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USGS 3D San Francisco Bay Region Seismic Velocity Models

History, Construction, and Access

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Summary

- **USGS SF-CVM = 3D geologic model + rules assigning elastic properties**
  - Leverages a wide variety of geologic, geophysical, and seismological information
  - Used in ground-motion simulations and the USGS National Seismic Hazard ModelK (NSHM)
- **Storage Scheme**
  - Flexible, efficient, self-describing storage scheme for 3D gridded models
  - Accessed via C/C++ open-source software with macOS and Linux binary packages

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USGS SF-CVM: US Geological Survey San Francisco Bay region 3D seismic velocity model (Aagaard and Hirakawa, 2021a,b; Hirakawa and Aagaard, 2022)

Outline

- **USGS San Francisco Bay Area geologic and seismic velocity models**
  - Science drivers
  - Background
  - Construction
- **Storage scheme and access**
- **Future directions**

Science Drivers for the USGS 3D SF-CVM

- **Input to 3D ground-motion simulations**
  - Fault geometry from 3D geologic model
  - 3D elastic properties (density, Vp, Vs, Qp, Qs)
- **USGS National Seismic Hazard Model**
  - Depth of sedimentary basins (Z1.0 and Z2.5)
  - San Francisco Bay region and Great Valley

Previous 3D Seismic Velocity Models in San Francisco Bay Region

Frankel *et al.*, 1992 Santa Clara Valley

Stidham *et al.*, 1999 Regional model with major geologic units and sedimentary basins

Hole *et al.*, 2000 Regional model from travel times and 1991 refraction survey

Thurber *et al.*, 2007 Regional P-wave model using double-difference tomography

Hardebeck *et al.*, 2007 East Bay P-wave model using double-difference tomography

USGS 3D San Francisco Bay Region Seismic Velocity Model

2005 **Models developed for the 1906 earthquake ground-motion modeling**

- Detailed model for the San Francisco Bay Area
- Coarse resolution model for surrounding area

2006 **Initial analysis by Rodgers *et al.* and Kim and Dreger**

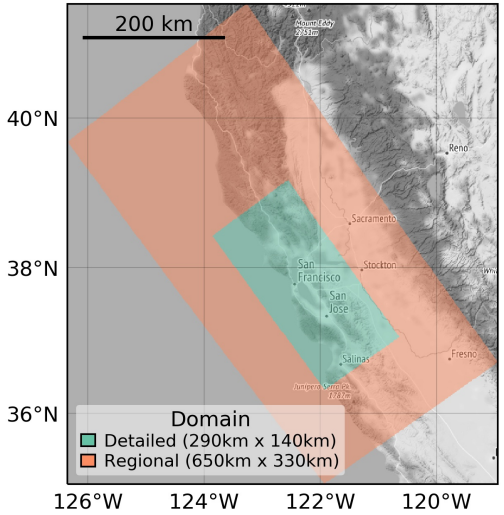
- Shear wave speed about 5% too low in East Bay
- Difficult to isolate regions needing improvement

2008 **Minor updates to correct significant discrepancies**

- Increase shear wave speed in East Bay
- Correct significant discrepancies with Thurber tomographic model

Model Domain: Map View

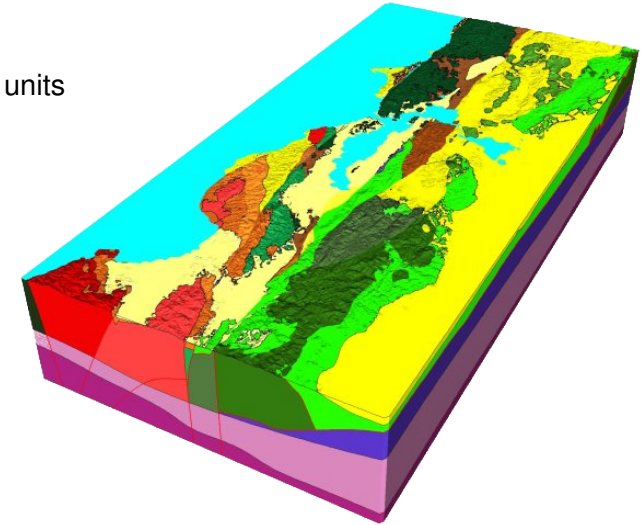
Detailed domain surrounded by coarser regional domain



San Francisco Bay Region 3D Geologic Model (Jachens, 2006)

Constructed from geologic mapping, gravity, seismicity, etc using Earth Vision

- 23 faults
- 29 lithologic units
- 130 blocks



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The detailed domain consists of 130 blocks defined by 23 faults and 29 lithologic units.

