstrating a survey with a conventional dense station configuration.

2.2. Velocity modeling

The velocity modeling of WARR data is an inversion problem where travel times are inverted to find the velocity structure producing the wave arrivals on wide-angle sections. A popular approach for acquiring a velocity model from WARR data is trial-and-error type iterative forward modeling based on ray tracing. Description of this modeling procedure in this report is based on Kuusisto (2007).

Two-dimensional trial-and-error velocity modeling is conducted by a program calculating ray paths, travel times and amplitudes for a velocity model iteratively (Figure 2). The initial model used is usually a layered model acquired from one-dimensional models. This model is then altered between iterations to better fit the observed data until a sufficient data fit is obtained. The data fit is compared through synthetic seismograms constructed from program calculations for each iteration. Model alteration between iterations is done by modifying the velocity distribution and interfaces in the model. A common ray tracing velocity modeling software is the SEIS83 program package (Cerveny and Psencik 1983) also used in the construction of models presented in this report. The synthetic data produced by SEIS83 is compared to observational data with the program ZPLOT (Zelt 1994) also used in the modeling.

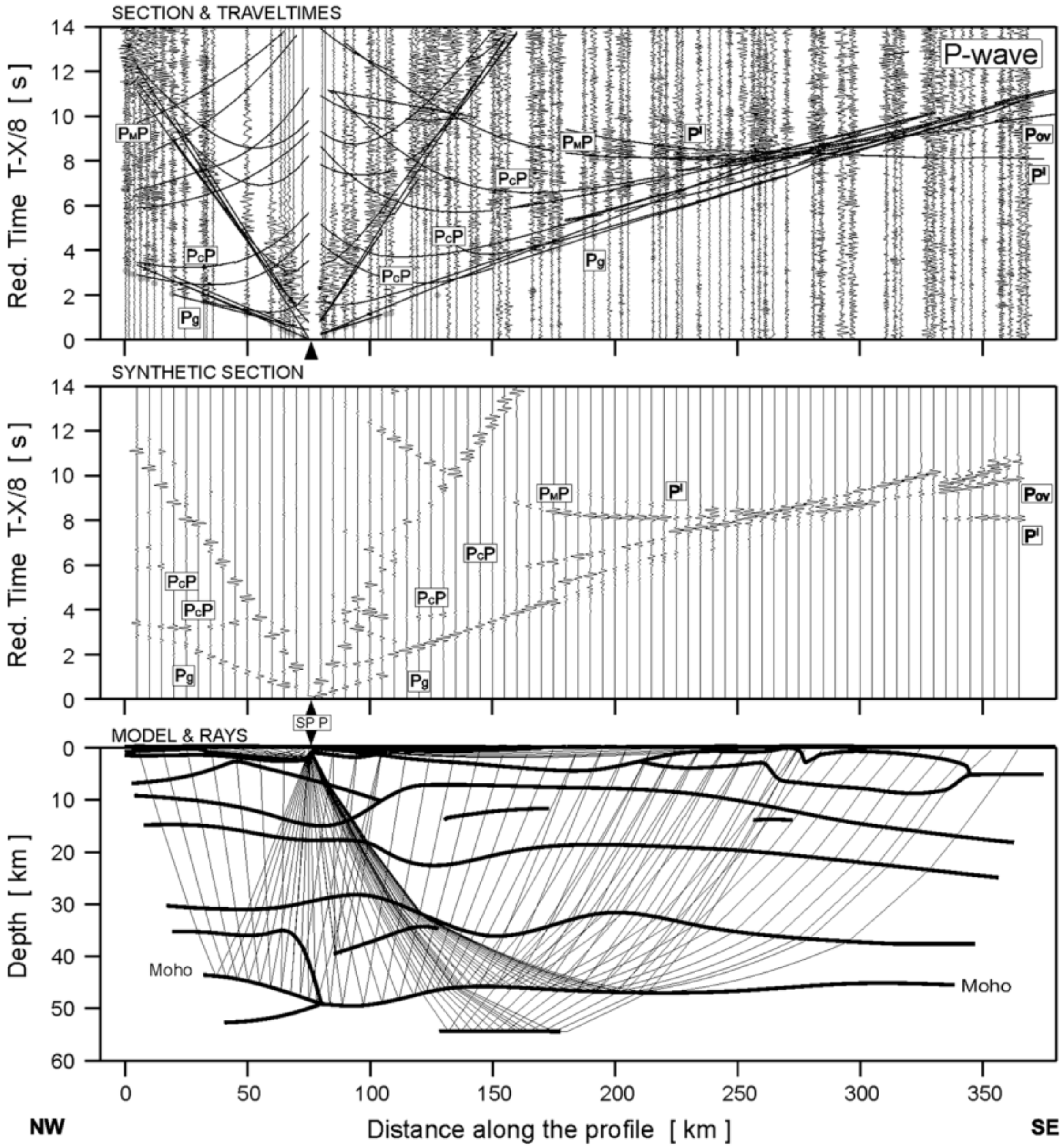

Figure 2. *Trial-and-error velocity modeling procedure. Top panel: wide-angle section with theoretical travel time curves denoted by lines. Middle panel: synthetic data section used to test the fit of the model to observed data. Bottom panel: ray diagram showing ray coverage of selected rays in the model. The model from bottom panel is altered until a good fit is achieved between synthetic and observed data (after Tiira et al. 2014).*

