RESQML Technical Usage Guide

For RESQML v2.0.1

RESQML Overview	The RESQML standard facilitates data exchange among the many software applications used along the E&P subsurface workflow, which helps promote interoperability and data integrity among these applications and improve workflow efficiency and flexibility.
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1 Introduction

1.1 What is RESQML?

RESQML is an XML- and HDF5-based data-exchange standard that facilitates reliable, automated exchange of data among software packages used in subsurface workflows. RESQML consists of a set of XML schemas (XSD files) and other standards-based technology, which developers implement into software packages. Software that has implemented RESQML can read and write the standard format.

RESQML has been developed by a global consortium of operators, service companies, software vendors, and government agencies under the umbrella of Energistics.

1.1.1 Subsurface Workflow Challenges

The exploration and production (E&P) subsurface workflow is lengthy, iterative, and complex. It involves many people from different disciplines, sometimes different companies, and use of many different software packages for complex analysis, interpretation, modeling, and simulation.

This multi-discipline, multi-company, multi-software environment is iterative and requires users to move data back and forth between different software packages. Many of these packages use different data formats—often proprietary and incompatible.

This inherently complex process and inability to easily exchange data means E&P companies and their people face challenges that include: knowledge loss, rigid workflows, difficulty characterizing and sharing uncertainty, data loss, and productivity loss.

1.1.2 How RESQML Helps Address These Challenges

RESQML-compliant software can read and write this standard, common format, eliminating data incompatibility and the need for reformatting. **Figure 1-1** below is a high-level overview of how RESQML works and the workflows it supports. The newest capabilities (see Section 1.5.2 (page 15)) help RESQML deliver these benefits:

- Delivers a "knowledge hierarchy" to organize data and transform it into knowledge.
- Increases workflow flexibility, for example, with partial model transfers that allow you to update/transfer only data that has changed.
- Supports traceability, with universally unique identifiers for each top-level data object and key metadata for data sources, updates, dates of change, etc.
- Supports uncertainty management through increased ability to run more scenarios and realizations and reliably update models.
- Defines a rich set of subsurface data objects and enables transfer of detailed models and a variety of model types.
- Improves efficiency for both petro-technical and IT professionals.

For more information on the challenges of subsurface workflows, how RESQML helps address them, and some key supported workflow use cases, see the *RESQML Business Overview and Use Case Guide*. (For a link to this document, see Section 1.4 (page 13).

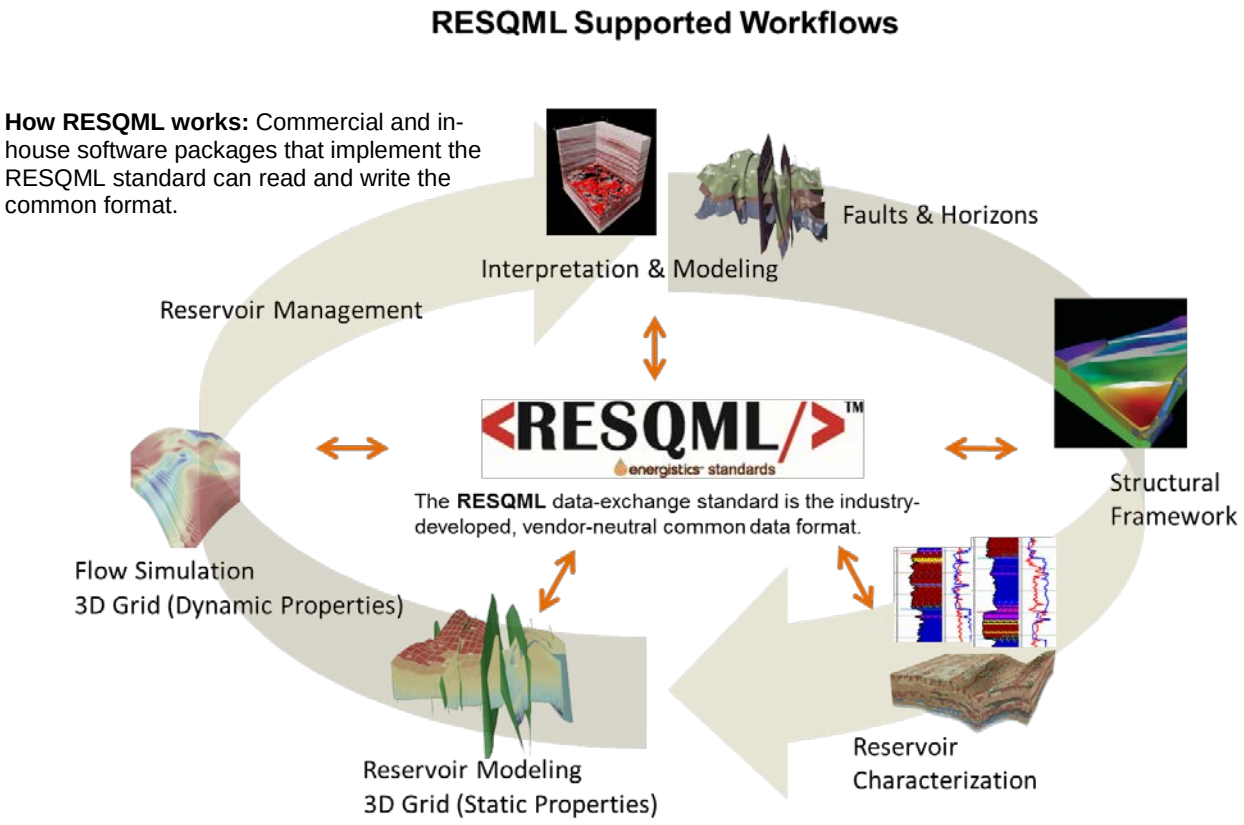


Figure 1-1—Implementing RESQML in software used in the E&P subsurface workflows streamlines data flow among the many different software packages used. The latest version supports more workflows and more flexible workflows. New capabilities provide a rich set of data objects, a well-defined knowledge hierarchy throughout the model, methods for specifying and transferring relationships among data objects, and the ability to group all of the information into a single, structured package.

1.1.3 RESQML Workflow: A Simple Example

Figure 1-2 is an example of a very simple subsurface workflow using RESQML-enabled software. When users need to move data to the next software application in their workflow, they choose to write (export) data to the RESQML format. In this example, User A using Software A writes the data to the RESQML format, which is transported in an EPC file (sometimes called an Energistics package; for more information, see Section 2.2.1 (page 20)). That next software application may be a tool used by another discipline in the workflow or by a partner company in a joint venture. If that software application is RESQML-enabled, it can read (import) the EPC file containing the RESMQL data and process the data in its native environment.

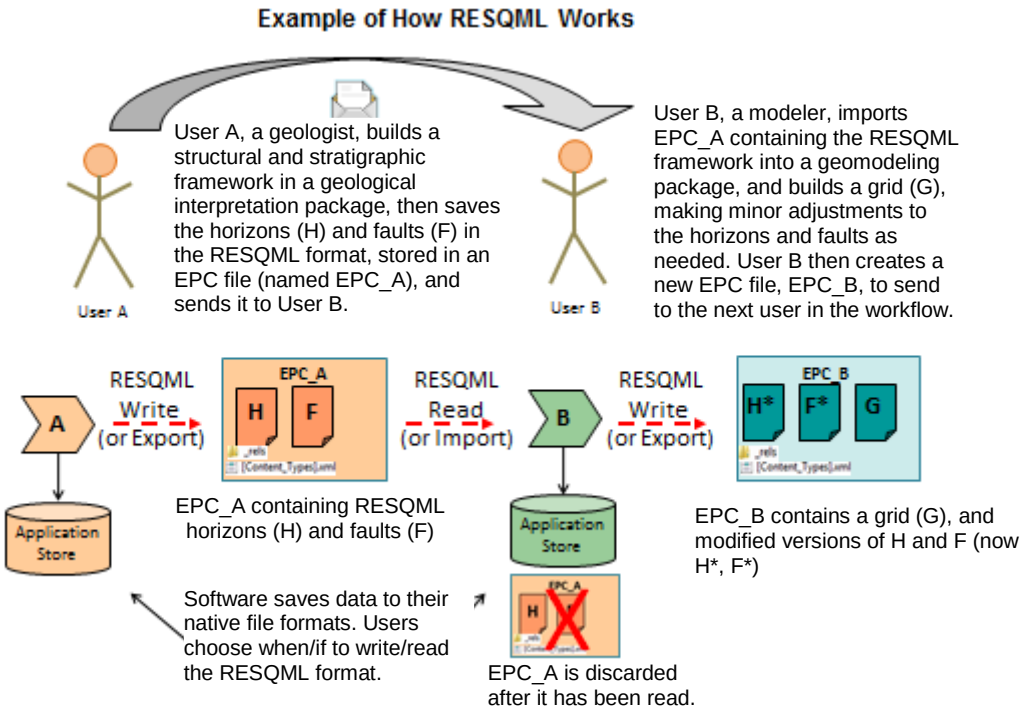


Figure 1-2—A user writes (exports) a file to the RESQML format, which is stored in an EPC file and may be read (imported) by other RESQML-enabled software.

1.2 Audience, Purpose, and Scope

This guide is intended for Information technology (IT) professionals—programmers, developers, architects and others—who are implementing RESQML into a software package.

This guide introduces and explains key RESQML capabilities and concepts—what it can do and how it works.

Specifically, this guide includes:

- Technologies and standards used in RESQML (Chapter 2 (page 18)).
- Organizing principals and key concepts of the RESQML design (Chapter 3 (page 23)).
- Detailed explanations and examples of the concepts introduced in Chapter 3 (see the Table of Contents of this guide).

1.2.1.1 Scope for 2.0.1

New data objects added have been designed to work with the previously published v2.0 RESQML model. Nothing has changed in the v2.0 model. As such, new v2.0.1 data objects are documented in Appendix C (page 224); they include:

- **Activity model**. Its purpose is to capture tasks or actions that occurred to create and edit a subsurface model, and how the activities relate to the data being exchanged.
- **Property series**. Makes it possible in RESQML to capture the evolution of property values through time and/or for multiple realizations of values during stochastic processes.
- **Streamlines**. In a reservoir engineering context, streamlines are a way to visualize and represent fluid flow. They have many applications; for example, they have been used as a basis for fluid flow simulation, sweep management, well rate optimization, and infill well placement.

A few minor documentation corrections and clarifications have been made to the main body of the document (as noted in the Amendment History on page 3). These edits do not change intended behavior of v2.0; they only clarify the previously published document.

1.3 Documentation Conventions

Documentation for RESQML observes the conventions listed in the following table.

	Document/Resource	Description
1.	Mandatory Behavior	Mandatory behaviors are specified as business rules as shown in the example below. For more information, see Section 2.3.1 (page 22). BUSINESS RULE: Array length is the number of cells in the grid or the blocked well.
2.	Document Hyperlinks: Internal	Though no special text-formatting convention is used: All section, page and figure numbers in this and all RESQML and Energistics documents are hyperlinks. The table of contents is also hyperlinked.

1.3.1 RESQML Jargon

The notion of "transfer" is referring to the exchange of data between any two RESQML-enabled software packages. Frequently we also refer to "exporting" or "writing" data to the RESQML format and "importing" or "reading" data.

In this context, the terms "software," "software package," "application" and others are used interchangeably—no special distinction is made between these terms. Software that writes or exports RESQML data is informally referred to as a "writer", and a package that is reading or importing RESQML data is referred to as the "reader."

1.4 Resource Set

RESQML is a set of XML schemas (XSD files) freely available to download and use from the Energistics website.

To download the latest version of RESQML, go to the Energistics website at: http://www.energistics.org/reservoir/resqml-standards/current-standards.

The download includes all the resources listed in the following table and the table in Section 1.4.1. For easier access, the main documents are also available for direct download from the above link.