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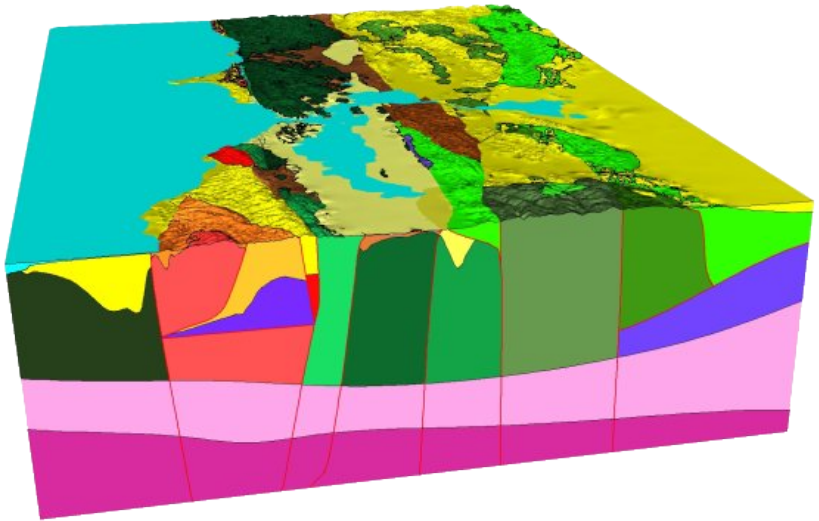
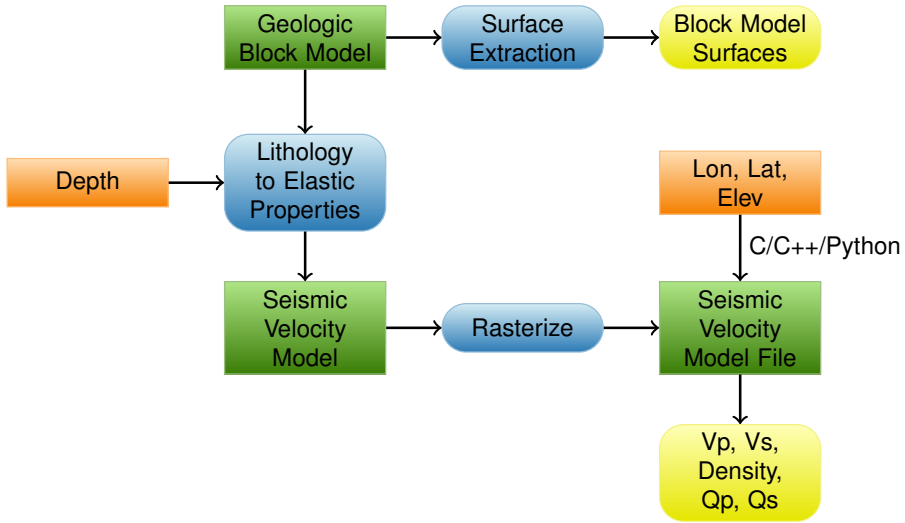
San Francisco Bay Region 3D Geologic Model

Vertical slice through Santa Clara Valley shows basin structure



The figure shows a vertical slice through the Santa Clara Valley with sedimentary basin structures on the east and west sides.

Geologic Model → Seismic Velocity Model



We create the seismic velocity model from the geologic model by assigning elastic properties as a function of depth to each geologic unit.

