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Open Access Earth System Science Data Discussions

A community-driven metadata model for describing and integrating Controlled Source Seismic data in multidisciplinary data-driven Earth Sciences

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Abstract. Controlled Source Seismic (CSS) data are key to understanding the structure and composition of the lithosphere at different scales. They are highly valuable both in their own right and as input to multidisciplinary studies and Earth system modelling. The challenge for scientists is to find existing data, assess their relevance for a particular purpose, and eventually get access and permission to reuse selected data sets. The European research infrastructure for solid Earth sciences, EPOS (European Plate Observing System) was designed to solve such problems. It is a multidisciplinary, distributed research infrastructure that facilitates the integrated use of data, data products, and facilities from the solid Earth science community. FAIR principles are put into practice, enabling access to data and products from hundreds of scientific data services across Europe.

A community building effort for Controlled Source Seismic data was started at the EGU24 and SEISMIX2024 conferences, with the aim of developing a metadata model for data set discovery, as no existing standards or common practices for describing CSS data sets could be identified. This objective was achieved by early 2026 and the results are presented in this paper, together with a data service as an interface to the EPOS Platform. The metadata model is sufficiently detailed to allow a scientist to decide whether a discovered data set is fit for the intended reuse purpose or not. On the other hand, obligatory attributes are limited to avoid incompatibility with the diverse metadata models of potential data providers.

The EPOS CSS metadata catalogue will meet FAIR and Open Data principles. The data sets registered in the metadata catalogue should ideally also be FAIR and Open. However, enforcing such a policy would exclude a large part of the existing seismic data. Therefore, the metadata model was designed to also describe closed data by providing suitable information on the legal constraints. In this way, the CSS metadata catalogue will be most useful to the scientists by providing the largest coverage while also advertising FAIR data and Open Science to the data providers.

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1 Background

Controlled Source Seismics (CSS), often referred to as Active Source Seismics, is key to understanding the structure and composition of the Earth's lithosphere at different scales (Christensen and Mooney, 1995; Yilmaz, 2001). In addition to the fundamental relevance in basic research, CSS is most frequently utilised in applied research, such as the investigation of natural resources (e.g. hydrocarbons, ores, groundwater, geothermal energy), carbon capture and storage (CCS), reservoir management, and subsurface engineering.

1.1 The Controlled Source Seismic method in a nutshell

The CSS method implies that a seismic source generates energy at the Earth's surface, which then travels as elastic waves through the subsurface rocks. These seismic waves are reflected, refracted and diffracted when the physical properties of the rocks change sharply along their path. Such phenomena occur, for example, at the interfaces between different lithologies, stratigraphic contacts or across structural faults. Also, the pore space of the rock and the type and amount of pore fluid affect the seismic wave propagation. At the surface, usually an array of regularly spaced receivers registers the returning energy (Fig. 1). With expert knowledge and advanced processing strategies (Yilmaz, 2001; Forel et al., 2005), an image of the subsurface structure and physical composition is created. This image is then interpreted with the help of available geological knowledge (e.g. from boreholes and/or by extrapolating the surface geology) and with the help of other geophysical methods and integrated numerical modelling (Fig. 2). Each survey is designed for a certain purpose, depending on the investigation scale and resolution required. Although the physical principles remain the same, a high-resolution survey of the near-surface for, e.g. geotechnical purposes, differs from deep seismic sounding for imaging major structures down to the crust-mantle boundary (Mohorovičić discontinuity; e.g. Yilmaz, 2015, 2021). For each target and observational environment, specific equipment is chosen, parameters of the seismic source and of the receivers are adapted, such as the amount of energy and the frequencies of the source wavelets, the receiver type and number, their spacing and the recording time. The most elementary setup images the subsurface in two dimensions: the source and receiver points are located along a line to generate a profile of depth vs. distance. For better control on the three-dimensional structure of the subsurface, crossing lines/profiles can be used. Most advanced are three-dimensional surveys, in which receiver and, possibly, source points are arranged in a two-dimensional pattern on the surface. Four-dimensional surveys refer to time series of three-dimensional surveys, e.g. used for reservoir monitoring or environmental studies. For specific purposes, the source and/or receivers may be placed in boreholes. In recent years, fibreoptic cables have also been used as receivers to provide very dense spacing of observations (distributed acoustic sensing, DAS; e.g. Spikes et al., 2019; Willis, 2022). The CSS methods are also applicable in water bodies (sea, lake, river) with specially developed equipment that is towed behind ships.

CSS has been used in geophysical research successfully for about a century. It is essentially the only method for obtaining detailed information about the subsurface at a larger scale and at (comparatively) reasonable costs. Therefore, it has been used extensively in the exploration of the underground for natural resources. Utilising these data in a multidisciplinary

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environment, by analysing, interpreting and integrating CSS data sets with data from other geoscientific methods is expected to provide additional value to these high value data sets.