	Resource / Document	Description
1.	RESQML:XSD files	The RESQML package includes a readme file that details the contents of the download package.
2.	RESQML UML Data Model	The entire UML data model that developers and architects can explore for better understanding of data objects, definitions, organization, and relationships. Developed using Enterprise Architecture (EA) modeling software (version 11), the UML model exists as an EA project (EAP) file. Information about EA, including a free EA Lite reader, is available at the Sparx Systems website, http://www.sparxsystems.com/. Included in the package when you download the RESQML standard.
3.	Examples	The download includes an example EPC file containing a basic RESQML model. Additionally, new examples will be added. Check the link above for updates.
4.	*RESQML Business Overview and Use Case Guide* (Also available for direct download from above link.)	An introduction to RESMQL for domain/petro-technical professionals. Provides: • an overview of the business value and domain challenge that RESQML helps to solve. • a representative list of supported use cases.
5.	*RESQML Technical Usage Guide* (this document) (Also available for direct download from above link.)	Detailed explanation of RESQML key concepts and design intended for software/IT professionals. See also in download: Separate spreadsheet with spline equations related to Chapter 7 (20131223 RESQML Cubic Splines.xlsx)
6.	*RESQML Technical Reference Guide* (Also available for direct download from above link.)	Lists and defines all packages, data objects, elements, including related business rules. This document also identifies relationships between/among data objects and highlights significant information about relationships (if any). Generated from the RESQML UML model.

1.4.1 Energistics Resource Set

The following documents are for use with all Energistics standards, including RESQML. These documents are included in the RESQML download. For easier access, the main documents are also available for direct download from: http://www.energistics.org/reservoir/resqml-standards/current-standards.

	Resource / Document	Description
1.	*Energistics common Technical Reference Guide* (Also available for direct download from above link.)	The package named *common* contains elements that will be shared by all Energistics standards (e.g., RESQML and other MLs in the future). This document lists and defines packages, data objects, elements, and relationships for the subset of common published in support of the current version of RESQML.
2.	*Energistics Packaging Conventions (EPC) Specification* (Also available for direct download from above link.)	Specifies the Energistics Packaging Conventions (EPC), which is the set of practices to store multiple files as a single entity for data transfer; this single entity is referred to as EPC file (or sometimes an Energistics package). EPC is an implementation of the Open Packaging Conventions (OPC), a container-file technology standard.
3.	*Energy Industry Profile of ISO 19115-1 (EIP)* (Also available for direct download from above link.)	An open, non-proprietary exchange standard for metadata used to document information resources, and in particular resources referenced to a geographic location, e.g., geospatial datasets and web services, physical resources with associated location, or mapping, interpretation, and modeling datasets. It is an ISO Conformance Level 1 profile of the published international standard ISO 19115-1:2014, which is the latest version of the mature conceptual specification ISO 19115:2003.
4.	*Energistics Unit of Measure Standard* (Also available for direct download from above link.)	A dictionary, grammar specification, and related documentation, which provide a consistent way to define, exchange, and convert between different units of measure. All Energistics standards (RESQML, WITSML, PRODML, etc.) must use this dictionary; other industry groups are also using it.
5.	*Energistics Coordinate Reference System Usage Guide* Status: DRAFT (available soon)	Explains how coordinate reference systems (CRS) work in Energistics data-exchange standards. Based on work and standards from the European Petroleum Survey Group (EPSG).

1.5 What's New for RESQML v2.0.1?

This latest version of RESQML adds the capabilities listed below to RESQML v2.0 (published in September 2014). Note, the v2.0 model is exactly as published previously; the new data objects have simply been added. As such, the main body of this document is essentially unchanged from 2.0 publication—with the exception of this chapter and some documentation clarifications that do NOT change v2.0 behavior. New objects are documented in Appendix C (page 224).

- **Activity model** (see Section C.1 (page 224)). Its purpose is to capture:
  - Tasks or actions that occurred to create and edit a subsurface model
  - How the activities relate to the data being exchanged.
- **Property Series** (Section C.2 (page 228)).
- **Streamlines** (Section C.3 (page 230)). In a reservoir engineering context, streamlines are a way to visualize and represent fluid flow. They have many applications; for example, they have been used as a basis for fluid flow simulation, sweep management, well rate optimization, and infill well placement.

1.5.1 Design Objectives for RESQML v2.0

RESQML v1.1 was the successor to RESCUE, an industry-defined data exchange standard based on binary files and used since the late 1990s. The goal of RESQML v1.1 was to leverage newer technologies and established standards, such as XML and HDF, to replicate RESCUE functionality.

The overarching design objectives of RESQML v2.0 are to:

- Improve the richness of existing domain objects.
- Add new domain objects to the data model to support the more sophisticated capabilities of the software packages used in E&P workflows.
- Add relationships among data objects.
- Support flexible workflows, for example, by supporting partial model updates.

1.5.2 New Capabilities in v2.0

In support of these design objectives, RESQML now includes these new or enhanced capabilities:

- A subsurface knowledge hierarchy based on "features, interpretation, representations and properties" that describes subsurface features, multiple interpretations of those features, multiple representations of those interpretations, and the properties that may be "attached to" the representations.
- Provides a standard methodology for the representation of subsurface scenarios and uncertainty.
- Support for structural, stratigraphic, and reservoir models, referred to as organizations.
  - At the interpretation level: definition of the involved geologic features with their relationships, i.e., contacts and their characteristics, within the context of the model.
  - At the representation level: topology and geometry of the model, either surface or volume. Ability to define contacts using nodes of associated geologic features.
- Associations between structural and stratigraphic features with the 3D reservoir grid.
  - Achieved using subrepresentations of the grid, which are defined by selecting particular elements of the grid such as the layers, pillars, cells, cell faces, etc.
- Structured and unstructured grids or a mixture of both. New grid capabilities include:
  - Block-centered grids defined by cell-centered geometry and properties, and their associated connectivity, to support both simple grids and current unstructured simulators.
  - Polyhedral and perpendicular-bisector (PEBI) grids to provide the visualization and geometry required by current fluid flow and geomechanical reservoir simulators.
  - Corner-point grids as used by reservoir simulators.

  - Tetrahedral grids as used by geomechanical simulators.
  - Ability to use parametric lines for pillar grid definitions.
  - Simplified grid descriptions for simple grid types, e.g., rectilinear or tartan grids.
  - Higher order extensions for grid cell geometry and for grid properties.
- Use of wellbore information from WITSML, the Energistics exchange standard for well and log information, which includes:
  - Support for wellbores, trajectories, logs, markers, and blocked wellbores.
  - Use of HDF5 storage.
  - Reference to existing WITSML data.
- Support for multiple topologies, geometries, and properties for multiple time steps and multiple model realizations.
  -- These capabilities are shared across the schema and are not restricted to specific data objects.
- Ability to transfer only those parts of a model that have changed (partial model transfer), which enables the workflow flexibility to test alternative scenarios and characterize the range of uncertainty in structural and stratigraphic frameworks, as well as reservoir rock and fluid properties.
- Ability to group a variety of data objects and files from multiple sources into a single "package" for transfer using the new Energistics Packaging Convention (EPC), which is an implementation of the Open Packaging Conventions (OPC) standard.
- Ability to combine data referenced to different coordinate reference systems (CRS), for example, a RESQML reservoir model and WITSML wellbores, trajectories, and markers. The RESQML package supports a single global CRS and one or more local CRSs.

1.5.3 Energistics Common Technical Architecture (CTA)

One of the goals of digital oilfield technology is to break down domain silos in E&P workflows. In support of this goal, Energistics is working to better harmonize its domain-based standards, including RESQML, WITSML (for drilling), and PRODML (for production operations). For example, RESQML now uses the wellbore data object from WITSML.

Conversely, Energistics is also moving towards sharing resources and establishing processes across its standards where this approach makes sense, for example, with coordinate reference systems, units of measure, and file packaging conventions. These shared resources are referred to as the Energistics Common Technology Architecture (CTA). For more information, see Section 4.2 (page 40).

1.5.4 Moving from RESQML v1.1 to v2.0+

RESQML v2.0 is a significant re-design of RESQML v1.1, including more and richer data objects, a clearly defined knowledge hierarchy, and the ability to create and transfer complete or partial models. Although some of the underlying concepts and infrastructure are retained from v1.1, it is best to consider v2.0+ a new data-exchange standard.

When Energistics publishes a new version of an XML-based standard, it also typically publishes an XML/XST transform, to convert old schemas to updated versions. However, RESQML uses additional technologies with XML, including HDF5 and EPC. These additional technologies and related considerations make the development of a transform quite complex, so none are available.

For information on how v1.1.data objects and concepts map to v2.0, see Section 3.4.1 (page 36).

1.6 Where to Begin

RESQML is a data exchange format, which has been designed based on existing industry practice. During its development, industry professionals, through their work with Energistics and its RESQML special interest group (SIG), were striving to design a standard that would meet the needs of the data and diversity of practice along the major phases of subsurface workflows. The resulting data standard is

extremely flexible, to the point where no existing application will be able to consistently implement all of RESQML's capabilities.

This makes it imperative for RESQML enabled software to focus onto specific usages of basic elements, to help ensure that they are handled in a consistent fashion by any RESQML application. Where necessary, each chapter in this document begins with a "quick start" section, providing advice on import and export practices, to help with this consistency.

1.6.1 Further Development, Refinement of Use, and Experimentation

Data-exchange standards can be a "chicken-and-egg" situation. For example, only one of the six grid classes now supported in RESQML has seen wide-spread historical use in the industry; that is corner-point grids.

Lack of shared data standards for 2.5D unstructured column-layer grids and for fully 3D unstructured grids have limited their use and accessibility in the industry, and have impeded cooperation between different technical domains, e.g., flow simulation and geomechanical calculations. Now that these newer grid types are defined in RESQML and their data can be exchanged, it should enable and foster experimentation and learning about how the data might be shared and used.

2 Standards & Technology Used in RESQML

RESQML leverages existing standards and technology, which contributes to its rigor and flexibility. This chapter describes key standards and technology and how they are used in RESQML.

The standards are presented in these groups:

- **Information Technology Standards** (Section 2.1 (page 18)) are used as published from their respective standards organizations.
- **Energistics Standards** (Section 2.2 (page 20)) are based on existing standards and/or industry best practices, but have been tailored to meet the specific needs of upstream oil and gas and/or data exchange.
- **RESQML Conventions** (Section 2.3 (page 22)) are standard practices or conventions used in RESQML.

Related resources:

- For RESQML definitions, key concepts, and organization, see Chapter 3 (page 23).
- For a concise list of all standards used in RESQML and their sponsoring organizations, see Appendix A (page 221).

2.1 Information Technology Standards

RESQML uses the standards listed in this section. For a concise list of the standards and their respective publishing organizations, see Appendix A (page 221).

2.1.1 Data Modeling with UML and EA

Beginning with v2.0, the RESQML Special Interest Group (SIG) began using the Unified Modeling Language™ (UML®), implemented with Enterprise Architecture (EA), a data modeling software tool, to design RESQML. The UML model has these uses:

- Source for generating the schemas (XSD files) that developers use to implement RESQML into a software package.
- Important resource for understanding RESQML. Developers can explore the class diagrams to get a quick understanding of organization and relationships, and drill down on objects to get definitions in context.
- Source of content for the *RESQML Technical Reference Guide*. For convenience, the content of the UML model is also produced in a technical reference guide, with the objects organized alphabetically within the main EA packages.

The Enterprise Architecture project (EAP) file containing the RESQML UML model is available as part of the RESQML download. A free UML reader, EA Lite, is available for download at http://www.sparxsystems.com/.

For a description of the organization and contents of the RESQML UML model, see Section 3.3 (page 33).

2.1.1.1 Energistics and RESQML Conventions

Like the upstream oil and gas industry, Energistics is working towards breaking down domain silos. A special Energistics team is working to harmonize technology, conventions, and operations across all Energistics standards, including RESMQL, WITSML, and PRODML. This effort is reflected in the model and EA package organization and explained in Section 3.3 (page 33.