Geologic Model $\rightarrow$ Seismic Velocity Model (Brocher, 2006)

Franciscan (Foothills) elastic properties as a function of depth

$$V_p(\mathsf{km/s}) = \begin{cases} 0.13 + 2.5 + 2.0d & 0 \leq d \leq 1.0\mathsf{km} \\ 0.13 + 4.5 + 0.45(d-1) & 1.0\mathsf{km} \leq d \leq 3.0\mathsf{km} \\ 0.13 + 5.4 + 0.0.0588(d-3) & 3.0\mathsf{km} \leq d \end{cases}$$

$$density(\mathsf{g/cm^3}) = 1.74 V_p^{0.25}$$

$$V_s(\mathsf{km/s}) = 0.7858 - 1.2344V_p + 0.7949V_p^2 - 0.1238V_p^3 + 0.00064V_p^4$$

$$Q_s = \begin{cases} -16 + 104.13V_s - 25.225V_s^2 + 8.2184V_s^3 & V_s > 0.3\mathsf{km/s} \\ 13 & V_s \leq 0.3\mathsf{km/s} \end{cases}$$

$$Q_p = 2Q_s$$

Example of rules assigning elastic properties (V_p: P wave speed; V_S S wave speed; $density$, Q_s: quality factor for S wave; Q_p: quality factor for P wave) as a function of depth, d in km, for the Franciscan (Foothills) geologic unit.

Recent Updates

- **Recent and upcoming releases (Evan Hirakawa presentation)**
  - v21.0 Re-release of v08.3.0 in new storage scheme
  - v21.1 Updates to East Bay based on 3D ground-motion simulations of moderate earthquakes
  - v24.0 Updates to the shallow properties in the central SF Bay
- **GeoModelGrids**
  - New HDF5-based storage scheme for georeferenced 3D raster models
  - Build on CMU Etree and EarthScope EMC
  - API for serial access with binary packages for Linux and macOS

HDF5: Hierarchical Data Format**CMU**: Carnegie Mellon University**EarthScope EMC**: EarthScope Earth Model Collaboration**API**: Application Programming Interface

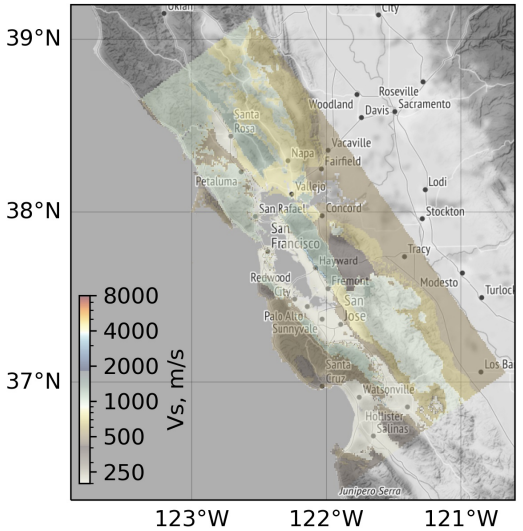
Seismic Velocity Model Discretization

Depth range	Detailed		Regional	
	Horiz.	Vert.	Horiz.	Vertical
$0 \leq z < 0.5$km	100m	25m	500m	125m
0.5km $\leq z < 3.5$km	200m	50m	500m	125m
3.5km $\leq z < 10$km	500m	125m	500m	125m
10km $\leq z < 45$km	1000m	250m	1000m	250m

We use a coarser discretization for the regional domain, consistent with the lack of detail in the top few kilometers.

Current Release: v21.1

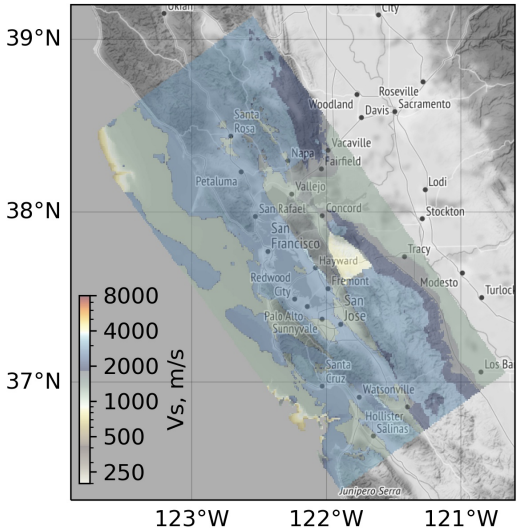
Vs @ surface



Horizontal slices through the model at depths of 100m, 1km, and 5km. The colors indicate the shear wave speed.