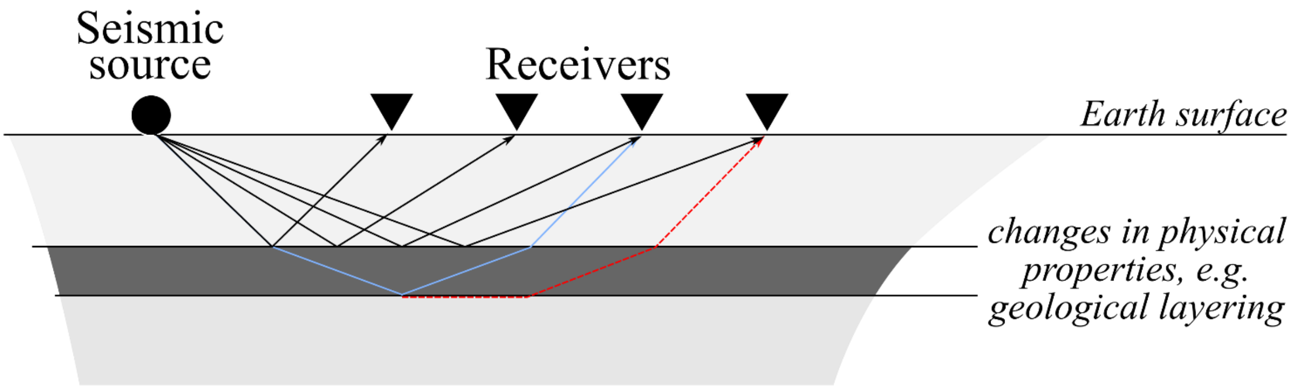

Figure 1 Basic principle of Controlled Source Seismics. A seismic source (e.g. explosive, vibrator truck, drop weight) transfers energy into the ground. The generated elastic wave propagates outward from the source in all directions and is influenced by the physical properties of the subsurface. At the first interface between materials with different physical properties (here: horizontal layering of the bedrock), part of the wave energy is reflected and recorded by receivers. The corresponding ray paths are drawn with black arrows. The remaining energy is refracted and travels deeper. The next interface illustrates how a refracted ray is reflected and critically refracted along the interface (blue and red arrows, respectively).

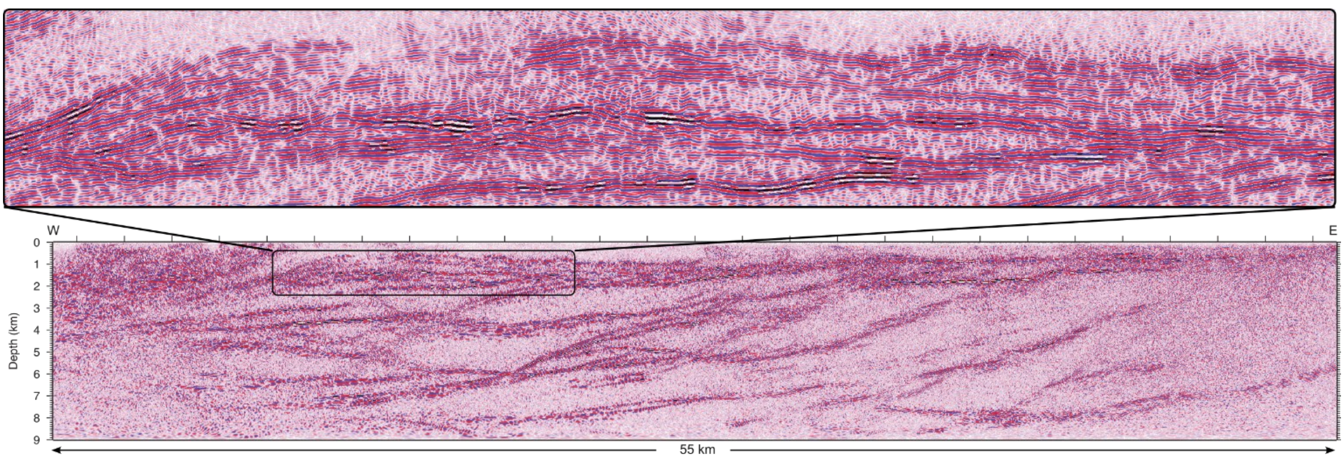

Figure 2 An example of a depth-converted 2D seismic section that is processed for geological interpretation. The lower half of the illustration shows a 55 km long and 9 km deep profile that was acquired for siting scientific boreholes. For a better understanding, a part of the profile is enlarged in the upper half of the illustration. For the origin of the data and for examples of studies with multidisciplinary data integration, please refer to Hedin et al. (2016), Yan et al., (2016), Lorenz et al. (2022), Lescoutre et al. (2022), Lehnert et al. (2024) and Juhlin et al. (2025).

1.2 Controlled Source Seismic data and their availability

The vast majority of CSS data are of industrial origin (mainly from hydrocarbon exploration), and their availability depends largely on the legislation in the country that is surveyed. For example, in Denmark and Norway, legislation forces companies to submit their exploration data to national organisations (Klima-, Energi- og Forsyningsministeriet, 2023; Nærings- og

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energidepartementet, 1996). Thus, individual surveys can be found in the databases at the Geological Survey of Denmark and Greenland (GEUS) and Norwegian Offshore Directorate, respectively (Subsurface Data Denmark, 2026; DISKOS, 2026). This does not imply that the data are publicly available. Although a part of the data might be open and directly accessible, other data in the same database can be closed, embargoed, or only accessible on request. In Italy, industrial legacy data from expired exploration licences are publicly available in the national ViDEPI repository (Visibilità dei Dati afferenti all'attività di Esplorazione Petrolifera in Italia; ViDEPI, 2026). In countries that do not have such legislation in place, industrial data usually stay in corporate databases and are not accessible at all. Nor is it known which data exist.