2.1.2 XML and HDF5

In RESQML v1.1, a RESQML document consisted of one XML file and one HDF5 file, associated together by standard naming conventions. The RESQML document was a single XML file with all data objects (horizons, faults, etc.) organized hierarchically. The optional HDF5 file was used for better

processing efficiency of large arrays of data. Both XML and HDF5 are still used in RESQML, but now multiple XML and HDF5 files are used.

The latest version of RESQML adds new capabilities and many more data objects, which are now stored in separate XML files. RESQML has also moved from a hierarchical data model to an object-relationship data model (see Section 3.1 (page 23)). These changes were crucial because they make it possible to represent the rich set of features in earth models, to capture the many relationships among these data objects, and to include this relationship information as part of the data exchange.

2.1.2.1 XML

Each data object in RESQML is defined by an XML schema definition (XSD) file; RESQML XSDs are generated from the UML data model. For example, objects such as structural and stratigraphic features and organizations and grids are defined by XSDs. Each data object is stored as an XML file. XML is used because of its portability and ability for humans to read and understand it.

For a list of key RESQML data objects, see Section 3.4 (page 35).

Where possible, RESQML is based on the design patterns, common types, and reference data from the previously published Energistics-stewarded standards, WITSML and PRODML.

Leveraging these existing standards and schemas allows integration of a rich set of data objects for cross-domain workflows and makes it possible for RESQML to adopt the WITSML version of well data (such as logs, directional surveys, formation markers, etc.), instead of developing new ones.

2.1.2.2 Hierarchical Data Format 5 (HDF5)

XML is not very efficient at handling large volumes of numerical or array data, so for this purpose RESQML uses the Hierarchical Data Format, version 5 (HDF5). HDF5 is a data model, a set of open file formats, and libraries designed to store and organize large amounts of data for improved speed and efficiency of data processing. Specifically, HDF5 provides:

- Machine/architecture-independent "binary" format (supported on Windows, Linux, etc. APIs are available in C++, Java, and .NET).
- Built-in data compression.
- Hyper-slabbing of array data so that sub-arrays may be extracted without reading the entire data file.

Applications for HDF5 in earth modeling workflows include storage and retrieval of geometry and property data and multi-million cell models.

- For more information on how RESQML uses HDF5, see Section 3.2.6.1 (page 31), Section 6.2.2 (page 61), and Appendix D (page 237).
- For more information on HDF, including available tools and tutorials, or to download the libraries, see the HDF Group website at: http://www.hdfgroup.org/HDF5/. The HDFView tool is especially useful for visualizing and understanding the data stored in an HDF5 file.

2.1.3 Universally Unique Identifiers (UUIDs)

To manipulate and exchange data objects independently, RESQML requires use of a universally unique identifier (UUID) for each instance of a RESQML data object.

RESQML uses UUID standard RFC 4122 from the Internet Engineering Task Force (IETF) (https://tools.ietf.org/html/rfc4122).

According to the abstract of the RFC: "This specification defines a Uniform Resource Name namespace for UUIDs (Universally Unique IDentifier), also known as GUIDs (Globally Unique IDentifier). A UUID is 128 bits long, and can guarantee uniqueness across space and time."

For UUIDs, RESQML is case-insensitive.

2.2 Energistics Standards

The standards listed in this section are based on existing industry standards and/or best practices, but have been tailored by the Energistics community to meet the specific needs of upstream oil and gas and data exchange.

2.2.1 Energistics Packaging Conventions (EPC)

EPC is a set of conventions that allows multiple files to be grouped together as a single package (or file), which makes it easier to exchange the many files that may make up a model. Adopted initially for use with RESQML, EPC is now part of the Energistics Common Technical Architecture. EPC is an implementation of the Open Packaging Conventions (OPC), a commonly used container file technology standard supported by two international standards organizations.

Essentially, an EPC file (sometimes referred to as an Energistics package) is a “zip” file, which may be “unzipped” to view its components. In RESQML, the zipping/unzipping is done using the OPC libraries (per the EPC specification) implemented as part of RESQML. However, any software tool that can read a zip file can be used to unzip and see the contents of an EPC file. (To open an EPC file with a zip tool, do the following: Select the EPC file, right-click with the mouse, and select the command to "Open with", and then choose your zip reader tool.)

IMPORTANT! Data exchange using RESQML v2.0 (or higher) requires the use of an EPC file.

- For an overview of how EPC is used to group RESQML data objects, see Section 3.2.6 (page 30).
- For more information on how EPC works, see the *Energistics Packaging Conventions Specification*. (For a link to this document, see Section 1.4.1 (page 14).)

2.2.2 Coordinate Reference System (CRS)

RESQML uses both global (projected) and local coordinate reference systems. A CRS is a top-level data object in the RESQML data model (for more information, see Section 3.2.1 (page 24)).

- **Global CRS**. From the perspective of an earth modeler, use of a global CRS allows models to be accurately located on the earth. The global CRS is a projected 2D CRS specified using either EPSG codes (see below) or, if you have a coordinate reference system that does not have EPSG codes, then use the Geographic Markup Language (GML) (see below). For work where location in the world is irrelevant, you can specify "unknown."

  BUSINESS RULE: For a RESQML dataset, only one projected 2D CRS is allowed in an EPC file. Local CRS transformations are supported (see below).

- **Local CRS**. Each data object that contains geometric information must be specified with respect to a local coordinate reference system, which is defined relative to the projected 2D CRS (with optional rotation and translation). A local CRS vertical axis may represent depth, elevation, or time. Several local CRSs are allowed inside a package. Conversion between local CRSs requires only simple translations and rotations. RESQML requires at least one local 3D CRS.

For more information, see the *Energistics Coordinate Reference System Usage Guide*. (For a link to this document, see Section 1.4.1 (page 14).)

2.2.2.1 EPSG Codes

The RESQML schema can use EPSG codes for geolocalization as part of defining a CRS. The EPSG database includes geodetic parameters and assigned codes for easy reference to well-known global locations (http://www.epsg-registry.org/).

The EPSG codes database is maintained and published by the Geomatics Committee of the International Association of Oil & Gas Producers (OGP http://www.ogp.org.uk/), which absorbed the now-defunct European Petroleum Survey Group (EPSG) (http://www.epsg.org/). The OGP is considered to be the single global source for positioning advice, guidance, and formats provision for the upstream oil and gas industry.

2.2.2.2 Geographic Markup Language

The OpenGIS® Geography Markup Language Encoding Standard (GML) is an XML grammar for expressing geographical features from the Open Geospatial Consortium (OGC) http://www.opengeospatial.org/standards/gml.

2.2.3 Energy Industry Profile of ISO Metadata Standards

As part of data object identification and traceability, RESQML uses key metadata, such as when a data object was created and updated and by what software. The current version of RESQML uses the *Energy Industry Profile (EIP) of ISO 19115-1:2014,* which replaces the Dublin Core metadata standard used in v1.1.

The *Energy Industry Profile (EIP) of ISO 19115-1:2014* is an open, non-proprietary exchange standard for metadata used to document information resources, and in particular resources referenced to a geographic location, e.g., geospatial datasets and web services, physical resources with associated location, or mapping, interpretation, and modeling datasets.

EIP is an ISO Conformance Level 1 profile of the published international standard ISO 19115-1:2014, which is the latest version of the mature conceptual specification ISO 19115:2003.

The goals of the EIP are to:

- Realize metadata standards and guidelines that enable stakeholders in the energy industry ("the community") to effectively and efficiently discover, evaluate, and retrieve a diversity of information resources from widely distributed repositories and collections.
- Support both proprietary data management needs and exchange of data between and within organizations.
- Leverage existing standards to encourage adoption within the community and integration into the business and exploit existing organizational resources needed for governance and long-term maintenance.

Implementation of the EIP into RESQML is included in the current version of the schemas.

For more information, see the *Energy Industry Profile (EIP) of ISO 19115-1:2014*. (For a link to this document, see Section 1.4.1 (page 14).)

2.2.4 Units of Measure

The *Energistics Unit of Measure Standard* (*UOM Standard*) is a set of resources that defines a standard unit of measure (UOM) dictionary to promote consistent usage, data exchange, and unit conversions. The set includes the base Energistics Unit of Measure Dictionary and related documentation for creating, implementing, and maintaining a UOM dictionary that is patterned after the Energistics dictionary.

BUSINESS RULE: RESQML models must adhere to this standard, although there are currently no constraints within the schema. (For information about RESQML business rules, see Section 2.3.1 (page 22).) Use of the *UOM Standard* replaces the more restrictive treatment of units of measure in RESQML v1.1, which only used SI units.

For more information about implementing units of measure, see the *Energistics Unit of Measure Standard.* ((For a link to this standard, see Section 1.4.1 (page 14).)

2.2.5 Property Kinds

RESQML includes a list of standard property names that represent the basis for the commonly used properties in the E&P subsurface workflow. Use of this list allows programmers implementing RESQML to map their software property names to the RESQML standard property software names, which makes it possible for RESQML-enabled software packages to translate property names between each other.

For example, if *Software A* names “porosity” as POR and *Software B* names it PORO, and both *A* and *B* are RESQML enabled, then the software can recognize that these properties are equivalent because they refer to the same RESQML parent property, e.g., "porosity". They can also exchange without ambiguity the numerical values that are recorded because those values will be in the same unit of measure.

For more information on properties, see Chapter 8 (page 77).

2.3 RESQML Conventions

In addition to the standards listed above, RESQML observes the rules and conventions described in this section.

2.3.1 Business Rules

Business rules are currently designated and documented in the UML model (in the EA software), the *RESQML Technical Reference Guide,* and, as appropriate, in other documentation.

Examples of business rules in the documentation include requirements for matching counts, for example, for array lengths to match cell counts for grids and blocked wells; or for other requirements, such as use of the *Energistics Unit of Measure Standard* (see Section 2.2.4 (page 21)). The following is an example (for a specific class in the UML model) of a business rule:

BUSINESS RULE: Array length is the number of cells in the grid or the blocked well.

No method for business rule validation exists for the current version of RESQML, but validation approaches are being explored and considered for future versions.

2.3.2 Naming Conventions

RESQML adheres to the *Energistics Naming Conventions Specification* (currently in draft form). Of specific interest to RESQML is the list of reserved data object names below.

Reserved data object names should typically appear as part of the name of an object of this kind, when it improves the clarity of the schema, but never otherwise.

- Abstract
- Feature
- Interpretation
- Representation
- Geometry
- Property
- Patch
- Array
- Set
- Reference
- Choice

3 Organization and Key Concepts: Overview

This chapter explains the "big picture"; it provides an introduction to and overview of RESQML basic definitions, key concepts, and organization.

Related resources:

- The standards and technology referred to in this chapter are defined in Chapter 2 (page 18).
- For the list of related documents to help in understanding and implementation of RESQML, see Section 1.4 (page 13).

3.1 From Hierarchical to Object-Relationship Data Model

RESQML now uses an object-relationship model to organize its data objects.

v1.1 used what was *essentially* a hierarchical data model. The World Wide Web Consortium (W3C) does not explicitly state that XML is hierarchical, and the XML specification includes some capabilities that are not purely hierarchical. Yet, in v1.1, all semantic information was assembled in only one XML instance consisting of one XML file, with hierarchical “implicit” XML containment to associate the data objects together. An optional, associated HDF5 file contained large sets of numeric data.

However, because the relationship between components of an earth model are inherently complex (not truly hierarchical), the RESQML Special Interest Group (SIG) members determined an earth model could be more accurately represented with an object-relationship model. This change allowed the components of the earth model to be represented as separate data objects and the relationships among them to be more accurately represented as parent-child, with one-to-many or many-to-may relationships.