Kuva 2. *Seismisen nopeuden mallintaminen iteratiivisella mallinnuksella. Ylin kuva: laajakulmasektio, johon merkitty teoreettiset kulkuaikakuvaajat viivoilla. Keskimmäinen kuva: mallin säteiden perusteella laskettu synteettinen sektio, jolla voidaan tutkia mallin istuvuutta havaintoihin. Alin kuva: valikoitujen säteiden reitit mallissa. Alimman kuvan mallia muutetaan iteratiivisessa mallinnuksessa, kunnes synteettinen ja havaittu data kohtaavat (Tiira et al. 2014).*

3. Description of the data

3.1. Velocity models

Altogether 33 two-dimensional velocity models were converted from their original model format to a velocity point data format to allow for more universal data use (example in Figure 3). Velocity models include the models stored by the Institute of Seismology, University of Helsinki consisting of most of the major WARR profiles measured in Finland (Figure 4). P-wave velocity models are available for all of the profiles included and S-wave models are mostly available for the more recent profiles. The original velocity models were converted to velocity point data with the MODEL program (Komminaho 1998). The velocity points were coupled with corresponding coordinates by interpolating a line between the end points of the survey line determined by shots or stations. The station and shot positions of profiles do not exactly fall along the velocity model coordinates which should be noted in the use of the models.

The available two-dimensional velocity models are text files containing modeled seismic velocity data points at specific coordinates (Figure 3). Each row of the file denotes a single velocity point at x and y coordinates in the ETRS-TM35FIN (EPSG: 3067) coordinate system and a depth (z) coordinate in meters. The velocity value is shown in units of m/s. A row in the model file is of the form (x,y,z,velocity) where the columns are separated by commas. The BABEL velocity models differ from others by not having specific coordinates due to more complicated survey geometry. Instead, the BABEL models only specify the velocities at distances and depths along the model. The spacing between the velocity points is 500 m in all models. Note that this resolution is generally higher than the uncertainty of the models.

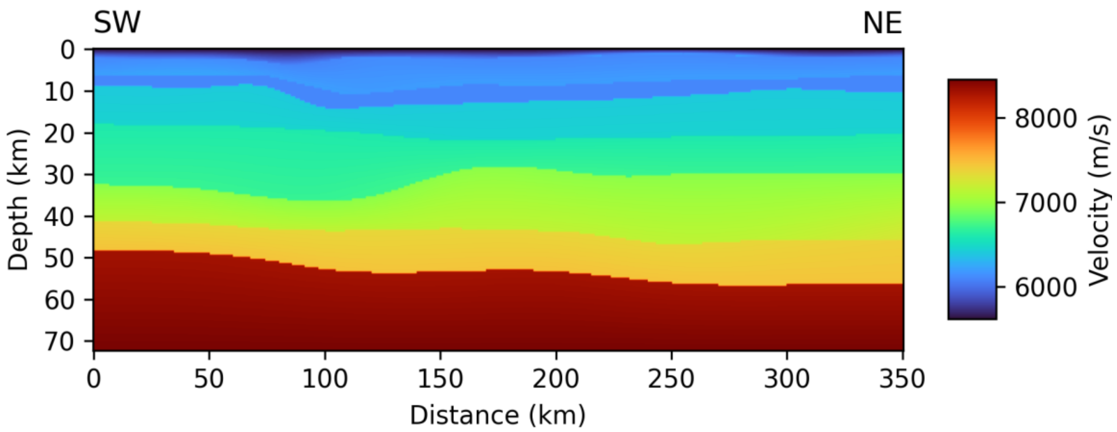

Figure 3. *Velocity model of the SVEKA'91 profile originally modeled by Luosto et al. (1994).*

Kuva 3. *SVEKA'91 profiilin nopeusmalli. Alkuperäisen mallin tekivät Luosto et al. (1994).*