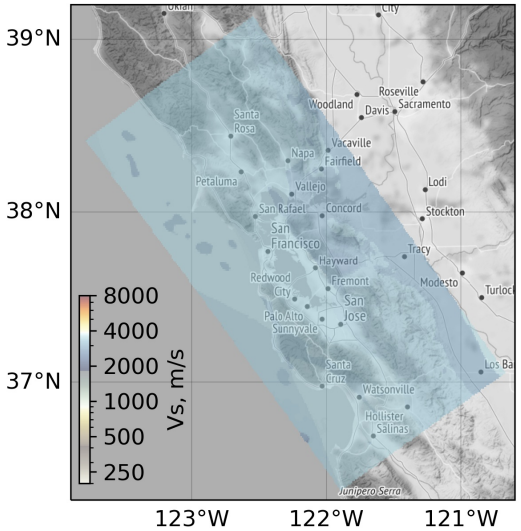
Current Release: v21.1

Vs @ z=-0.1km



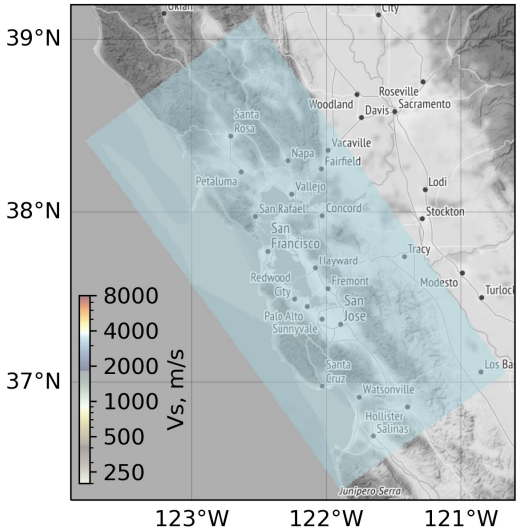
Current Release: v21.1

Vs @ z=-1.0km

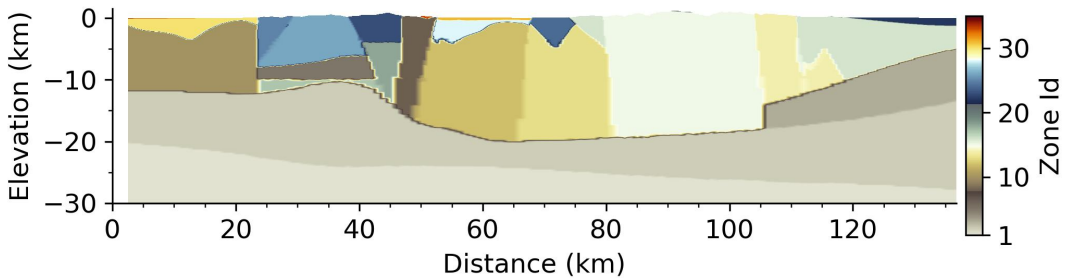


Current Release: v21.1

Vs @ z=-5.0km



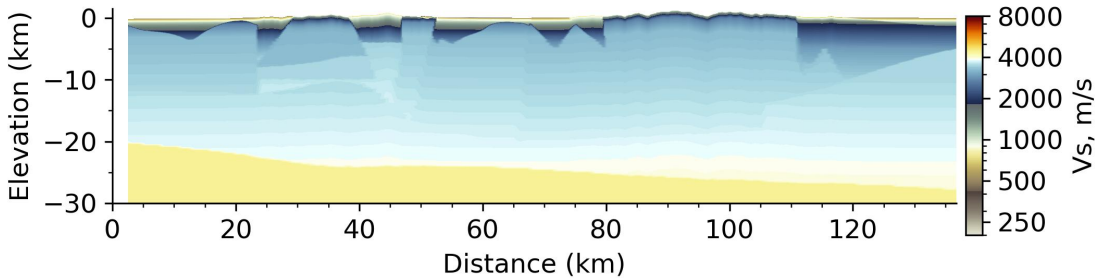
San Jose West-East Cross-Section: Zone id



Vertical slice of the model through San Jose with colors indicating the Zone id (geologic unit).