An important point: with an object-relationship data model, the child data objects can now be exchanged without their parent, which supports the exchange of only those parts of a model that have changed, what RESQML refers to as partial model exchange. (For more information on partial model exchange, see the workflow use cases in the *RESQML Business Overview and Use Case Guide*. For a link to this document, see Section 1.4 (page 13).)

3.1.1 Challenges of This Data Model

An object-relationship model provides many benefits to RESQML, but it also presents new challenges, which include the need to:

- Designate relationships between the data objects.
  For information on how RESQML addresses this challenge, see Section 3.2.5 (page 29).
- Group data objects together as a related "package" (such as a model or project).
  For information on how RESMQL addresses this challenge, see Section 3.2.6 (page 30).

3.2 Definitions and Concepts

This section provides basic definitions and key concepts. The standards and technology referred to in this chapter are explained in Chapter 2 (page 18).

3.2.1 RESQML Data Objects

A RESQML data object is the atomic part of a RESQML transfer. It contains the semantics associated with the data model (or modeling data) in the context of RESQML. Key naming and organizing concepts of these semantics are explained in Section 3.2.3 (page 28) and Section 3.2.4 (page 29).

Data objects are exchanged mostly as XML files; associated explicit array data is transferred as one or more HDF5 files.

3.2.1.1 Data object Identification and Traceability

- For identification, each RESQML data object must have a UUID. NOTE: For UUIDs, RESQML is case-insensitive.
- For traceability, RESQML uses EIP metadata, which includes information such as when a data object was created and updated and by what software.
- These stand-alone data objects are also informally referred to as *top-level* data objects or elements.

Both UUIDs and EIP are explained in Chapter 2 (page 18).

For information on how the UUID and EIP metadata can be used together to manage data object identity during extended data exchange during an interactive session, see Section 3.2.2 (page 25).

3.2.1.2 Relationships and References

A RESQML data object can be associated with many other data objects. For example, a CRS can be associated with many different geometries.

The use of multiple, independent data objects requires a way to specify relationship or associations between and among them, which is explained in Section 3.2.5 (page 29).

3.2.1.3 Packaging Together Data Objects

The use of multiple data objects also requires a way to group them together as a single package, which makes it easier for software and the people using it to understand the "whole" and all of its parts. For information on how RESQML packages data objects (and related parts), see Section 3.2.6 (page 30).

3.2.1.4 "Content" of a Data Object and Partial Model Transfer

A partial model transfer refers to the ability to transfer only the data in a model that has changed, instead of the entire model. However, to do this exchange correctly, you still need the context of the data objects that have not changed, so they must be included in the package (data transfer).

In support of partial model transfers, a data object, with only its mandatory identification data, may be transferred. Any other data contained in the data object, may or may not be included, depending on the requirements of the two applications exchanging data (for example, all the data for data object may have been transferred previously or may be transferred in the future).

For more information on partial model transfer, see the *RESQML Business Overview and Use Case Guide.* (For a link to this document, see Section 1.4 (page 13).)

3.2.1.5 Abstraction from Super Classes in the UML Data Model

To ensure consistency of design, all RESQML data objects inherit from the same abstract super classes in the UML model:

- AbstractObject and AbstractDataObject in the Energistics-common package (in UML under common in the package named *Abstract*) which contains the UUID, Schema Version, and optional EIP metadata citations.

- AbstractResqmlDataObject in the RESQML common package (in UML under resqml, v2.0.1, xsd_schemas, in the package named *Common*) is a restriction of the AbstractDataObject for which the EIP metadata citations are mandatory.

For more information on the UML model organization, see Section 3.3 (page 33).

For more information on common data objects and how they work, see Chapter 4 (page 39).

3.2.2 Using UUIDs and EIP Metadata for Traceability to Help Manage Different Versions of a Data Object

EIP metadata can be used during the modeling process itself—when RESQML models are frequently updated and exchanged between software packages—to help users determine the latest version of a model.

3.2.2.1 Overview

In Figure 3-1 , Software A and B represent applications used in consecutive stages of a subsurface workflow. When new information becomes available for a given model in Software A, users of Software B will typically have to reload a new RESQML document containing the entire updated model. If users of Software B already modified the model, they will have to either:

- Discard their modified model and manually add their modifications to the updated/newly imported model, or
- Manually resolve the conflict between these two versions of the same model.

3.2.2.2 How it Works

EIP metadata can help tremendously in the process of conflict resolution. Some examples are available below.

The two key pieces of information available for each individual data object are:

- The UUID used to indicate if an entity present in an EPC file (RESQML data) is already available in the current session of Software B, indicating the potential conflict between two versions of the same entity.
- The "modified" time inside the EIP metadata elements (or the "created" time if the entity has not yet been modified) indicating that the version in New File A is more recent than the edition (or version) of the entity in the Software B model.

After a conflict has been detected, Software B can extract other EIP metadata to help users select one version, either manually or following a common strategy (for example, always overwrite, ignore, keep the most recent one, import as a copy, and so forth).

In the above process, Software B is “kept live” between the initial import of the model and the import after modification. However the same resolution process can also occur in two different sessions of Software B, for example, if Software B saves the model in another EPC file or in its own persistence mechanism (e.g., database). IMPORTANT! For this approach to work, the persistence mechanism MUST retains the UUID and EIP metadata.

3.2.2.3 Conflict Resolution: Frequent Exchange in One Session

Figure 3-1 shows an example workflow for resolving data conflicts resulting from frequent update and exchange of data models during one session.

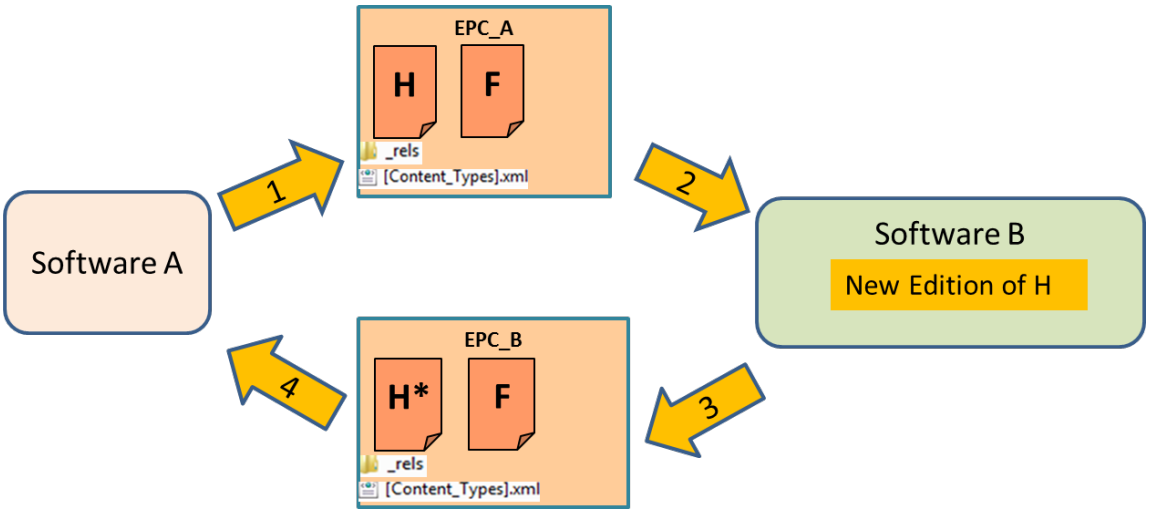


Figure 3-1—Conflict resolution: frequent exchange in a single session.

The scenario is:

1. Software A exports H and F in EPC_A.
2. Software B imports EPC_A, modifies H.
3. Software B exports EPC_B: F + H*, (where H*=edited H).
4. When Software A imports EPC_B, it should have enough information to know:
   - F has not been modified, and does not have to be reloaded
   - H* is an edited version of H; there is enough information to let a user decide what to how to reconcile the two versions.

3.2.2.4 Conflict Resolution: Exchange in Multiple Sessions with Persistent Data Store

Figure 3-2 shows an example workflow for resolving data conflicts resulting from updates and exchange during multiple sessions with persistent data store.

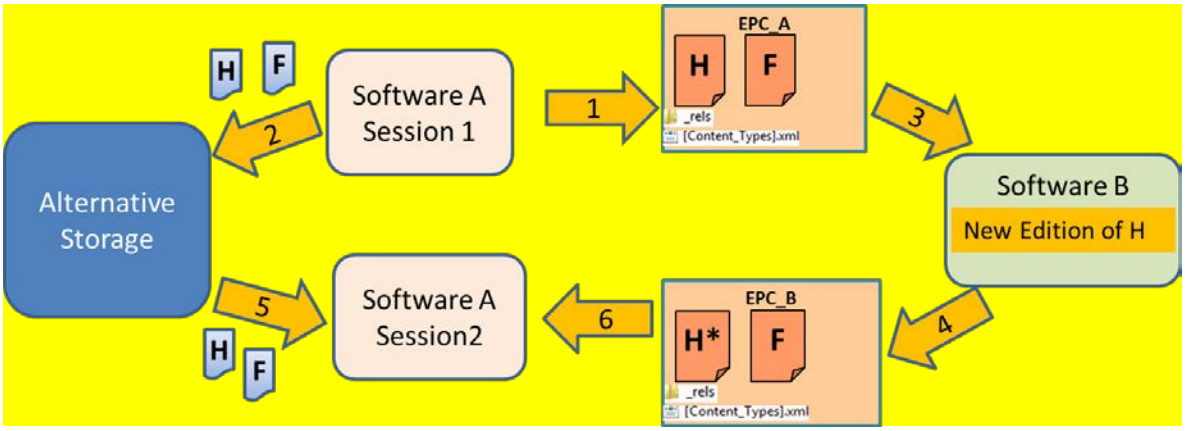


Figure 3-2—Conflict resolution: exchange with alternative persistence.

The scenario is similar to the single-session scenario:

1. Software A exports EPC_A.

2. Software A saves (persists) H and F in alternative storage (for example, a database), then Software A Session1 is closed.
3. Software B imports EPC_A and edits are made to H, creating H*.
4. Software B exports document EPC_B: H* and F (no changes).
5. Software A begins a new session, Session 2, and reloads H and F from alternative storage.
6. When Software A imports EPC_B into Session 2, Session2 has enough information to know without using EPC_A that:
   - F has not been modified, and does not have to be reloaded.
   - H* is an edited version of H; there is enough information to let a user decide how to reconcile the two versions.

3.2.2.5 Conflict Resolution Example

Figure 3-3 shows how RESQML with EIP metadata can be implemented in a software package to help resolve data conflicts that arise from frequent update and exchange of data models—a common occurrence in the subsurface workflow.

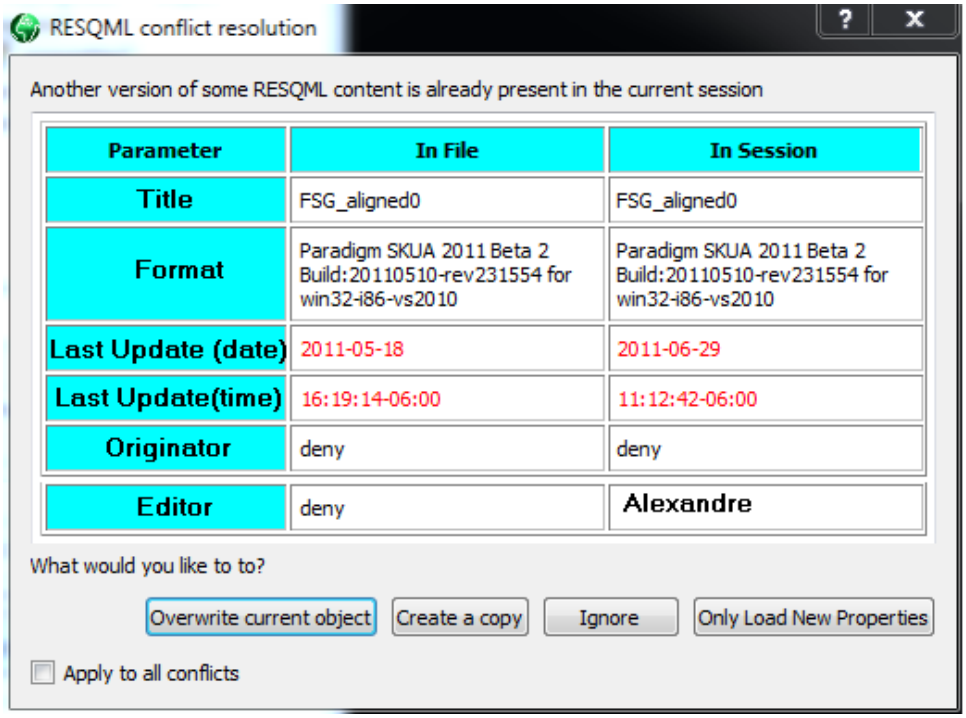


Figure 3-3—Conflict resolution example of how RESQML and EIP metadata can be used in software to resolve data conflicts.