In addition to the vast amount of industry data, some national organisations, such as geological surveys, conduct or contract CSS surveying campaigns to investigate the subsurface of the country for a certain purpose (e.g. GEUS CSS 2026, SGU CSS 2026) or basic research, often together with academic partners (e.g. the CELEBRATION 2000 Project, Guterch et al., 2003; the Finnish Reflection Experiment (FIRE), Kukkonen and Lahtinen, 2006; the Italian CROP (CROsta Profonda) project, Scrocca et al., 2003; Finetti, 2005).

Quite different is the situation with scientific data sets. Most importantly, their targets and localities are defined by curiosity-driven research and thus they are often located in areas that are physically remote to industrial interests. The scale ranges from very local and shallow studies (e.g. in the field of engineering) through medium-depth studies (sedimentary basins, etc.) to the crustal and lithospheric scale. Most investigations on the largest scale were conducted before the beginning of this century as part of major research programs to explore the Earth's crust and mantle, such as the American research program COCORP (Consortium for Continental Reflection Profiling; Brewer and Oliver, 1980), the German Continental Reflection Seismic Program (DEKORP; Meissner and Bortfeld, 1990), or the European Geotraverse (EGT; Blundell et al., 1992). A comprehensive overview of seismic experiments at the crustal and lithospheric scale can be found in Prodehl and Mooney (2012). The results of the accompanying research are usually published in the scientific literature, but the availability of the related data varies widely. A common denominator over decades has been that the data stayed with the research groups that were involved in the fieldwork, and that confidentiality agreements with industry partners may exist. The situation changed only recently, when funding organisations and scientific journals started to require proper data publications in open repositories.

Older data can still be stored on legacy storage media where a successful retrieval could be questionable due to degradation over time, like tape reels and cassettes from the 1990s and earlier. The possible loss of technical metadata that is required to decipher the data is another complicating factor. For many old seismic investigations, the original analogue or digital recordings and processed data files are missing. Only print-outs on paper or microfiches are available, sometimes showing low to poor quality and old line-drawings made by industry seismic interpreters, which severely limits the reuse for scientific purposes and interoperability with other data. Recognising that even scanned paper and microfiche copies have a high value for reuse, domain experts developed workflows for digitising these data (Sopher, 2018; Maesano, 2026; Pertuz et al., 2026), showing that even without the original field records, it is possible to recover information useful for subsurface modelling.

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1.3 Towards FAIR Controlled Source Seismic data

Legacy CSS data of acceptable or better quality are high-value data sets, because i) seismic surveying is a cost-intensive method while funding is limited; ii) it might not be possible to reinvestigate a certain area due to changes in land usage, social acceptance, or the political situation; iii) it might not be possible to use certain methods due to modern environmental regulations/legislation and public acceptance, like large explosive charges as a seismic source; iv) in the case of a reinvestigation, the old data set is a valuable reference for research, particularly when re-evaluated with modern tools (e.g. Ercoli et al., 2020), and it can supplement the information in the newly acquired data.

High-value data sets should be taken care of properly and made available to the public as FAIR (Findable, Accessible, Interoperable, Reusable; Wilkinson et al., 2016; Bailo et al., 2020) and, if possible, Open Data. The latter requires data curation including quality control and data publication on a suitable platform. As mentioned above, best practices or a community standard for the description of CSS data do not exist. Furthermore, the target audience has to be able to find the data. Subsequently, the data quality has to be assessed. Initially, based on available metadata and previews, followed by an assessment of the actual data sets once these are selected and retrieved. Already the first step is an intricate challenge. The amount of legacy data is immense and their curation requires substantial dedicated work by experts. However, funding schemes for the curation of legacy data are lacking on national or international levels, while funds for research are focussed on new, innovative research and thus, cannot support a systematic approach to legacy data. Consequently, initiatives for curating legacy data have been limited mainly to large research organisations that have an interest in taking care of their legacy or are bound by a commission to do so, and which have sufficient resources available. GFZ Helmholtz Centre for Geosciences, for example, archives CSS data obtained with instruments of the (German) Geophysical Instrument Pool Potsdam (GIPP) at the GFZ Data Services repository as data publications (e.g. Baumann-Wilke et al., 2015; Ryberg and Haberland, 2021) and makes them visible in the “GIPP Experiment and data archive" (Haberland and Ritter, 2016). The National Institute of Oceanography and Applied Geophysics (OGS) in Italy has developed the Seismic data Network Access Point (SNAP) for their data (Diviacco et al., 2015). Also, the marine seismic community archives seismic data in repositories such as PANGAEA (e.g. Weigelt et al., 2025). Spain hosts SeisDARE (DeFelipe et al., 2021), a dedicated repository for the archiving, preservation, and dissemination of active-source seismic data, maintained by Geociencias Barcelona (GEO3BCN), an organisation under the Spanish National Research Council (CSIC; SeisDARE, 2026).

After successful curation, another pitfall may prevent the release of the data – its legal status. The data holder might not be the data owner, the ownership of the data could be unclear, or the data are owned by multiple organisations without provision for new concepts such as re-use of data, data publication and Open Data. This and other regulations in the history of a legacy data set could prevent the application of an open license.