Current Release: v21.1

San Jose West-East Cross-Section: Vs

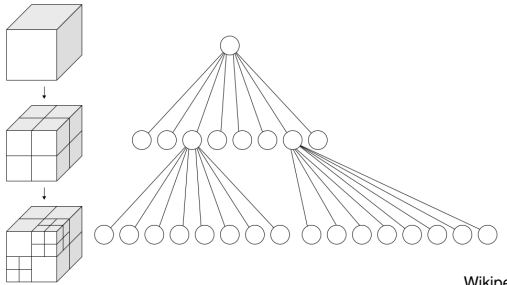


Vertical slice of the model through San Jose with colors indicating the shear wave speed.

Storage Scheme and Query Interface (before v21.0)

Detailed model: 8.9 GB; Regional model: 6.5 GB

- **Storage scheme**: Etree format from CMU based on octrees



Wikipedia: WhiteTimberwolf, CC BY-SA 3.0

- **Query library**
  - Custom C/C++/Fortran API on top of CMU Euclid/Etree C library
  - Only part of model is loaded into memory (user-specified cache size)
  - Stair-stepped top surface; uniform properties within a grid cell
  - File format is opaque to user
  - Euclid library cannot read Etree files written on machines with different endian type

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The Etree storage scheme used in versions before 21.0 was based on octrees and a library developed at CMU. It provided varying the discretization size horizontally and vertically, but had a stair-stepped top surface and yielded uniform elastic properties within a grid cell. Additionally, the file format was opaque to the user and Etree files were not portable across machines with different endian types.

GeoModelGrids Storage Scheme (v21.0 and after)

Detailed model: 2.0 GB; Regional model: 1.0 GB

- **Goal**
  Portable, flexible, efficient storage of raster-based Earth models
- **Requirements**
  - Storage
    - Self-describing binary format
    - Models with and without topography
    - Independent of model coordinate system
    - Resolution can vary with depth
    - Vertical resolution independent of horizontal resolution
  - API
    - Serial: Allow loading only a piece of the model into memory
    - Parallel: Efficient loading of models on massively parallel computers

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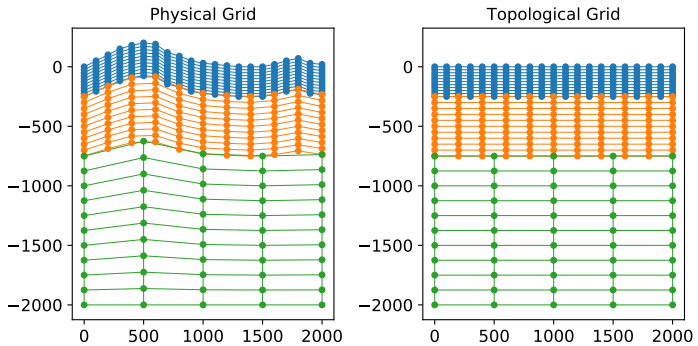
The HDF5 storage scheme used in version 21.0 and after offers several improvements, such as use of a portable, widely-used scientific file format and library and facilitates interpolation within a grid cell.

GeoModelGrids Storage Scheme

New, improved storage scheme using mapped grid



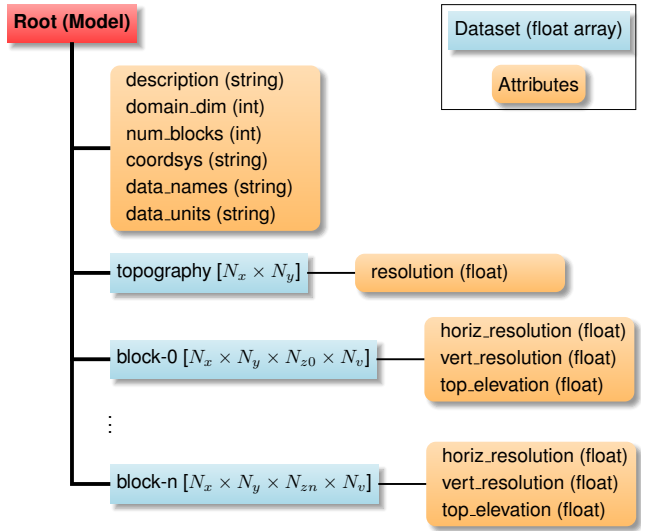
Linear mapping between positions in logical grid, $z^{logical}$, and positions in physical grid, $z^{physical}$.

$$z^{physical} = z_{bottom} + (z^{physical}_{topo} - z_{bottom})/(z^{logical}_{top} - z_{bottom}) * (z^{grid_i}_{top} - z^{logical} - z_{bottom})$$

We use a linear mapping to allow storing the model as a set of uniform logical grids while also conforming the top of the model to topography.