When the same object is present in an EPC file (RESQML data) and session, a user can decide what to do based on the differences (red text):

- Replace the content of the session by the content of the file.
- Create a new copy with the content of the file.
- Do not load the content of the file.
- Load only the new properties.

3.2.3 "Knowledge Hierarchy": Features, Interpretations, Representations, and Properties

RESQML has now expanded the concept of "data" to include the relationships between data objects, which allows a more precise classification. The current design now supports the transfer of abstract subsurface features, human interpretations of those features, the data representations of those interpretations, and the properties indexed onto those representations, which results in a well-defined knowledge hierarchy of feature/interpretation/representation/properties (informally referred to as "FIRP")—a key organizing concept in RESQML. Additionally geometry is integral to RESQML organization. (Geometry is also an important part of the RESQML data model.)

The table below defines these terms; each of these is a type of RESQML data object.

- For a high-level list of RESQML data objects and their organization, see Section 3.4 (page 35).
- For more information about these classifications, the knowledge hierarchy, and how it works, see Chapter 5 (page 51).

Construct / Term	Definition
Feature	Something that has physical existence at some point during the exploration, development, production, or abandonment of a reservoir. For example: It can be a boundary, a rock volume, a basin area, but also extends to a drilled well, a drilling rig, an injected or produced fluid, or a 2D, 3D, or 4D seismic survey. Features are divided into these categories: • Geological, for objects that exist a priori, in the natural world, for example, rock formations and how they are positioned • Technical, for objects that exist by the actions of humans, for example, wells.
(Feature) **Interpretation**	RESQML uses the definition of David Gawith, which explains an interpretation as a single consistent description of a feature. An interpretation is subjective and very strongly tied to the intellectual activity of the project team members. The initial curiosity and reasoning of the people on the project team initiates the early pre-screening campaign (remote sensing, surveys). They make hypotheses that consist of as many interpretations as necessary to describe the features. (Gawith and Gutteridge 2007; for citation, see Section 5.5 (page 58). **NOTE:** The RESQML formal name is actually "feature-interpretation" and some of the class names use this full term. For conciseness of documentation, we use simply "Interpretation" where this usage is not confusing.
(FeatureInterpretation) **Representation**	A digital description of a feature or an interpretation. For example, currently in RESQML, a horizon interpretation may be represented by a point set, a set of triangulated surfaces, or a set of orthogonal grids. A representation contains the topology and the geometry of the data objects. These terms are defined in Section 3.2.4 (below). **NOTE:** Like "feature-interpretation" in the previous table row, this term is formally "feature-interpretation-representation", but we use "representation" for conciseness.
Properties	A property can be attached to any indexable element of any representation. Properties refer to semantic variables (for example, porosity, permeability, etc.) and the corresponding data values, which are recorded in arrays, which may be stored in HDF5 datasets. For more information about properties, see Chapter 8 (page 77).

3.2.4 Topology and Geometry

For an optimized design and to support workflow flexibility, topology, geometry, and properties are handled differently than in the hierarchical approach of RESQML v1.1.

To support partial model updates, the topological description of a data object has been separated from its properties. This construction is consistent with the knowledge hierarchy (explained in Section 3.2.3 (page 28)) in which a description of a feature without properties is an interpretation, while a representation is required for property data. This construction is also similar to how seismic data is stored in SEGY, with the seismic trace headers and header information separated from the seismic trace records and data.

Term	Definition
Topology	Each representation contains a topological description, which defines how to associate nodes and other “indexable elements” to represent points, lines, surfaces or volumes (like structured and unstructured grids). For complex objects like simulation grids, much of the topological description can be implicit. For more information about indexing, see Section 6.2 (page 60) and the *RESQML Technical Reference Guide*.
Geometry	Each representation contains its geometry, which is the spatial location of each selected indexable element, mainly nodes. This information may be provided as numerical arrays stored in HDF5 datasets, or specified implicitly. Geometry may be contained within a representation (as just described) or, if not used to define the geometry of a representation, implemented as a “point property”. For more information about geometry, see Chapter 7(page 66).

3.2.5 Specifying Relationships in RESQML

RESQML uses the standard XML hierarchical relationship, for example, where one data object is contained inside another. However, the nature of subsurface description means there are many possible hierarchies in a reservoir model with more complex relationships between RESQML data objects, which cannot be modeled in a single hierarchical fashion. For example:

- Relationships between feature, interpretations, and representation that create the knowledge hierarchy defined in Section 3.2.3 (page 28).
- Relationship between data objects of the "same level" of the knowledge hierarchy, such as two horizon features that intersect to form a contact feature, and which may be combined to make-up part of a structural framework.

To address these more complex relationships, RESQML uses a data object reference, which is explained in Section 5.4 (page 56).

Additionally, relationships are specified in the context of an Energistics Package, which is explained in Section 3.2.6 (page 30).

3.2.6 EPC File for Grouping Data Files

Use of an object-relationship data model and individual data objects requires a way to package together all related "parts" as a single, coherent RESQML package for data exchange. This packaging is done using the Energistics Packaging Conventions (EPC), which was introduced in Section 2.2.1 (page 20). The collective object is referred to as an EPC file. For more information on EPC, see the *Energistics Packaging Convention Specification* (For a link to this document, see Section 1.4 (page 13).).

Table 1 lists the types of files that can be contained in an EPC file. **Figure 3-4** (page 31) shows a high-level overview of the relationship among these files.

Table 1—Parts of an EPC File

EPC Part	Definition, Purpose, and Requirements
XML data objects	XML data objects defined in RESQML V2.0 or data objects from other Energistics data-exchange standards, such as WITSML or older versions of RESQML, may be included. These files use the file extension: *.xml*
EpcExternalPartReference	Any file that is part of an EPC file but stored externally to the EPC file must have an external part reference that points to the external part. For example, because an HDF5 file is designed for random access (not streaming) and can already compress its data sets, RESQML requires that an HDF5 file(s) be stored outside of an EPC file. However, to accurately maintain all relationships, the EPC file requires use of an external reference to the HDF5 file. For more information about HDF5 files, see Section 3.2.6.1 (page 31)).
Other types of files	Optionally, other files that contain additional, informal information relevant to the contents of the EPC file, such as these listed below. As a guideline these files are stored in a folder named "media". • PDF • Video • SEGY • Images • Microsoft Word documents
_rels	Describes the relationship(s) between parts in the EPC file.
[ContentType].xml	Special file required for EPC to associate file name extensions used in the package with specific mime content types.

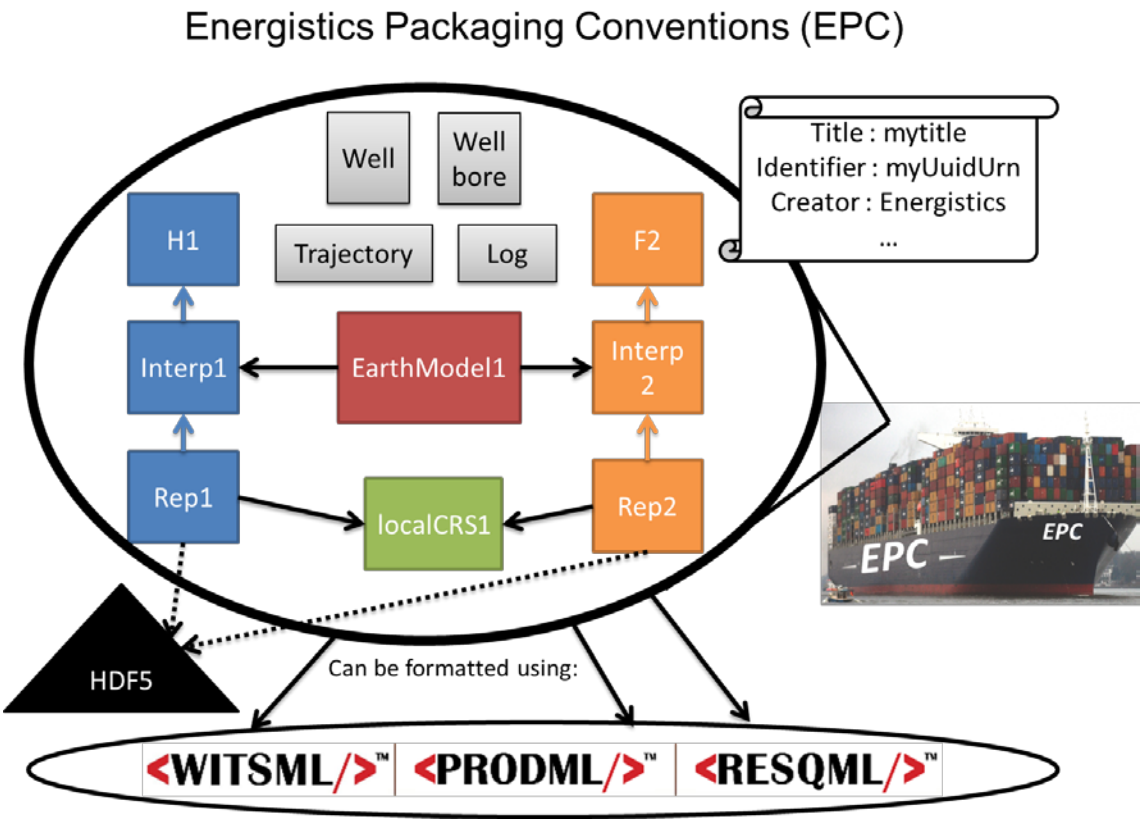


Figure 3-4. Diagram showing how EPC provides the technology to group together related data files and exchange them as a single file. (Container ship photo from Wikipedia: http://fr.wikipedia.org/wiki/Fichier:CMA_CGM_Marco_Polo_arriving_Port_of_Hamburg_-_16._01._2014.jpg. Licence : Creative Commons paternité – partage à l'identique 3.0 (non transposée)

3.2.6.1 HDF5 Files and EPC External Part Reference

In some cases, it may be desirable to store parts of an Energistics package externally to the EPC file; the most common example is HDF5 files, which store all of the explicit array data in RESQML.

Hierarchical Data Format (HDF) is a data model, library, and file format for storing and managing data. It supports an unlimited variety of data types, and is designed for flexible and efficient I/O and for both high volume and complex data—particularly when compared to XML. HDF version 5 is part of the Energistics Common Technical Architecture and is used in RESQMLV2+ and in other Energistics standards. (For more information on how HDF5 is used in RESQML, see Section 6.2.2 (page 61) and Appendix D (page 237).)

The EPC file is designed for data streaming, and in some implementations, has limitations in the amount the data which may be included. In contrast, an HDF5 file is designed for large data files, random access (not streaming), and can already compress its data sets. As a consequence, RESQML requires that HDF5 files be stored outside the EPC file. To accurately maintain all relationships, the EPC file requires use of an external reference to the HDF5 file.