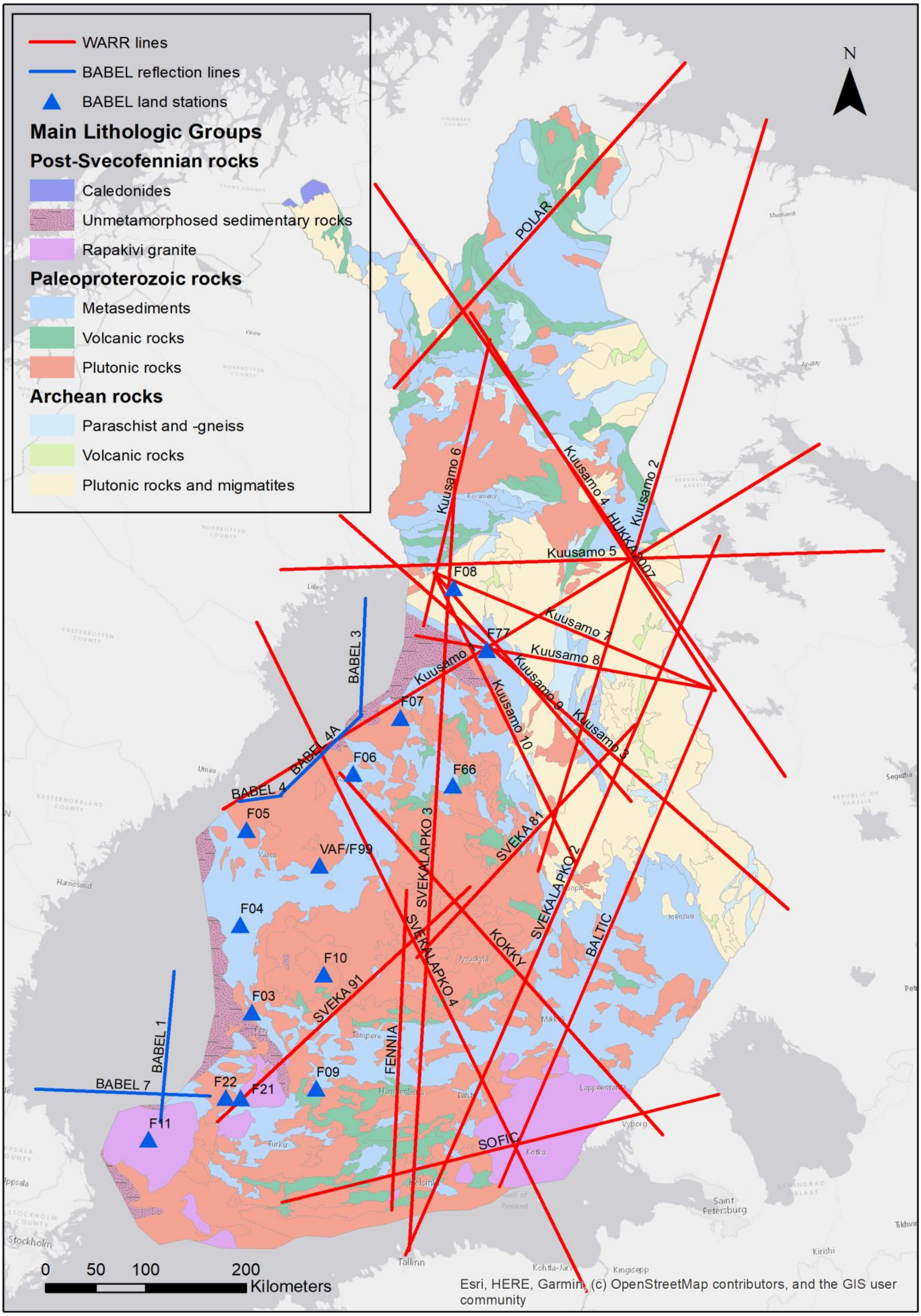
WARR lines
BABEL reflection lines
BABEL land stations
Main Lithologic Groups
Post-Svecofennian rocks
Caledonides
Unmetamorphosed sedimentary rocks
Rapakivi granite
Paleoproterozoic rocks
Metasediments
Volcanic rocks
Plutonic rocks
Archean rocks
Paraschist and -gneiss
Volcanic rocks
Plutonic rocks and migmatites
N
POLAR
Kuusamo 6
Kuusamo 4
Kuusamo 2
HUKKA2007
Kuusamo 5
Kuusamo 7
Kuusamo 8
Kuusamo 9
Kuusamo 10
Kuusamo 3
Kuusamo
BABEL 3
BABEL 4A
BABEL 4
BABEL 1
BABEL 7
F08
F77
F07
F06
F66
F05
VAF/F99
F04
F10
F03
F09
F22
F21
F11
SVEKALAPKO 3
SVEKA 81
SVEKALAPKO 2
SVEKALAPKO 4
SVEKA 91
KOKKY
BALTIC
FENNIA
SOFIC
0 50 100 200
Kilometers
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