Even functional databases at large research programmes risk termination when the funding runs out. For example, the Site Survey Data Bank (SDDB) of the International Ocean Discovery Program (IODP 2) was closed at the end of the programme in early 2025 (IODP SSDB – Shutdown Notice, 2026). SDDB contained both open and restricted data. A small subset was

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published as Open Data on Zenodo (e.g. Gohl et al., 2025), while information on the remaining data apparently was removed from public access.

From the above, it is clear that the thematic area of CSS lacks a common approach for making data sets FAIR. Even when data are properly published or archived, it might not be easy to find them. Data holders and data owners who want to make their data accessible have to start from scratch by defining their own metadata content or make the best out of the repositories' existing metadata schemata (e.g. Juhlin et al., 2023a, b). Data and metadata are dispersed on various databases and data repositories, and a function to find suitable data sets for reuse does not exist. In this context, it is important to point out that also information about closed data is of importance, as it allows the scientist to identify the data owner and ask for access.

1.3.1 The European Plate Observing System (EPOS)

The European Plate Observing System (EPOS ERIC, a European Research Infrastructure Consortium) is the only pan-European research infrastructure for solid Earth sciences. The distributed e-infrastructure provides homogenised data, data products and services that span both national and thematic boundaries. It includes data, data products and services from, or based on, geophysical monitoring networks, local observatories (including permanent in-situ and volcano observatories), topographic information, surface and subsurface geological information, experimental and laboratory functions, and satellite data of different types. EPOS is an ambassador for FAIR data, Open Access and Research Data Management, and it is the solid Earth sciences partner in the European Open Science Cloud (EOSC). EPOS is continuously developed in order to preserve its relevance for solid Earth sciences and thus, it is open to new thematic communities to join.

Data provision to EPOS is organised in thematic communities. These communities decide on and develop the required data and metadata standards and data services, reusing existing standards and best practices where possible. When development on EPOS started in 2010, the original nine thematic communities were formed by the participating scientists. For reasons difficult to pin down, CSS was not part of it, despite being a central piece in solid Earth sciences. Several attempts were made to change this, most notably the working package on Deep Seismic Sounding (DSS) in the SERA project (Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe, 2017-2020; SERA, 2026). Based on the results, the SeisDARE (Seismic DAta REpository) open access data repository was implemented at GEO3BCN-CSIC (SeisDARE, 2026). The related data model is clearly geared towards data publication and archiving. In the end, SERA did not generate the required momentum for a community action towards EPOS. To amend the situation, "Bringing Controlled Source Seismic Data to EPOS" was initiated. The results are described below.

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2. Development work

Standardisation and harmonisation are central in EPOS. Existing standards need to be reviewed and evaluated. When suitable standards do not exist, a solution needs to be developed. To ensure broad acceptance, a reasonable representation of the topical community needs to be involved.

2.1 Community building

A community-building effort was initiated to reach out to the wider CSS community. ”Bringing Controlled Source Seismic Data to EPOS” started with a Splinter Meeting at the European Geosciences Union (EGU) General Assembly 2024 (EGU Session SPM75, 2024), targeting both data producers and data consumers. This was followed by e-mailing invitations to geophysicists in most European countries, outreach at the SEISMIX2024 conference and the IAGA/IASPEI Joint Scientific Meeting 2025 (Palomeras et al., 2025), and word-of-mouth between colleagues. The result was a group of about 30 individuals from 12 countries, which is referred to here as the “EPOS CSS Community”. This incipient community developed the metadata model with associated data service that is described in this paper and which was first presented at EGU 2026 (Lorenz, 2026).

2.2 Definition of goals

EPOS is a distributed e-infrastructure that provides discovery and access to distributed data through a single access point, the EPOS Platform. Thus, the primary target of “Bringing Controlled Source Seismic Data to EPOS” is providing the means for discovering CSS data in EPOS. This implies that information about the available data sets has to be provided in a coherent and uniform way. Initially, the EPOS CSS Community considered whether it is aware of any existing or forthcoming standard that defines how a seismic data set is described. The result was negative – neither an official/published standard nor an unofficial/community standard was known. Thus, it became clear that the model for such “discovery data” (scientific metadata) had to be developed from scratch. This metadata model has to i) be flexible enough to describe all diverse varieties of CSS data; ii) have sufficient detail to describe complex data sets; iii) have a limited set of obligatory attributes, to facilitate broad integration of existing databases by avoiding conflicts that could shut out potential data providers; iv) utilise controlled vocabularies wherever possible.

It also became clear that researchers need guidance for curating and publishing their scientific data sets, including the vast amount of legacy data. The establishment of best practices for data publications that provide easy integration with EPOS was defined as the second goal. This work is not finalised and only touched briefly upon in the discussion.

2.3 Survey of existing data models

The content of scientific metadata needs to be based on commonly available information. In addition, it is helpful to reflect on what others regarded as essential information when describing their data scientifically, e.g. in the national and

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organisational databases mentioned above. For this purpose, existing metadata models were collected, mapped to each other, compared and analysed:

- SERA/SeisDARE (Spanish seismic repository hosted by DIGITAL.CSIC; SeisDARE, 2026),
- OpenFIRE (Finish Reflection Seismic Experiment; a legacy metadata model of the Geological Survey of Finland (GTK); Väkevä et al., 2017),
- open information on the DISKOS database (Norwegian Offshore Directorate; DISKOS, 2026),
- Subsurface Data Denmark (Geological Survey of Denmark and Greenland, GEUS; Subsurface Data Denmark, 2026),
- the Lithosphere Research Centre (Institute of Geophysics of the Polish Academy of Sciences; Wójcik et al., 2019), and
- DEKORP (German Continental Reflectionseismic Program at GFZ Helmholtz Centre for Geosciences; DEKORP, 2026).