GeoModelGrids Implementation

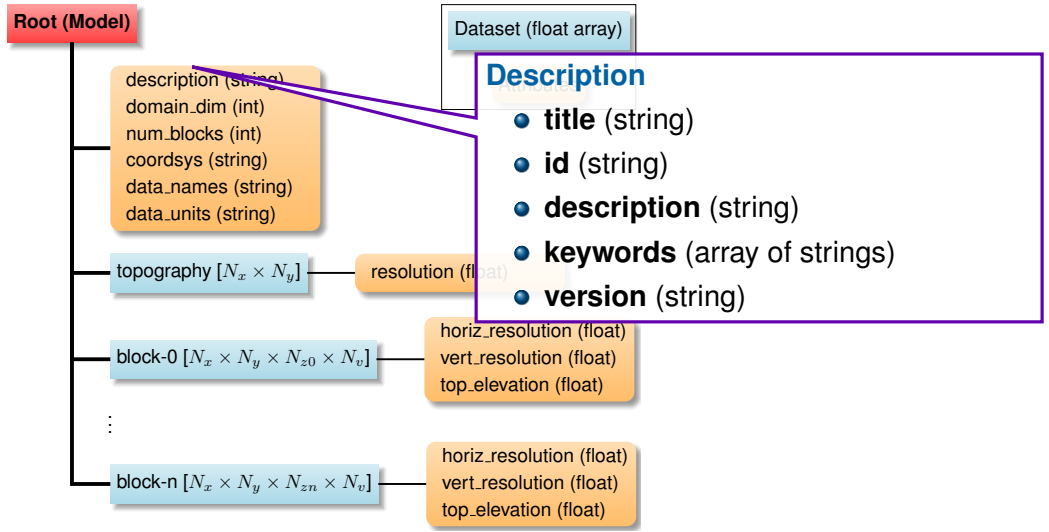
HDF5 File: Widely used self-describing binary layout



The model includes metadata consistent with EarthScope EMC so that no additional information is needed to query the model.