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Figure 4. *Wide-angle refraction and reflection profiles of Finland placed on top of a generalized geological map. BABEL marine reflection lines and land stations are differentiated by blue. The velocity models of WARR profiles (denoted by red) coincide with respective profiles. BABEL velocity models do not coincide with the BABEL reflection lines, but instead are placed between the lines and corresponding land stations (geological map: Mikkola 2017).*

Kuva 4. *Suomen laajakulmaiset taittumis- ja heijastusluotausprofiilit yleisellä geologisella kartalla. BABEL-heijastusluotauslinjat ja maa-asemat merkitty erikseen sinisellä. Laajakulmaisten taittumis- ja heijastusluotausprofiilien (merkitty punaisella) paikat ovat samat kuin niistä tehdyillä nopeusmalleilla. BABEL-nopeusmallit eivät osu BABEL-heijastusluotauslinjojen kohdille, vaan linjojen ja niiden tekemiseen käytettyjen maa-asemien väliin (geologinen kartta: Mikkola 2017).*

3.2. Wide-angle sections

Wide-angle seismic sections are collections of seismic traces along a WARR profile. Traces of even lengths with same start time are placed side by side in the order of station location along the profile. Wide-angle sections are not to be confused with near-vertical seismic data that provide a sonar-like image of underground reflectors. Instead, wide-angle sections can be treated similar to travel time curves showing seismic phase arrivals along a transect. Wide-angle refracted and reflected waves can be identified and picked on the wide-angle seismic sections to be used as observational data for velocity modeling. To aid the phase identification and enhance the differences between arrivals of rays traversing varying velocity structures, section trace times are typically reduced with a reduction velocity similar to travel time curves. A wide-angle seismic section is typically composed of a seismic source recorded on multiple traces. The first arriving refracted waves form a hyperbola-like (or a half hyperbola if recorded only on one side of the source) shape on the seismic section with a flattening slope at greater distances due to higher seismic velocities at depth (Figure 2, top panel).

Wide-angle sections are available from the major WARR studies in Finland. The available sections are in the standard IBM SEG-Y format containing multiple recorded sources in each file. Most sections are vertical component (z) data and time reduced for P-waves, but separate files with S-wave time reduction and other measurement axes may also be available for some profiles. The measured component is denoted by z (vertical), n (north-south), e (east-west), r (radial) or t (transversal) in the file name. The reduction velocities are 8 km/s for P-waves and 4.62 km/s for S-waves. The section trace and source coordinates are scaled geographic coordinates in units of seconds of arc. The scaling factor along with other detailed file specific information is specified in SEG-Y textual, binary and trace headers.

The original wide-angle sections used in velocity modeling were converted from ZPLOT modified SEG-Y format to standard IBM SEG-Y to allow for more general data use. The SEG-Y headers were modified to a uniform format for the available and relevant data fields. The SEG-Y textual header was freely formatted due to the irrelevancy of standard SEG-Y textual header data fields for this application.

3.3. Data and model descriptions

Table 1. *Available data and velocity models with original publications and Digital Object Identifiers to be used when citing the data.*

Taulukko 1. *Tallennettu data ja nopeusmallit sekä niihin viittaamiseen käytettävät alkuperäiset julkaisut ja IDAn pysyvät DOI-tunnisteet.*

Data	Publication	DOI
BABEL 1 and 7 velocity models	Heikkinen and Luosto 1992	https://doi.org/10.23729/e163d50e-2553-483b-8ec0-26563ca29677
BABEL 3 and 4 velocity model	Komminaho and Yliniemi 1992	https://doi.org/10.23729/e163d50e-2553-483b-8ec0-26563ca29677
BABEL wide-angle sections	BABEL Working Group 1993	https://doi.org/10.23729/e163d50e-2553-483b-8ec0-26563ca29677
BALTIC velocity model (1990) and wide-angle sections	Luosto et al. 1990	https://doi.org/10.23729/782793a3-3c4d-4715-9745-f34ea7715802
BALTIC velocity models (2010)	Janik 2010	https://doi.org/10.23729/782793a3-3c4d-4715-9745-f34ea7715802
FENNIA velocity model (1998) and wide-angle sections	FENNIA Working Group 1998	https://doi.org/10.23729/0db3cba6-d1eb-42b4-91b9-d2caf971182d
FENNIA velocity models (2007)	Janik et al. 2007	https://doi.org/10.23729/0db3cba6-d1eb-42b4-91b9-d2caf971182d
HUKKA 2007 velocity model and wide-angle section(s)	Tiira et al. 2014	To be published
KOKKY velocity models and wide-angle section(s)	Tiira et al. 2020	To be published