These were complemented by the attributes of the header information in the industry standard SEG-Y data format (Barry et al., 1975; SEG Technical Standards Committee, 2002, 2017, 2023) and preliminary results from earlier work by EPOS TCS (Thematic Core Service) Geological Information and Modelling (which remained unfinished due to lack of community support after 2017).

2.4 Attribute selection

The first step in the development work was to compile additional information about the types of seismic data owned by the participating organisations. This was followed by questioning the community's experts about how to best describe these data types:

1. Make a list of attributes that are required for data discovery. We start with the assumption of an optimal case, that all information that comes to your mind is available.

   Question 1: Think about yourself as the scientist who wants to discover data sets for a certain purpose. What information (which attributes) do you need to be able to decide whether a data set is suitable for your needs or not?

   Question 2: Think about yourself as the data provider. What information (which attributes) is needed for a full description of a data set?
2. Optimal scenario vs real-world. What information (which attributes) is usually known and easily accessible for future data integration? Attach the following labels to the attributes: a) obligatory, b) important (should be obligatory, but might not always be available), and c) optional. Label b) is relevant, as too many obligatory attributes might exclude data sets that otherwise are important and useful.

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The answers were compiled and equivalent terms mapped to each other, circulated and discussed in the community. This resulted in a draft data model, which could be compared to the compilation of existing data models. Based on this comparison, attributes were defined as obligatory or optional. Then each attribute was described and a data type assigned.

2.5 Controlled vocabularies

The situation for controlled vocabularies was similar to that of the data model. Published vocabularies did not exist, but vocabularies are used in the previously reviewed national or organisational databases. Thus, the attributes that require controlled vocabularies were specified in the CSS metadata model, and the vocabularies composed by the community. The input was harmonised and, where relevant, checked against established information (e.g. SEG Wiki, 2026, various manuals/documentation by equipment manufacturers). Additionally, linkages to synonymous terms in published vocabularies and ontologies were explored and added. In one case, a published vocabulary from another topic was used as a basis, and adjusted and extended: INSPIRE Borehole Purpose (Borehole Purpose - INSPIRE registry, 2026) was extended by EPOS TCS Geological Information and Modelling for their borehole services (Borehole Purpose - European Geoscience Registry, 2026). This extended borehole purpose vocabulary was then adapted for the purpose vocabulary of CSS.

2.6 Testing and revision

The metadata model and the vocabularies were developed in a shared spreadsheet. By adding columns for information on actual data sets, this spread sheet was also used as the first stage of testing. Community members had the opportunity to fill the attributes of the metadata model with information on their data sets, or map it to the metadata models of their database. In this way, problems could be discovered and addressed, and changes immediately tested against already submitted testing data.

2.7 Data service

The data service is not strictly part of the metadata model. For its development, existing data transfer standards were used. As it is part of the CSS data provision to the EPOS Platform, it is described concisely below.

3. The Controlled Source Seismics metadata model

Table 1 presents the initial version of the CSS metadata model: the attributes, their description and data type. Each attribute has a multiplicity assigned, describing whether it is obligatory or optional, and whether it may take multiple values. For easier understanding and navigation in the data model, the attributes are grouped: “Core” attributes are those regarded as indispensable for describing CSS data, including information required in an Open Science environment. “Descriptive” and “Technical” attributes carry optional complementary information. These terms are self-explanatory. “Data” attributes provide details about the digital data set as supplied by the data provider. Supplementary attributes carry information about the data provider and the metadata record, which are partially obligatory.

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3.1 The Controlled Source Seismics metadata schema and metadata catalogue

The CSS metadata model is translated into a metadata schema that controls the content of the CSS metadata catalogue. Its physical implementation is a JSON Schema based on the latest draft (Wright et al., 2022), defining the content of the metadata instances in GeoJSON format, an international standard (Butler et al., 2016). Thus, it is easy to compile CSS metadata and validate them against the schema in a code editor that supports the format. As a GeoJSON feature collection, the metadata catalogue is fully standards-compliant and accessible.

Table 1 The Controlled Source Seismics metadata model

	attribute name	multi-plicity	description	type
CORE	surveyName	1	Name of the individual survey.	text (free)
	campaignName	1	Name of seismic campaign/project.	text (free)
	acquisitionYear	1	The year in which the data acquisition was conducted.	integer
	surveyType	1	The geometry of the acquisition (2D, 3D, others?)	text (vocabulary)
	investigationMethod	1	The principle of seismic investigation (e.g. reflection/refraction)	text (vocabulary)
	content	1..*	The content of the data set.	text (vocabulary)
	domain	1	The domain (land, marine) in which the survey was conducted.	text (vocabulary)
	license	1	The license that applies to the data set (that is described by this instance of metadata).	text (vocabulary)
	uid and/or dataUri	1	Either 'uid' or 'dataUri' or 'uid and dataUri'	
	uid	0..1	The URI that identifies and points to the landing page of the data publication/data set (a DOI, if it exists).	URI
	dataUri	0..1	An URI that points directly to the data set (file). If several data sets exist, it should point to the highest level data set.	URI
	provenance	1	Provides a hint on the origin of the available digital data, e.g. "paper to digital", "analogue to digital", "digital", or similar.	text (vocabulary)
	geolocated	1	Is the data set geolocated? For raw data: source and receiver positions, for processed data coordinates of the data bins.	boolean
	geometry	1	A spatial geometry (polygon, line, point) that describes the surface coverage of the survey.	geometry
	size	1	The size of the survey. "length [km]" if "survey geometry" is "2D", "area [km2]" if "survey geometry" is "3D".	real