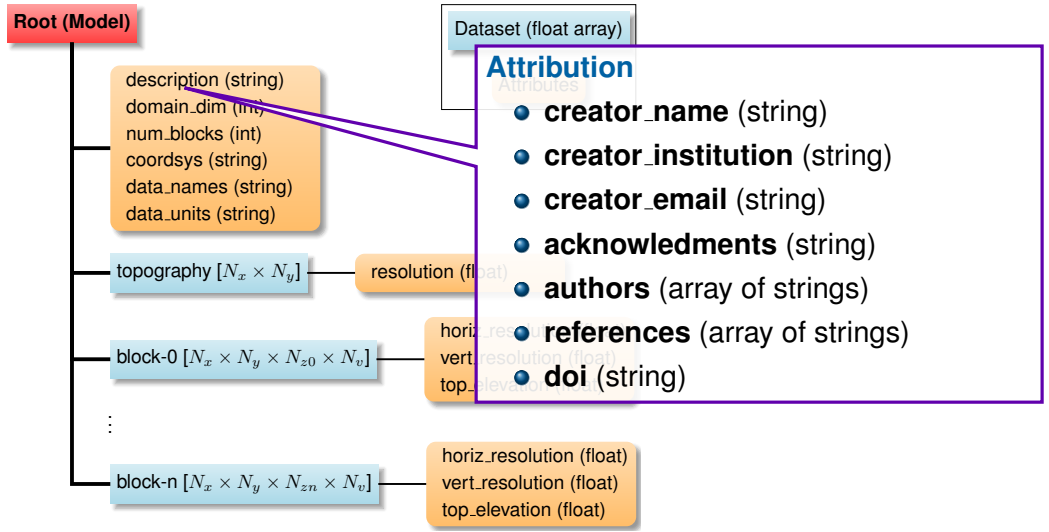
GeoModelGrids Implementation

HDF5 File: Widely used self-describing binary layout



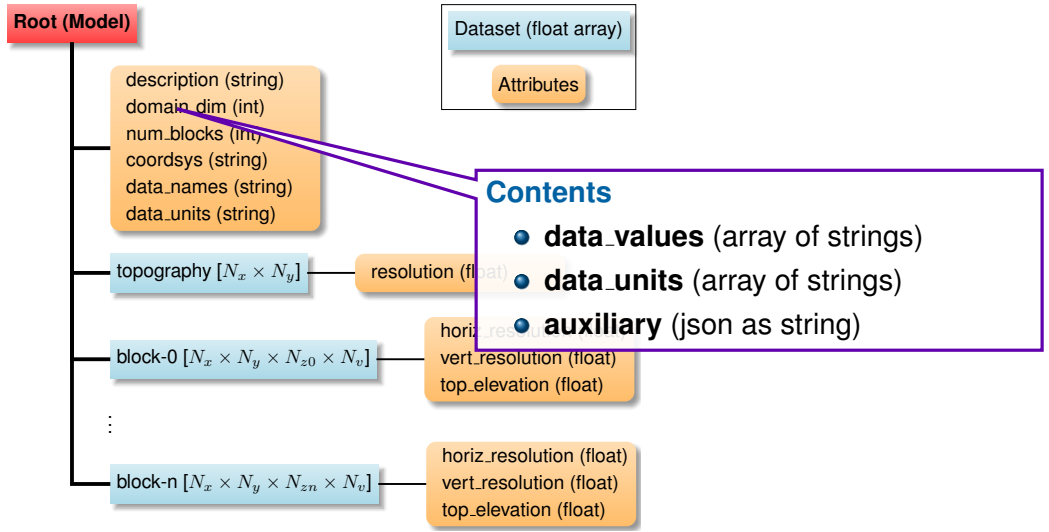
GeoModelGrids Implementation

HDF5 File: Widely used self-describing binary layout



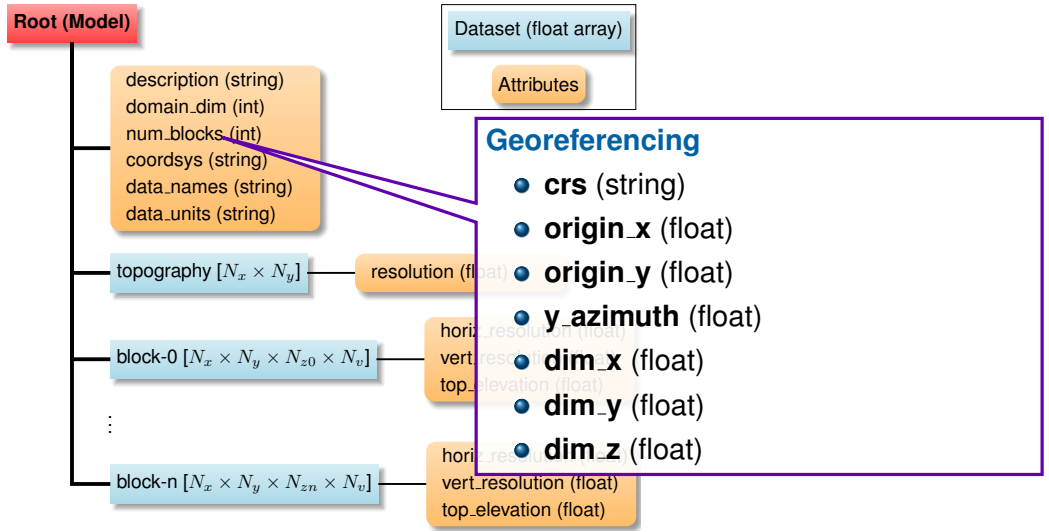
GeoModelGrids Implementation

HDF5 File: Widely used self-describing binary layout



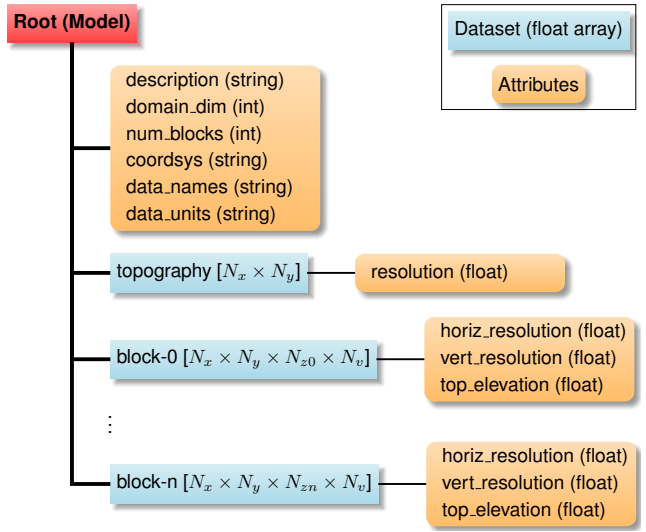
GeoModelGrids Implementation

HDF5 File: Widely used self-describing binary layout



GeoModelGrids Implementation

HDF5 File: Widely used self-describing binary layout



GeoModelGrids: Command Line Tools and API

- **Command line tools**

  geomodelgrids_query Query for values in models
  geomodelgrids_queryelev Query for elevation of top surface or bathymetry
  geomodelgrids_info Display model metadata
  geomodelgrids_borehole High-level interface for 1D vertical profiles
- **C/C++/Python API**
  - Library for accessing models in serial with 98% test coverage
- **Known limitations**
  - Vp and density are interpolated across the water/solid interface.
  - Vs is not available in grid cells spanning water/solid interface.
  - Fault block and zone ids are interpolated across geologic units.
  - Parallel API not yet implemented; LLNL SW4 has custom implementation.

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GeoModelGrids includes several high-level command line tools to make it easy to query the models.

Release Information

- **Seismic Velocity Model**
  - Models for detailed and regional domains as HDF5 files
  - Z1.0 and Z2.5 as GeoTiff file

    v21.0 `https://doi.org/10.5066/P98CA3D5`
    v21.1 `https://doi.org/10.5066/P9TRDCHE` (Google: Aagaard v21.1)
    v24.0 Coming soon: Spring 2024
- **GeoModelGrids v1.0.0** Coming soon

Five-Year Science Plan

Outcome of Mar 21–22, 2018, workshop

Aagaard, B.T., Graymer, R.W., Thurber, C.H., Rodgers, A.J., Taira, T., Catchings, R.D., Goulet, C.A., and Plesch, A., 2020, Science plan for improving three-dimensional seismic velocity models in the San Francisco Bay region, 2019—24: U.S. Geological Survey Open-File Report 2020–1019, 37 p., https://doi.org/10.3133/ofr20201019.