Kuusamo velocity models	Uski et al. 2012	https://doi.org/10.23729/7dc49d32-382c-42f0-9940-816448170d36
POLAR velocity model (1989) and wide-angle sections	Luosto et al. 1989	https://doi.org/10.23729/30356f10-2e28-47d3-9e77-2f01f80a9207
POLAR velocity models (2009)	Janik et al. 2009	https://doi.org/10.23729/30356f10-2e28-47d3-9e77-2f01f80a9207
SOFIC velocity model and wide-angle section(s)	Unpublished (Tiira et al. 2022)	To be published
SVEKA velocity models	Janik et al. 2007	https://doi.org/10.23729/6b888b28-2593-4d54-afa8-f0aa951ec043
SVEKA'81 velocity model and wide-angle section	Luosto et al. 1984	https://doi.org/10.23729/1a2f3233-d7ac-4d1e-88a8-c50a4fcd43f6
SVEKA'91 velocity model and wide-angle section	Luosto et al. 1994	https://doi.org/10.23729/24f42b76-6f67-4804-897c-899e3fb6dc3b
SVEKALAPKO velocity models	Yliniemi et al. 2004	https://doi.org/10.23729/30164c22-dfe1-490a-baa6-1580b628e4a2

3.3.1. BABEL

The BABEL seismic experiment was conducted in September and October of 1989 in the Baltic Sea (BABEL Working Group 1993). Reflection seismic as well as wide-angle reflection and refraction data were acquired in a marine seismic survey resulting in 2,268 km of seismic measurement lines. The available data includes wide-angle recordings of marine air gun shots of lines 1, 3, 4 and 7 recorded at land stations in Finland and Sweden. Line 1 runs in southern Gulf of Bothnia and is oriented south to north. Line 7 is oriented west to east and crosses line 1 at the southern end. Both lines 1 and 7 transect the Åland rapakivi granites. Lines 3 and 4 are located in northern Gulf of Bothnia and transect the Skellefte district.

Three velocity models are available of the BABEL lines. Modeling of lines 1 and 7 produced two separate models modeled by Heikkinen and Luosto (1992) and a single model of lines 3 and 4 was constructed by Komminaho and Yliniemi (1992). The models differ from other presented velocity models as they do not contain specific spatial coordinates. The models only contain information about the velocity at certain depth and distance along the profile. This is because of the geometry of the wide-angle survey configuration. The marine shots were recorded by only a few land stations at large offsets from the original survey line. As the shots were not recorded along the line, the recordings do not represent the velocity structure along the survey line, but rather the midpoint of wide-angle reflections placed approximately in the middle between the line and the recording station. Each of the velocity models is composed of multiple land station recordings with different midpoints. This means that the models do not necessarily represent a continuous geographical line. More detailed explanation of the model positioning is provided by the original publications (Heikkinen and Luosto 1992, Komminaho and Yliniemi 1992, BABEL Working Group 1993).

Wide-angle section data are available from the modeled lines (1, 3, 4 and 7) and some additional data from Finnish stations is available from lines 2, B and C. The wide-angle data of BABEL lines differs from other wide-angle data presented as each section file is from a single station with each marine shot presented as an individual trace. The unusual station geometry must be considered when using the data. The sections are in standard IBM SEG-Y format with separate files for P- and S-waves and stacked sections. More information of the data acquisition is provided by BABEL Working Group (1993).

3.3.2. BALTIC

The deep seismic sounding BALTIC was conducted in 1982 to investigate the crustal structure of the Fennoscandian shield (Luosto et al. 1990). The 560 km (including Kostomuksha shots, main part 430 km) long survey profile runs northeast from the Gulf of Finland to Kostomuksha, Russia. Seismic sources were explosions shot at eight different shot points at sea, in shallow lakes and in a quarry. These shots were recorded by 48 seismic stations along the profile at an average receiver spacing of 2 km. The stations included 36 three-component stations: 16 “MARS 66”, 10 “ASS”, 10 “SN-PCM80” and 12 six-channel stations: 10 “Taiga-2” and 2 “SN-PCM-80”. The profile crosses the Wiborg rapakivi batholith, the Svecokarelian geosynclinal complex and the Archean basement complex in southeastern Finland. Two-dimensional crustal velocity models of the profile have been constructed by a trial-and-error ray tracing method. The model displays variability of 40 to more than 60 km in crustal thickness, the thickest crust being situated in the border region of the Svecofennian and Karelian domains.

Three different velocity models are available for the BALTIC profile. The original P-wave velocity model was constructed by Luosto et al. (1990). New P- and S-wave models were published later by Janik (2010). Wide-angle P-wave sections are available from the profile measured at three different orientations.