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DESCRIPTIVE	clientName	0..1	The organisation that initiated the survey (project owner).	text (free)
	clientId	0..1	ROR or other identifier (https://ror.org)	URI
	contractorName	0..1	The organisation that was responsible for conducting the survey.	text (free)
	contractorId	0..1	ROR or other identifier (https://ror.org)	URI
	purpose	0..1	The original purpose for which the survey was conducted.	text (vocabulary)
	sourceType	0..*	The type of the seismic source.	text (vocabulary)
	sourceParameters	0..1	Information on e.g. sweep or charge size.	text (free)
	sensorType	0..*	The type of the seismic sensor.	text (vocabulary)
	sensorParameters	0..1	Information on e.g. model, frequency response.	text (free)
	verticalScaleUnit	0..1	The unit of the vertical scale. Required if "vertical scale" is provided.	text (vocabulary)
	verticalScale	0..1	The value of the vertical scale. Required if "vertical scale unit" is provided.	real
	spread	0..1	The type of the prevailing spread used during the survey.	text (vocabulary)
	processing	0..*	A concise description of the processing steps that led to the described data set.	text (vocabulary)
	description	0..1	Text with additional information on the survey purpose and/or summary of results, e.g. abstract.	text (free)
	detailedDocumentation	0..1	Report, publication or similar with detailed information on the survey.	URI
	velocityModel	0..1	Is a velocity model available/specified?	boolean
	preview	0..1	A preview image for the data set.	URI
TECHNICAL	spacingSource	0..1	Prevailing distance between source points [m].	real
	spacingReceiver	0..1	Prevailing distance between receiver points [m].	real
	samplingRate	0..1	The sampling rate used while recording [ms].	real
	countSourcepoints	0..1	Total number of source points.	integer
	countReceiverpoints	0..1	Total number of receiver points.	integer
	offsetNear	0..1	Minimum offset between source and receiver [m].	real
	offsetFar	0..1	Maximum offset between source and receiver [m].	real
	countChannels	0..1	Number of channels of the acquisition system	integer
	foldNominal	0..1	The nominal fold of survey.	integer
	specification	0..1	Text with additional information on the survey design & acquisition (including environmental conditions and other factors that could have an influence on the data).	text (free)

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DATA	format	0..*	Format of the data file.	text (vocabulary)
	volume	0..1	Size of the data file [GB].	real
	legalConstraints	0..1	A description of legal constraints, in particular for data sets without license or with restricted access.	text (free)
	datePublication	0..1	Date of first availability or publication.	date
	dateMoratorium	0..1	End date of a moratorium/embargo period. When this attribute is filled, the license and legal information should describe the status after the end of the moratorium/embargo.	date
PROVIDER	dataProviderName	1	The organisation that is responsible for the instance of discovery data.	text (free)
	dataProviderId	0..1	ROR or other identifier (https://ror.org)	URI
	contactName	1	Name of contact person, possibly with contact information if not available as URI.	text (free)
	contactId	0..1	Preferably ORCID, or other identifier (https://orcid.org)	URI
	contactUri	1	Link to contact information.	URI
	dateUpdated	1	Date when the record was last updated.	date

3.2 Publication and versioning

For best transparency, the CSS metadata catalogue will be published under the CC BY 4.0 license as a package with the appropriate versions of the metadata model, schema document and the vocabularies. Changes to the model and vocabularies may only happen when a new version is published. This effectively decouples data discovery from the legal status of the metadata catalogue, providing discovery not only for Open CSS Data, but for all data with at least the information in the core attributes publicly available. The version numbering indicates both the status of the metadata catalogue content and the version of the metadata model used. This is achieved by combining the publication date with the model version, formatted as vYYYY.MM-mX.Y (e.g., v2026.06-m1.0). All updates will be published under the same Concept-DOI. The publications include relevant documentation and quality assurance statements. However, this initial publication lacks the latter as it focusses on the metadata model and provides only example metadata instead of a full metadata catalogue (Lorenz et al, 2026).

3.3 The Controlled Source Seismics discovery data service

The CSS discovery data service provides the CSS scientific metadata as a Web Feature Service (WFS) that follows the specifications of the respective OGC and ISO standards (Open Geospatial Consortium, 2014; International Organisation for Standardization, Technical Committee 211, 2010). This service can be used as part of the EPOS Platform (Fig. 3) but also interfaced directly. The GeoJSON standard (Butler et al., 2016) defines the primary payload format, as it is the native format

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of the EPOS Platform (Bailo et al., 2023). GeoServer (Aime et al., 2026) was chosen as the platform because it provides advanced filtering capabilities in the form of CQL (Contextual Query Language)/ECQL (Extended Contextual Query Language) filters. CQL-filters implement the functionality of OGC XML-based filters in a URL-friendly way. However, while OGC-filters are part of the WFS-standard, CQL-filters are a platform-dependent extension. In addition, server-side pre- and post-processing is used to adapt functionality to the EPOS Platform, and to add EPOS' extended GeoJSON to the return payload. As the data model supports multiple types of geometries (points, lines, polygons), and in order to guarantee maximum functionality for serving CSS data to the EPOS Platform, the data service supports only the subset of WFS that is explained in its documentation (which will become available when the service is integrated in EPOS).