Objectives:

- Summarize state of 3D seismic velocity models in the San Francisco Bay region
- Identify short-term and long-term goals
- Develop strategy for community effort

As part of the development of the SF-CVM, we held a workshop in 2018 and developed a five-year science plan.

California Community Models

- SCEC: Southern CA Earthquake Center $\rightarrow$ Statewide CA Earthquake Center
- Many models exist beyond those produced by SCEC researchers
- **California Community Models online workshop: March 4–5, 2024**
  - What community models (e.g., seismic velocity models) exist and where?
  - How do we coordinate community efforts?
  - Look for announcements in coming weeks on SCEC and EarthScope mailing lists

In March 2024 with the transition of SCEC to the Statewide California Earthquake Center, we will be holding an online workshop to discuss coordinating community efforts to build and maintain Community Earth Models in California.

COSMOS Simulation Working Group

COSMOS = Consortium of Organizations for Strong Motion Observation Systems (`strongmotion.org`)

Objective: Develop international standards and guidelines for curating, validating, and disseminating simulated earthquake ground-motion data for engineering applications.

- **2022 workshops** Report available at `strongmotion.org` → Projects
- **Sessions at conferences**
  - Special interest group at 2023 SSA Annual Meeting
  - Session at 2023 SSA Physics-Based Ground Motion Modeling Meeting
  - Special session at 2023 International Conference on Earthquake Engineering and Seismology (7ICEES)
  - Session at 2024 World Conference on Earthquake Engineering
- **Partnering with other groups to engage the community on these topics**
  - COSMOS + GeoInquire workshop: September 2–4, 2024, Potsdam, Germany
- **Planning for future in-depth workshops to develop the standards**

On a related note, COSMOS has formed a working group to develop international standards and guidelines for curating, validating, and disseminating simulated earthquaek ground-motion data for engineering applications.

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