3.3.3. FENNIA

The FENNIA deep seismic sounding survey was carried out in the May of 1994 in Southern Finland (FENNIA Working Group 1998). The 330 km long profile is oriented from south to north and runs through the Svecofennian lithological units of the late orogenic migmatite, metasedimentary and metavolcanic belts of Southern Finland and the synorogenic Central Finland Granitoid Complex. Seismic refraction measurements were made by recording large explosions from six shot points with spacings of 60 to 80 km. 50 three-component seismic stations were deployed in three separate groupings during the experiment, equaling to 150 different station positions. Trial-and-error ray tracing method was used to obtain a two-dimensional crustal P-wave velocity model in 1998. The model shows thick crust (57 to 61 km Moho depth) in northern and central parts followed by an abrupt thinning of the crust to 48 km depth at the southern end of the profile. The seismic data was reprocessed in 2007 to address the inconsistencies in Moho depth data acquired by wide-angle, receiver function and reflection data. This yielded new two-dimensional P- and S-wave velocity models for the FENNIA profile obtained by similar ray tracing methods.

The three available velocity models of the FENNIA profile were modeled by FENNIA Working Group (1998) and Janik et al. (2007). Wide-angle sections of three different seismic measurement axes are available for the FENNIA profile.

3.3.4. HUKKA 2007

Seismic wide-angle reflection and refraction measurements were conducted in the low cost deep seismic sounding experiment HUKKA 2007 in Central Lapland (Tiira et al. 2014). In August of 2007, shots from seven shot points were recorded using 98 portable seismic stations, two permanent broad-band seismic stations and two semi-permanent short period stations of the Kuusamo network. The portable seismic recording instruments used were 80 one-component Reftek-125 recorders, 17 three-component recorders and one Reftek-130 recorder. Military and commercial explosions were used as sources of seismic energy to keep the cost of the experiment down. The 455 km long seismic profile begins near the Kittilä allochthon at Hukkavaara shot point where large military explosions were used as seismic sources. The profile runs through the Central Lapland greenstone belt, the Suomu complex, the Central Lapland granitoid complex, ending in the Central Karelian craton at Kostomuksha quarry shot point. In the middle of the profile, shots from other quarries at maximum 62 km line offset were also recorded.

A single two-dimensional P-wave velocity model was obtained using a trial-and-error ray tracing method by Tiira et al. (2014) and will be made available for HUKKA 2007. The model shows a heterogeneous upper crust with three high velocity zones and a relatively high velocity middle crust with a low velocity layer. The Moho depth varies in the range of 46-50 km depth. Wide-angle section(s) of the HUKKA 2007 profile will also be later made available.

3.3.5. KOKKY

The Kokkola-Kymi (KOKKY) profile is the first Finnish structural seismology survey fully based on industrial blasts, after finding out the functionality of data from quarries in HUKKA 2007 experiment (Tiira et al. 2020). The 500 km long profile begins in Central Ostrobothnia on the coast of the Bothnian Bay and runs south-east towards the Russian border in South Karelia. The geological environment comprises three Late Proterozoic units: Pohjanmaa area (PA), Central Finland Granitoid Complex (CFGC), and Saimaa area (SA). The two first ones are located in the Western Finland Subprovince (WFS) of the Svecofennian domain. Data were gathered in summer campaigns in 2012 and 2013, resulting in 63 usable seismic sections. Two-dimensional P-, and S-velocity models are available for the profile, revealing a Moho 54 km deep below PA, 63 km deep below CFGC and 43 km deep below SA. However, a 55-km gap without an obvious Moho reflection was present in the middle. The main result was that the thickest crust in Europe exists roughly below the city of Jyväskylä. The KOKKY profile crosses SVEKA and BALTIC profiles, and results are in agreement in the crossing points.

Separate P-wave and S-wave velocity models modeled by Tiira et al. (2020) will be made available for the KOKKY profile. Wide-angle section(s) of the profile will also later be added to the data set.

3.3.6. Kuusamo

The Kuusamo seismic profiles are a collection of seismic P-wave velocity models obtained from multiple seismic experiments and published by Uski et al. (2012). The 10 profiles run mostly in the Archean Karelian bedrock in Northeastern Finland. In profiles 1, 2, 4 and 5, the recording was done by the Kuusamo seismic network and the nearest permanent stations MSF, SGF, OUL and KJN in 2003-2007. Profile 3 was recorded by broad-band stations of the SVEKALAPKO experiment seismic network in 1998-1999. Profiles 1-5 used local earthquakes and explosions as sources. The comparatively low number (11-26 stations) and geometry of the stations in profiles 1-5 limited the spatial resolution of the data. The remaining profiles 6-10 were older data from refraction experiments from the 1980s and 1990s. These profiles used military explosions and industrial explosions from mines and quarries as seismic sources. The distribution and density of data was better in profiles 6-10 due to larger number of stations (43-111 stations) and dense linear geometry (3-6 km average station spacing).