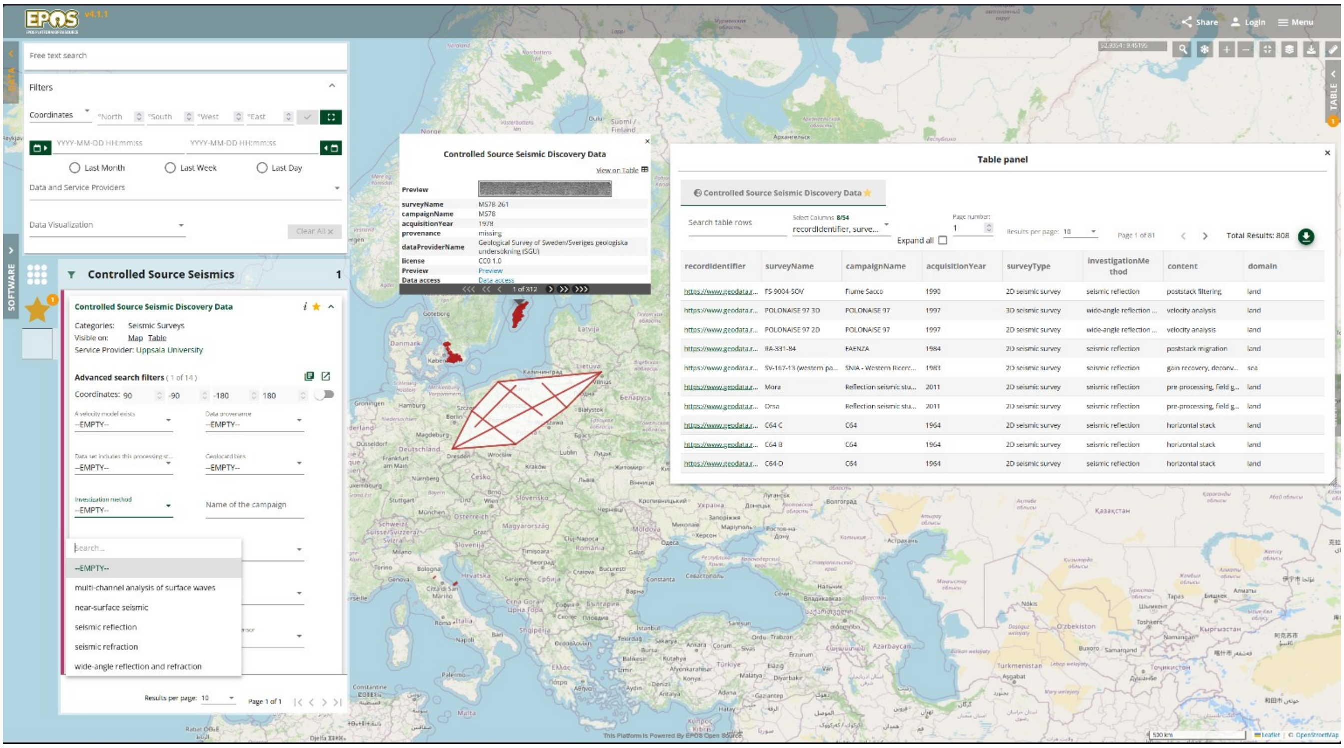

Figure 3 Screenshot of the Controlled Source Seismic discovery service in a testing instance of the EPOS Platform Open Source (Bailo et al., 2023): On the left is the service selection and filter panel. The discovered data sets are displayed in table (right) and map (background) views. On the map, data sets can be identified, displaying key information. Individual data sets or the filtered results can be downloaded. Not seen here are several functions of the EPOS Platform (production environment), which provides e.g. Virtual Research Environments (VREs) in which the data can be integrated and analysed with other data types available on the platform. The background map on this screenshot contains information from OpenStreetMap, which is made available at openstreetmap.org under the Open Database License (ODbL).

4. Discussion

The development of the CSS metadata model is the first step towards a community standard that provides a way to describe data sets across the full range of CSS methodologies, bringing the principles of FAIR data to CSS.