The following items describe how to store and reference HDF files in the context of an EPC file and RESQML:

- HDF5 files must be stored outside the EPC file.
- When HDF5 files are used with Energistics standards they must use the file extension: *.h5*
- It is recommended that the HDF5 files are stored in the same location as the EPC file.

- Each HDF5 file must have an EPC external part reference, which is a proxy that points to the HDF5 file. This reference must be stored inside the EPC file.
  - The HDF5 external part reference must have a relationship file that defines the actual location of the physical HDF5 file (which is recommended to be the same location as the EPC file).
  - The corresponding entry in the relationship file must have a type attribute set to: http://schemas.energistics.org/package/2012/relationships/externalResource
  - As an XML data object, an external part reference must have a UUID, which must be included as an attribute of the physical HDF5 file to allow cross validation.
  - The format of the UUID in the HDF5 file must be of data type *c_s1* (from HDF5 documentation) in its canonical format (lower case letters only).
- Multiple HDF files can be used to describe the array data of multiple Energistics parts. Although not recommended, one XML data object can reference multiple EPC external part references. However one EPC external part reference can be associated with only one HDF5 file.
  - The XML data object must reference the HDF external part reference.
  - The corresponding entry in the relationship file must have a type attribute set to: http://schemas.energistics.org/package/2012/relationships/mlToExternalPartProxy
  - The corresponding backward entry (in the rel file of the proxy) must have a type attribute set to: http://schemas.energistics.org/package/2012/relationships/externalPartProxyToMl

3.3 UML Model/Schema Organization

The RESQML UML model is implemented and organized in an Enterprise Architecture Project (EAP) file, grouped into packages as shown in **Figure 3-5** and explained below. Each package contains classes that represent the key data objects (see **Table 2** (page 35).

The UML model is available as part of the RESQML download. To view the model you need Enterprise Architecture or EA Lite, a free reader available from the company that develops EA, at its website http://www.sparxsystems.com/.

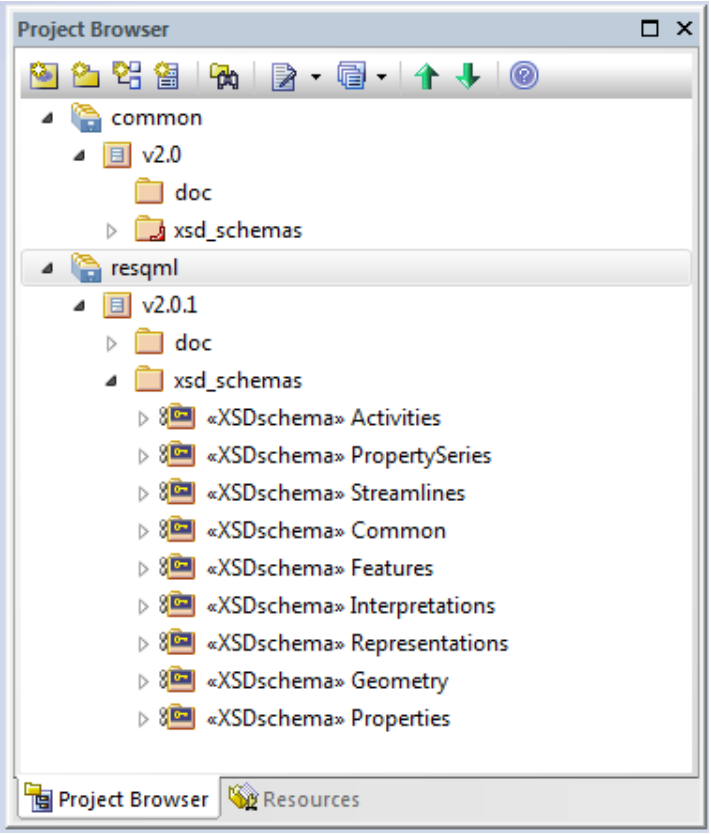


Figure 3-5—The RESQL Enterprise Architecture project (EAP) file contains the groupings shown here and explained in the text below.

Main packages of the RESQML UML model in EA are listed and described here.

common contains the classes that are used by all Energistics standards, which includes classes to consistently define base data objects and references, coordinate reference systems, and units of measure. For more information, see Section 4.2 (page 40).

resqml contains these main packages:

- The **doc** class (folder), which contains packages for:
  - **Class Diagrams** for the schema packages listed below (with the diagrams labeled appropriately). The class diagrams illustrate the attributes, inheritances, and the other relationships of the packages in the xsd_schemas class (folder).
  - **Instance Diagrams** with various examples for you to explore.
- The **xsd_schema** class (folder), which contains these packages:
  - **Activities**, **PropertySeries**, and **Streamlines**. New packages for v2.0.1. For more information, see Appendix C (page 224).

- **Common.** Shared data objects and related objects that are shared across all packages in a RESQML project. Many objects are extensions of data objects that appear in the shared Energistics-wide common package. For more information, see Section 4.2 (page 40).
- **Features.** Organized into two sub-packages—Geologic Features and Technical Features—this package contains all the classes that define the V2.0 business objects, which includes everything that needs to be defined to develop a subsurface model. Features include: horizon, fault, geobody, wellbore, as wells as structural, stratigraphic and earth model organizations, and more.
- **Interpretations**. Contains all the classes that allow an interpreter to formalize his/her opinion of a feature. A typical example of interpretation is based on the opinion of the geometry of a feature. Other specific interpretation information may include the description of the throw of a fault, the horizon classification in a sequence stratigraphic approach, or the contacts in a structural model.
- **Representations**. Organized into four sub-packages—Structural, Grids, Seismic and Wells—this package contains all the supported topology, such as triangulation, fault stick, grids (2D grid, IJK grid, PEBI grid, unstructured grid, etc.
- **Geometry.** Geometry is attached to the indexable elements of a representation. Geometries are not RESQML top-level data objects so cannot be transferred independently.
- **Properties**. Properties are attached to the indexable elements of a representation. Properties are designed to be transferred independently of a representation and are top-level data objects.

3.4 High-Level Organization

Table 2 presents a high-level overview of the current data model and schema package organization. This table shows the main classes of data objects and an example listing of data objects within these classes. The following sections provide an overview of key RESMQL domain concepts, how they map to this organization, and links to detailed chapters.

Table 2—RESQML High-Level Organization

Classes/Data Objects	Example Data Objects (Schemas are the "official" source for available data objects.)
Features	
• Geologic Features	Boundary Features, Fluid Boundary Features, Genetic Boundary Features, Tectonic Boundary Features, Phase Unit Features, Rock Features, Organization Features, Stratigraphic Unit Features, Geobody Features
• Technical Features	Frontier Features, Wellbore Features, Seismic Lattice Features, Seismic Line Features, Seismic Lattice Set Features, Seismic Line Set Features
• Related Objects	Global Chronostratigraphic Column
Interpretations	
• Geologic Interpretations	Feature Interpretations, Horizon Interpretations, Fault Interpretations, Boundary Feature Interpretations, Geobody Boundary Interpretations, Geobody Interpretations, Rock Feature Interpretations, Stratigraphic Unit Interpretations, Earth Model Interpretations, Structural Organization Interpretations, Fluid Organization Interpretations, Stratigraphic Column Interpretations, Stratigraphic Column Rank Interpretations, Stratigraphic Occurrence Interpretations
• Technical Interpretations	Wellbore Interpretations
• Related Objects	Stratigraphic Column
Representations	
• Geologic Representations	Framework Organization Representations, Sealed Volume Framework Representations, Sealed Surface Framework Representations, Non-Sealed Surface Framework Representations, Plane Set Representations, Point Set Representations, Polyline Representations, Polyline Set Representations, Grid2d Representations, Grid2d Set Representations, Triangulated Set Representations
• Grid Representations and Related Objects	IJK Grid Representations, Unstructured Column Layer Grid Representations, Unstructured Grid Representations, Truncated IJK Grid Representations, Truncated Unstructured Column Layer Grid Representations, (General Purpose) GPGrid Representations, Grid Connections Representation, Local Grid Set
• Wellbore Representations and Related Objects	Wellbore Trajectory Representations, Wellbore Frame Representations, Wellbore Frame Marker Representations, Blocked Wellbore Representations, Deviation Survey, MD Datum
• Seismic Surveys and Seismic Coordinates	Seismic Survey representations take advantage of previously defined representations, with the addition of seismic coordinates to their geometry.
• Related Objects	Redefined Geometry Representation, Representation Identities, Subrepresentation, Representation Set Representation
Properties	
• Abstract Values and Points	Continuous Property, Discrete Property, Categorical Property, Comment Property, Points Property
• Property Lookup	Double Table Lookup, String Table Lookup

Table 2—RESQML High-Level Organization	
Classes / Data Objects	**Example Data Objects** (Schemas are the "official" source for available data objects.)
• Related Objects	Property Types, Time Series, Property Sets, Units of Measure
Common	
• Coordinate Reference Systems	Global 2d CRS, Global 1d CRS, Global Time CRS, Local 3d CRS
• External EPC Reference	Used to associate a UUID with an object external to the schema so that it may be transferred using the Energistics Packaging Conventions (EPC).

3.4.1 Mapping of v1.1 Data Objects to v2.0 Data Objects

Table 3 below describes the mapping of v1.1 data objects to equivalent v2.0 data objects. RESQML uses HDF5 in addition to XML, which makes development of simple transforms to migrate from v1.1 to v2.0 sufficiently complex so that none are available.

Table 3—Mapping of v1.1 Data Objects to v2 Data Objects	
Version 1 Data Objects	**Version 2.0 Data Objects**
Dublin Core Metadata	Energy Industry Profile (EIP)
Coordinate Reference System	Coordinate Reference System
Area of Interest	Frontier Feature
Interface Feature Set (Faults)	Tectonic Boundary Feature + Fault Interpretation
Interface Feature Set (Horizons)	Genetic Boundary Feature + Horizon Interpretation
Gridded Volume Set (Grid and NSAs)	IJK Grid Representation and Grid Connections Representation
Gridded Volume Set (Blocked Wells)	Blocked Wellbore Frame Representation
Property Kind Set	Property Types
Property Group Set	Property Set

3.4.2 Common Data Objects

For consistency and ease of implementation, RESQML has two classes of common data objects:

- **common**. Contains the Energistics Common Technical Architecture elements, those data objects and related items used by all Energistics standards (e.g., WITSML, PRODML, RESQML, etc.). For example, common contains data objects such as coordinate reference system, units of measure and data object metadata.
- **Common** (in the **resqml** EAP package). Contains data objects and elements common across RESQML. For example, RESQML includes and abstract data object from which all RESQML data objects are derived.

For more information, see Chapter 4 (page 39).

3.4.3 Feature and Interpretations

Features and interpretations are discussed further in the context of the RESQML knowledge hierarchy (see Chapter 5 (page 51)). Additional details related to developing an earth model are discussed in Chapter 9 (page 82).

3.4.4 Representations

Representations for various business-objects may have unique sets of requirements, for example, the representation of a horizon compared to the representation of a well. However, all representations share a set of capabilities for various indexing schemes (indexable elements, patches and multi-dimensional arrays) and representation identities.

- These shared capabilities are explained in Chapter 6 (page 59).
- For specific information on structural and stratigraphic representations, see Chapter 10 (page 107).
- For specific information on grids, see Chapter 11 (page 126).

3.4.5 Geometry

Geometry is not an independent, top-level RESQML business object, which means that the points, lines, surfaces or volumes that may be described by RESQML cannot be transferred independently of one of the representations just described. With RESQML, you can define geometry in 2 main ways:

- Explicitly, i.e., the explicit (X,Y,Z) coordinates of a point (This was the only option available in RESQML v1.1.).
- Implicitly, which allows much more compact data transfer and provides more information about the underlying geometry of a grid, or wellbore trajectory, or fault (new for v2).

For more information on geometry, see Chapter 7 (page 66).