Two-dimensional crustal P-wave velocity models constructed by Uski et al. (2012) are available for all the 10 profiles. Profiles 1-5 show less detailed velocity structure and have larger uncertainties in velocities and boundary depths because of the large data spacing. In profiles 6-10, the velocities and boundary depths are better constrained. Wide-angle sections are not available for the Kuusamo data.

3.3.7. POLAR

The deep seismic sounding experiment POLAR was conducted in the northern Finland and Norway in August 1985 to investigate the crustal structure, composition and development of Precambrian crust in northern Fennoscandia (Luosto et al. 1989). Seismic wide-angle measurements were made along a 440 km long profile by recording large explosions at six shot points and smaller explosions at three shot points. The events were recorded using 42 portable seismic instruments used in five deployments to cover 210 receiver positions at average spacings of 2 km. The profile transects the Central Lapland complex, Karasjok-Kittilä greenstone belt, Lapland granulite belt, Kola province and Mesoproterozoic units of Varanger peninsula.

Two-dimensional crustal P- and S-wave velocity models are available from the profile. The models were obtained using a trial-and-error ray tracing method. The original P-wave model was built by Luosto et al. (1989) and new P- and S-wave models were obtained by Janik et al. (2009) through reprocessing and analysis of the original data. The velocity models show high velocity bodies in the upper crust beneath the Karasjok-Kittilä greenstone belt and the Lapland granulite belt, and lower upper crustal velocities beneath the Kola province. The newer models are characterized by more lateral variations in velocity and more complicated velocity structure. Wide-angle sections of three different seismic measurement axes are also available for the POLAR profile (Luosto et al. 1989).

3.3.8. SOFIC

The 450 km long Southern Finland Coastal (SOFIC) seismic profile is based on a controlled source seismology experiment very much similar to KOKKY (Tiira et al. 2022). Geophones were installed in a summer campaign in 2015 to register quarry blasts in the vicinity of the profile. The geological environment of the western 220 km part of the study area is dominated by the Uusimaa belt (UB) in the 1.7–1.9 Ga Southern Finland subprovince (SFS) of the Svecofennian domain. Eastward, a 170 km part crosses the 1.62–1.65 Ga Wiborg rapakivi batholith (WRB). The furthest 60 km of the profile is in Saimaa area (SA), consisting of supracrustal rocks and granitoids with small-scale variations. Moho is deepest, ca. 52–54 km below UB, and most shallow, ca. 40–45 km below WRB. The manuscript on the profile (Tiira et al. 2022) is under preparation.

A single two-dimensional P-wave velocity model will be made available for the SOFIC profile (Tiira et al. 2022) and wide-angle section(s) of SOFIC will also be later added to the data set.

3.3.9. SVEKA’81

The seismic experiment SVEKA’81 (also referred to as SVEKA) is the first high quality deep seismic sounding survey conducted in Finland (Luosto et al. 1984). The 325 km long SVEKA’81 profile runs from the Central Finland granitoid complex of the Svecofennian domain through the Ladoga-Bothnian Bay zone to the Archean Karelian province. The field measurements were made in June 1981 by recording 45 explosions at five shot points in shallow lakes using 19 seismic stations occupying different positions in multiple deployments. 4 five-channel and 15 three channel instruments, including both analog and digital recorders, were used at 2 km average station spacing along the profile.

A two-dimensional crustal P-wave velocity model for the SVEKA’81 profile was constructed from the wide-angle data by Luosto et al. (1984). The model shows Moho depths of around 55-60 km with the thickest crust in the middle of the profile and varying velocity structure in the upper crust. A wide-angle vertical component section of the SVEKA’81 profile is also available. A continuation of the SVEKA profile to the southwest called SVEKA’91 was surveyed in 1991. A simultaneous interpretation and modelling of these profiles has been carried out by Janik et al. (2007).

3.3.10. SVEKA'91

The deep seismic sounding profile SVEKA'91 is the continuation of the original SVEKA'81 profile (Luosto et al. 1994). SVEKA'91 wide-angle seismic measurements took place in August 1991 southwest of the original SVEKA'81 profile. The 350 km long profile begins near Uusikaupunki at the southwestern coast of Finland and ends in Kannonkoski, Central Finland, partly ovelapping with the SVEKA'81 profile. The objective of the SVEKA'91 project was to investigate and map the crustal structure in the area between the pre-existing BABEL and SVEKA'81 profiles. The SVEKA'91 profile runs through the Southwest Finland rapakivi intrusion, Satakunta sandstones, Tampere schist belt and the Central Finland granitoid complex. Large explosions (200-1440 kg) at five shot points and small explosions (80 kg) at two shot points were used as seismic sources along the profile. The explosions were recorded by 29 digital and 6 analog stations spaced on average 2 km apart.