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Ideally, all seismic data sets would meet FAIR and open principles. In practice, they range from non-FAIR and closed to fully FAIR and Open Data. While this is largely beyond the community's control, the CSS metadata model includes attributes ("license", "legalConstraints"; Table 1) that allow users to either filter out closed data during discovery, or include them, as even closed data sets may be valuable for specific studies if access is granted by the data owner. Closed data either have a proprietary licence, which can be referenced in the "license" attribute, or no licence at all. The latter case is implemented by the OGC NIL-value "missing" (http://www.opengis.net/def/nil/OGC/0/missing). In both cases, it is highly recommended to provide additional information on the legal status of the data set in the attribute "legalConstraints". Furthermore, the mode of access to the data sets differs with their legal status. This is taken into account by providing two attributes, "uid" and "dataUri" (Table 1). For FAIR and Open Data, "uid" is a persistent, globally unique and resolvable identifier that points to a landing page that provides information and data access in human and machine-readable form (e.g. a DOI). "dataUri" may point directly to the data file for better integration with EPOS Virtual Research Environments. A similar situation exists with public national and organisational databases. Though globally unique identifiers are not commonly used in this setting, data sets and their landing pages are usually identified and resolved via internally unique identifiers. These can be used in the metadata. If direct data access via an URI is not provided, "dataUri" is left empty and data access will be via the landing page only. The latter will also be the case for all closed data, with the difference that the landing page specified in "uid" has to provide information about how to obtain permission to use the data and who to contact, thus defining the lowest level that has to be met for a useful data discovery. In the public domain, data exist that were released without landing pages. In this case, "uid" is empty and the "dataUri" points directly to the data file. Any available documentation that otherwise would be part of a landing page can be included or resolved in the attributes "description" and "detailedDocumentation" (Table 1). The CSS metadata model cannot describe the case in which multiple surveys are supplied in a single archive file, as encountered in the public domain (e.g. SGU CSS, 2026). Archive files also impede data integration and analysis on the EPOS Platform. Integration of such data requires re-sharing/hosting in a suitable structure.

The metadata catalogue that describes the actual data sets is both FAIR and Open Data. Achieving FAIRness of seismic data sets is more complex and requires action by the data owners or holders. However, juxtaposing non-FAIR and/or closed data with their FAIR and Open Data counterparts while making them easily accessible via the CSS discovery data service and the EPOS Platform is expected to raise awareness and motivate change. The rich description of the data sets by the CSS metadata model is an important step towards FAIRness for CSS data sets. Major obstacles are the lack of licenses for closed data and the limited use of persistent, globally unique identifiers, even in databases that have a public interface with landing pages for both open and closed data sets. Addressing these issues requires both the willingness of the data providers and sufficient resources, e.g. for DOI-registration and necessary adaptation of the landing pages. In the meantime, the CSS metadata catalogue with its flexible approach to data and metadata provision can serve as a bridge towards FAIR until persistent, globally unique identifiers are adopted. Such changes can later be backtracked in the version history of the metadata catalogue. While not ideal, this is a practical approach to the problem.

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As mentioned above, data sets range from analogue tape recordings and digitised prints/microfiches to modern digitally recorded files, which makes a huge difference for how the data can be utilised in modern research. To address this issue already at the data discovery stage, the metadata model provides the obligatory, vocabulary-controlled attribute "provenance", which allows the user to include or exclude data sets based on their origin.

The CSS metadata model also provides a foundation for developing best practices for data publication and archiving. Until this is accomplished, individual scientific data sets should at least be published in a certified data repository. Since these repositories only offer universal metadata schemata, a complete description of the data set must be provided in text form. It is then crucial to populate the CSS metadata with the help of the schema document and submit the resulting metadata file to the community hub for inclusion in the next version of the CSS metadata catalogue (up-to-date instructions are provided in the GitHub repository https://github.com/epos-css/metadata). The GeoJSON file could also be added to the data publication. Once the next version of the metadata catalogue is published, the new metadata will become findable through the CSS discovery data service and on the EPOS Platform. SeisDARE, the previously mentioned community repository that was developed during an earlier project under the auspices of EPOS, focusses on data publication but lacks rich metadata for discovery. It could be used similarly to generic repositories, with CSS metadata attached in a validated GeoJSON file. Alternatively, it could be further developed to include these metadata as part of its data schema.

The CSS metadata model proposed here is the first step toward a community standard that will make it possible to archive the full range of seismic data sets in a unified way and make them available for reuse. At the same time, we are convinced that substantial resources are necessary to process additional data sets so that they become searchable and accessible in this standardised and useful manner. Existing metadata may need to be supplemented or reformatted and added to existing or new databases. Also, the actual data sets may need to be reformatted and/or modified to meet existing and future data standards. For example, the Geophysical Survey (GS) format has been developed by the United States Geological Survey (USGS) as best practice for storing geophysical data, metadata, and survey information in a single, self-describing file (James et al., 2022) that follows netCDF-4/HDF5 international standards (Open Geospatial Consortium, 2019). The format is presently under consideration by the EuroGeoSurveys (EGS).

Lastly, we hope that the CSS meta model can be used as a template for other geophysical communities using "active methods" (e.g. near surface applications) by adapting it to their needs and conditions.

5. Outlook

In the near to medium term future, the EPOS CSS Community has the following goals:

- To integrate with EPOS ERIC or one of the existing thematic communities and make the data service available to users on the EPOS Platform.

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- To successively populate the metadata catalogue, starting with metadata that require only little work and where some funding for curation is available while trying to obtain support for curation work on various levels (organisational, national, European).
- To enlarge the community, reach additional data providers and increase the support for community actions and development.
- To develop best practices for curating and publishing scientific CSS data sets.

Code and data availability

The metadata model and the metadata catalogue content are maintained under version control at the GitHub repository https://github.com/epos-css/metadata. Releases are published at GFZ Data Services (Lorenz et al. 2026).

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Author contributions

HL coordinated the CSS community and led the development work. All authors contributed actively to the development and testing of the data model, which subsequently was reviewed and discussed by the EPOS CSS community (“team”). HL, ME and CH wrote the draft manuscript, all authors reviewed and contributed to the final manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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