3.4.6 Properties

The usage of properties has continued to evolve from their implementation in RESQML v1.1. The most important change is that properties are now independent data objects—not contained within other data objects. In addition, array data must now be stored in HDF5 (see Section 3.2.6.1 (page 31).

Properties may be continuous, discrete, categorical, comments, or points. Property lookup tables are now supported so that tables of production data or relative permeability tables or any other tabulated information may now be transferred.

As in v1, properties may be grouped, for example, to simplify the transfer of reservoir simulation data, which may involve grouping multiple properties at a single time or a single property across multiple times. The grouping mechanism has been extended to support multiple realizations and more complex time relations. For example, time relations now allow field surveillance data to be grouped with “near-by” times from a simulation model for comparison.

Property types, units of measure, and their management are not specific to RESQML. As Energistics develops its common technical architecture—a foundation to be share across Energistics standards—many elements initially developed by RESQML are being moved into the shared architecture. One significant generalization for RESQML is that while v1 mandated the use of SI units, a richer set of units of measure are now supported.

For more information on properties, see Chapter 8 (page 77).

3.4.7 Earth Model

The RESQML "FIRP" knowledge hierarchy was defined in Section 3.2.3 (page 28). This hierarchy is useful for several reasons, but provides the most information within the context of the earth model.

In Table 2, an earth model can consist of all of the objects categorized as geologic: features, interpretations, and representations. Many of the geologic representations listed in the table have clear relationships with the corresponding interpretations and features. RESQML has the functionality to let you specify relationships to create organizations building up to a coherent earth model. In addition, RESQML provides generic digital representations corresponding to points and surfaces, or their collections, e.g., for 2D grids, triangulated sets, or polyline sets.

For more information on how RESQML helps with developing and updating earth models, see Chapter 9 (page 82).

3.4.8 Grids

The second large group of representations in the table is the grid group, which represents predominantly reservoirs. A gap analysis of current industry usage led to the design of six different grid representations:

- Three grid representations are fundamental, and although there has been a lack of data-transfer standards, they are of well-known types and include: IJK grid, unstructured column-layer grid, and unstructured cell grid.
- The other three are mixtures between the first three and consist of two truncated grid representations and a general purpose grid representation. The general purpose grid is notable because it is more of a grid description development toolkit than a specific grid type, and recognizes that unstructured grid usage is still evolving. Included are geometry-free grid representations, and both lower order and higher order finite element grids.

For more information about grids, see Chapter 11 (page 126).

3.4.9 Wells

The design of the wellbore representation draws heavily on the WITSML expertise within Energistics. The wellbore trajectory representation describes the geometry of the trajectory, and the wellbore frame representation provides the topological support for properties or relationships. Specific wellbore frames exist to represent geologic markers, and another wellbore frame is used to represent discretized wellbores along a grid.

For more information about wells, see Chapter 12 (page 197).

3.4.10 Seismic Surveys

Seismic survey representations take advantage of previously defined representations, with the addition of seismic coordinates to their geometry. A seismic survey feature describes a seismic lattice, a seismic line, or their collections. Any of the representations already described may be associated with a seismic survey feature, and then seismic coordinates, e.g., inline and crossline coordinates, may be associated with the geometric points of the representation. (In general, these coordinates are not integers because the points of a representation need not align with the geometry of a survey.)

The oil and gas industry already has a robust standard for the exchange of seismic data using the SEGY format. Therefore, RESQML does not attempt to redefine a new seismic data standard but can reference SEGY files in an EPC file.

For more information, see Chapter 13 (page 212).

4 Common Data Objects

For consistency and efficiency, RESQML leverages common data objects from two complementary sets:

- Energistics Common Technical Architecture (in the UML model: common)
- RESQML Common Architecture (in the UML model: resqml => v2.0.1 => xsd_schema => Common)

All RESQML data objects inherit from RESQML common, which inherits from the Energistics common. **Figure 3-5** shows the RESQML UML model and the location of each folder.

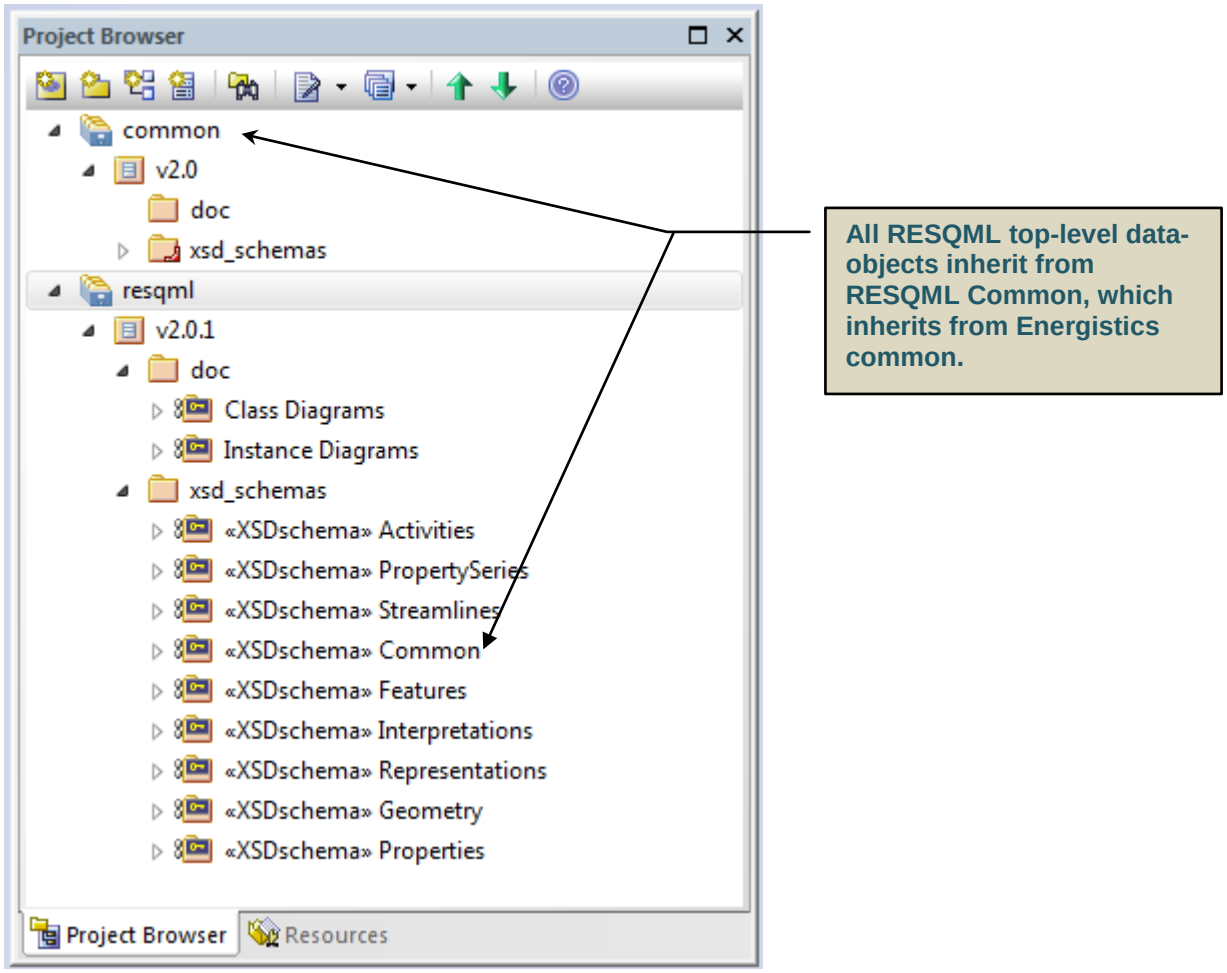


Figure 4-1—The RESQL EAP file contains the groupings shown here and explained in the text below.

This chapter gives an overview of the main data objects and capabilities of each group (Energistics common and RESQML Common) and explains how they are used when implementing RESQML. The main areas addressed by these common architectures include:

- Defining all data objects for consistency, which includes use of universally unique identifiers (UUID) and citation data (metadata).
- Referencing data objects.
- Coordinate reference systems.
- Units of measure.

4.1 Background: Standardizing the Standards

Because Energistics is a standards organization, it has always looked to standardize across its standards. However, much of the work to develop the main standards (WITSML, PRODML and RESQML) began organically, with different groups within traditional domain silos. Different project starts, schedules, development approaches, and maturity levels of the standards have imposed limits on what could be done in the past for consistency across all the standards.

However, more recently, the Energistics Board of Directors and special interest group (SIG) leadership agreed the time was right to begin a coordinate and focused effort for a common Energistics technical architecture. Since then, a team has been working to develop and deploy this common architecture.

Data objects common across all Energistics standards are in the common folder. To accommodate specific needs of the individual domain standards, each has its own "common" folder.

All RESQML top-level data objects inherit from RESQML common, which inherits from Energistics common.

4.2 Energistics Common Technical Architecture (common)

Figure 4-2 shows the packages in the Energistics common folder. This section describes how the data objects in these packages are intended to work when RESQML is implemented in software. Classes and attributes defined in the UML model are converted into XML elements, types, and attributes in the resulting XML schema, from where programmers can use proxy generators to create classes in their development environments. Because behavior is not specifiable in XML, the operations part of the class boxes is not used and the UML model does not hold methods.

Officially, common is part of the Energistics Common Technical Architecture. However, the current version has been released in support of RESQML. For more information, see the *Energistics: common Technical Reference Guide* (For a link to this document, see Section 1.4 (page 13).).

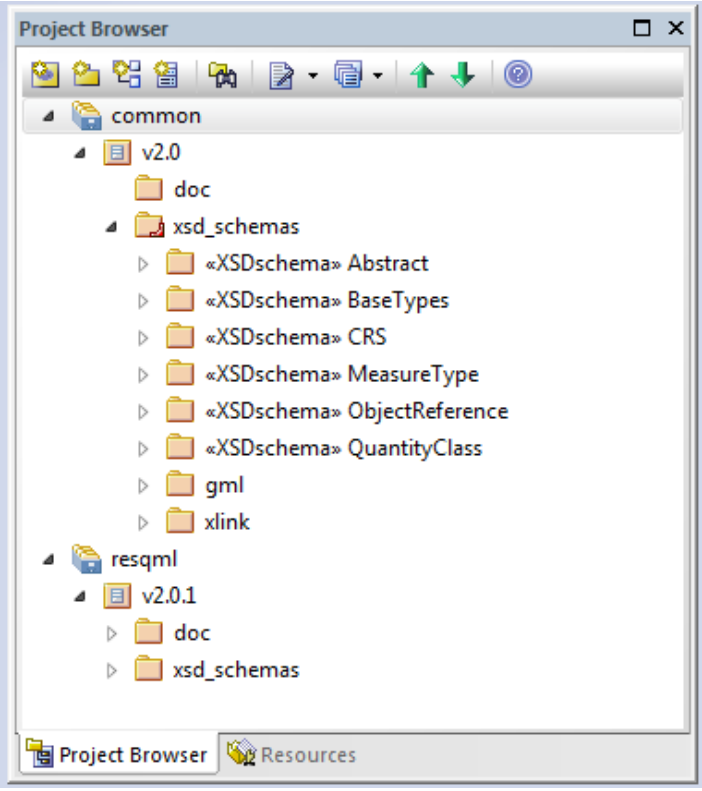


Figure 4-2—Main contents of the Energistics common folder (Energistics Common Technical Architecture).

4.2.1 Abstract Objects

Data objects in the Abstract package (**Figure 4-3**) are used as the roots of all global elements in Energistics' XML schemas. For RESQML, this means that their top-level elements inherit from this chain. In the RESQML UML model, they are abstract classes which provide some relationships and attributes across all RESQML top-level elements. The functionality provided from the root-most object—AbstractObject—includes aliasing, simple extensibility, and summary authorship metadata to provide some object traceability.