A two-dimensional crustal P-wave velocity model was obtained from the recordings of SVEKA'91 by Luosto et al. (1994). The velocity model shows smooth crustal thickening to the northeast from 48 to 56 km Moho depth. A wide-angle vertical component section is available for SVEKA'91. Also separately available are new P- and S-wave models of both SVEKA'81 and SVEKA'91 published by Janik et al. (2007).

3.3.11. SVEKA

The wide-angle refraction and reflection profiles of SVEKA'81 and SVEKA'91 were jointly modeled as one 580 km long profile here referred to as SVEKA. A P-wave and an S-wave model was constructed from the SVEKA profile by Janik et al. (2007). Models and wide-angle sections of SVEKA'81 and SVEKA'91 are separately available.

3.3.12. SVEKALAPKO

The SVEKALAPKO project was a multidisciplinary geoscientific research project aiming to investigate the evolution of the crust and lower lithosphere of the Fennoscandian shield. The project included a seismic experiment conducted with an array covering the southern half of Finland consisting of 40 broad-band and 88 short-period temporary stations as well as 15 permanent stations. The station spacings were on average 100 km for broad-band and 50 km for short-period stations. The array was operating continuously from August 1998 to May 1999. The final event list included 1356 selected events recorded by the array. The events included teleseismic, regional and local events. Four two-dimensional crustal P-wave velocity models were originally constructed from local event data recorded along profile swathes by Yliniemi et al. (2004). As the profile swathes are very wide, the position of the velocity models is not exact, being between shot points at the ends of the profile.

The three available models were obtained by Yliniemi et al. (2004) using a trial-and-error ray tracing method. In addition to a general velocity structure, the models show reflective structures in the upper mantle. Velocity model of profile 1 in Yliniemi et al. (2004) is not included in the available data as the original model has been lost. Wide-angle sections are not available for the SVEKALAPKO data.

4. Use and limitations

The velocity models, wide-angle sections and supporting coordinate information files are available in the Research Data Storage Service IDA and will be made available in the Hakku service of the Geological Survey of Finland. The data is open access and data use is licensed under the Creative Commons By Attribution version 4.0 license. The data set includes separate Digital Object Identifiers for subsets of Finnish WARR projects or profiles. These are to be used in citations along with the original model or data publications.

The presented data are made accessible in universal data formats for a wide range of use cases. The velocity models with velocity point format can be imported to 3D modeling software through columnar data options with ease and data columns are accessible for calculations and conversions. The wide-angle sections are in standard IBM SEG-Y revision 0 format able to be read with various seismic software.

Limitations of the velocity models should be considered while using the data. The presented models are not actual representations of subsurface structure and boundaries (cf. reflection sections), but rather models capable of reproducing observed data with a sufficient fit. A sufficient data fit for better quality recordings is considered to be less than 0.1 s difference between synthetic and observed travel times being on the order of the picking accuracy (e.g., Fennia Working Group 1998, Janik et al. 2009, Tiira et al. 2014). As determined by Janik et al. (2002), differences of this magnitude result in uncertainties on the order of ±0.1 km/s in model velocity and ±1 km model boundary depths. For complicated parts of profiles, such as faults, more conservative uncertainties of ±0.2 km/s and ±2 km are suggested (Janik et al. 2002). For profiles with less recording stations, such as Kuusamo profiles 1-5 and the SVEKALAPKO profiles, conservative uncertainties of ±0.2 km/s and ±3 km should be applied (Uski et al. 2012). The number and spacing of recording stations also affects the size of velocity structure details discernible in the model. For example, Kuusamo profiles 1-5 only show a rough layered velocity structure due to a low station number and wide station spacing. Station and source geometry along with the two-dimensional nature of velocity models should also be considered when using the models. WARR recordings are always generated by waves traversing a three-dimensional velocity structure while the velocity models only represent a velocity structure in two dimensions. This means that waves arriving from outside the two-dimensional profile may affect the observed data by creating artifacts in the two-dimensional models. This effect is likely larger when used sources and stations do not fall along a straight line.

5. Summary

Previously published data and models of Finnish wide-angle refraction and reflection studies were re-formatted and stored in the IDA Research Data Storage Service of CSC, and will be made available in the Hakku service of the Geological Survey of Finland. Stored data includes two-dimensional velocity models and wide-angle sections of WARR profiles. The velocity models were formatted to a point velocity format with velocity defined at specific coordinates and depths in the ETRS-TM35FIN (EPSG: 3067) coordinate system. The stored wide-angle sections are collections of seismic traces from stations used in each WARR study. The wide-angle sections were formatted to the standard IBM SEG-Y format accessible with typical seismic software.

The valuable data and models were stored to IDA for safe storage and easy access for researchers. The data can be cited with a Digital Object Identifier (DOI) along with the original publications. The stored data is open access, and usage of the data is defined by the Creative Commons By Attribution version 4.0 license. Limitations and resolution of the velocity models should be considered while using the data.

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