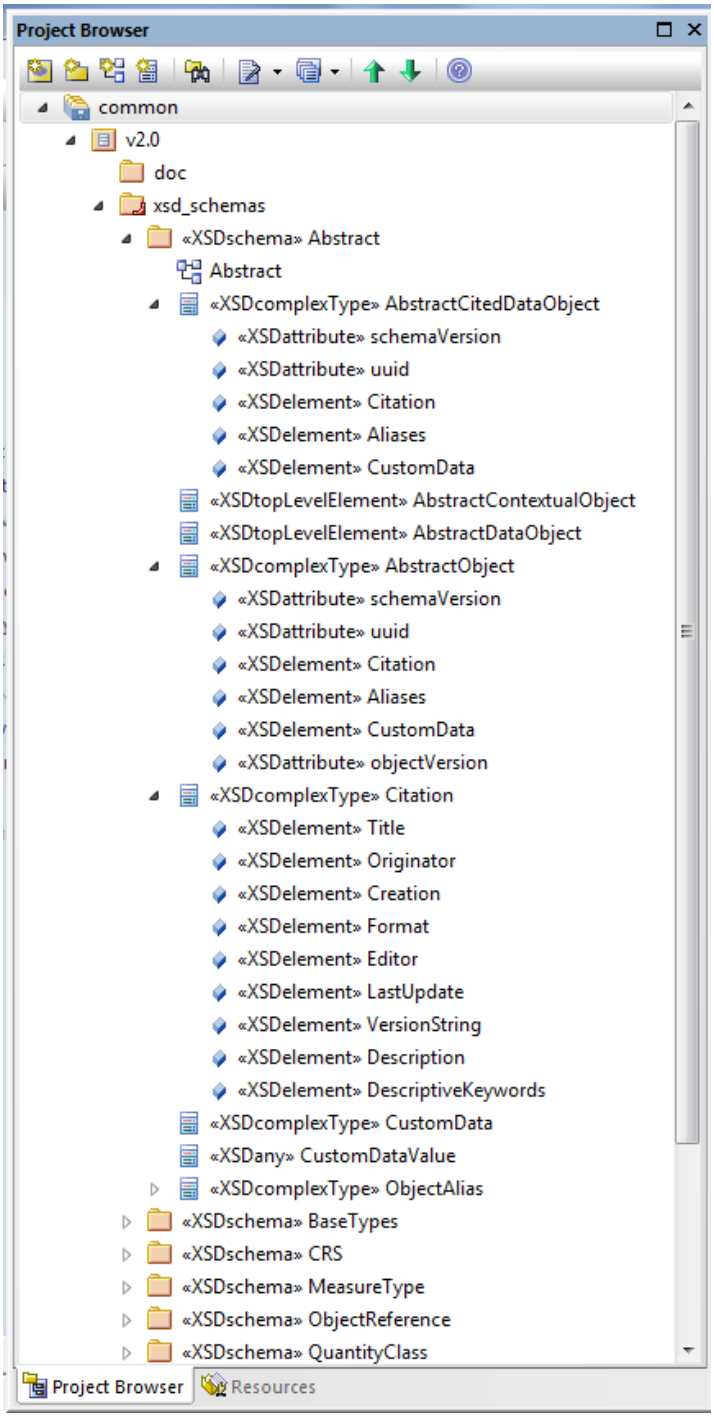


Figure 4-3—Abstract Class: data object class and elements (Energistics Common Technical Architecture).

4.2.1.1 ObjectAlias

Multiple aliases for any object instance can be created using the Aliases attribute. Note that an Authority is required for each alias.

4.2.1.2 CustomData

XML objects can be extended at runtime via the CustomData element. The CustomDataValue elements are untyped in XML (using xs:any) so any type of data can be included at runtime.

4.2.1.3 Citation

Simple authorship metadata can optionally be added to any Energistics object through the Citation data object. The Citation data object uses attributes like Title, Originator, Editor, LastUpdate, etc. from the *Energy Industry Profile of ISO 19115-1 (EIP).* (For a link to this document, see Section 1.4.1 (page 14).)

4.2.1.4 AbstractCitedDataObject

Because the RESQML community requires a Citation element on all its top-level objects, a specialization of AbstractObject called AbstractCitedDataObject was created where the Citation attribute is mandatory. Other SIGs may also follow this practice, so the specialization was left in Energistics common rather than the RESQML Common.

4.2.1.5 Identifiers

Each top-level object in Energistics standards that conforms to the Common Technical Architecture is identified by its UUID attribute, which must be implemented as a GUID in the XML document. All objects inherit the UUID attribute from AbstractObject.

4.2.1.6 SchemaVersion

Because a data transfer could potentially include XML objects from different versions of the standards, every top-level object must specify the version of the schema to which it conforms. It does this by setting the schemaVersion attribute inherited from AbstractObject.

4.2.2 Base Types

The base types class (**Figure 4-4**) defines the intended abstract supertypes for the data types shown. Each is defined in the EA model and the *RESQML Technical Reference Guide*. These types are specializations of normal XML schema datatypes with special purposes – like specific maximum lengths for string types. They provide consistency and protect consumers of the standard documents from potentially unlimited-length strings appearing in documents. In the case of UuidString, an XML regular expression pattern is applied so XML Schema validation could be used to reject an improperly-formed UUID.

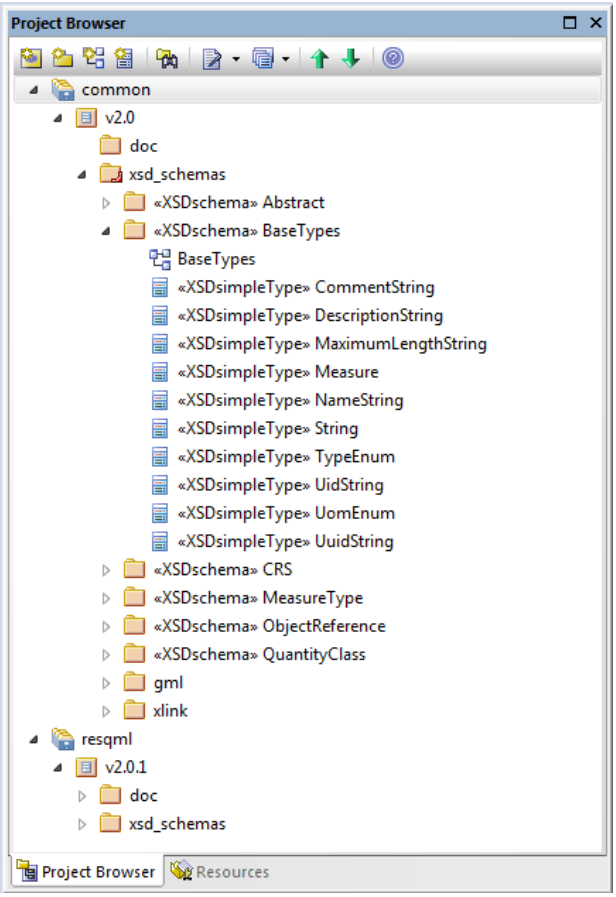


Figure 4-4— BaseTypes class (Energistics Common Technical Architecture).

4.2.3 Object Reference

When RESQML moved from a (mostly) hierarchical data model to an object-relationship model with top-level, stand-alone data objects, two new mechanisms were required (**Figure 4-5**):

- A way for data objects to reference one another, which is done using the DataObjectReference. (For more information on how data object references works, see Section 5.4 (page 56).)
- A way to group data objects, which required additional reference mechanisms.
  - Grouping data objects is done using the Energistics Packaging Conventions (EPC), which is a specialization of the Open Packaging Conventions (OPC).
  - With EPC, most data is stored internal to the EPC package. However, some data may (or must) be stored externally to the package, including HDF5 files (HDF5 has been used by RESQML since v1 for optimized storage, retrieval and performance of large numeric data sets). EpcExternalPartReference and Hdf5Dataset are used for these external references.
  - For more information on these EPC-related references, see the *Energistics Packaging Conventions (EPC) Specification.* (For a link to this document, see Section 1.4.1 (page 14).)

These mechanisms will be used across Energistics standards so have become part of Energistics Common Technical Architecture.

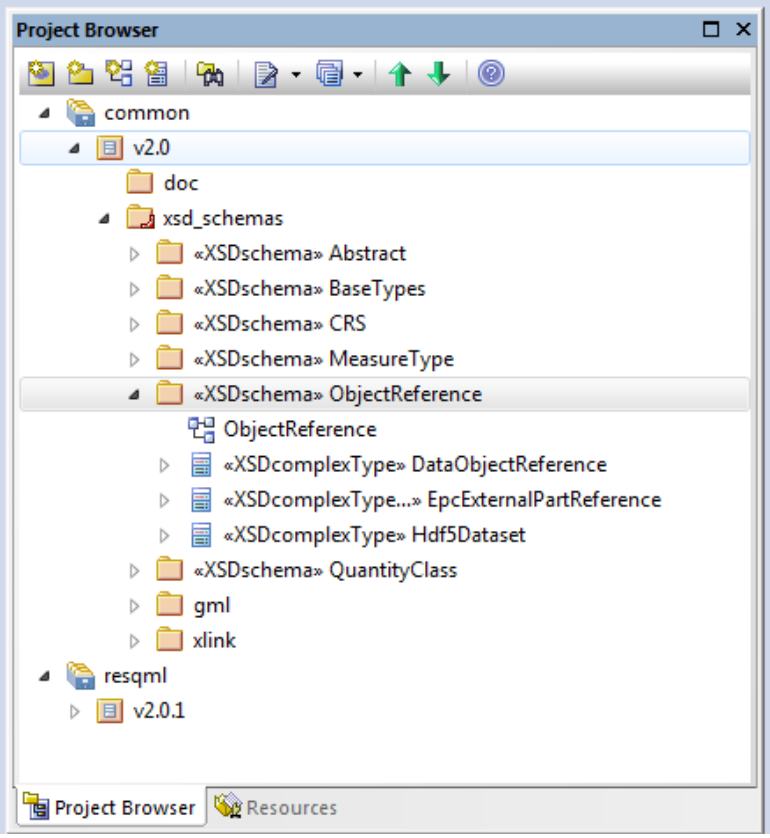


Figure 4-5—ObjectReference class (Energistics Common Technical Architecture).

4.2.4 CRS

For detailed information on how coordinate reference systems are used in Energistics standards, see the *Energistics Coordinate Reference System Usage Guide.* (For a link to this document, see Section 1.4.1 (page 14).)

This section provides an overview of the classes in Energistics common used by RESQML for coordinate reference systems.

Energistics common has a CRS package, which has two abstract classes—AbstractProjectedCrs and AbstractVerticalCrs. Each of these classes has three concrete children. The intent of the three children is to ensure that either a projected or vertical CRS is one of these:

- A projection identified by an EPSG code.
- A projection not known to the EPSG which is defined using OGC's Geographic Markup Language (GML).
- A projection that is intentionally obscured to anonymize a dataset. This is identified by a simple unvalidated string.

For more information on EPSG codes and GML, see Section 2.2.2 (page 20).

4.2.5 Units of Measure

For details about how units of measure work in Energistics standards, see the *Energistics Unit of Measure Standard.* (For a link to this standard, see Section 1.4.1 (page 14).).

This section provides an overview of the classes in Energistics common.

4.2.5.1 Measure Types

A handful of attributes in the EA model (elements in the XML schema) use complex datatypes which include a validated UOM as part of the attribute. These datatypes are in the measure type package.

4.2.5.2 Quantity Classes

A quantity class represents a set of units with the same dimension and same underlying measurement concept. For example, length is a quantity class.

Quantity classes are used to constrain items in the data model because the class defines all of the units that are allowed to be used with something that represents a specialization of that class.

4.3 RESQML Common Architecture (Common)

Figure 4-3 shows the data objects in RESQML Common. This section covers highlights of how these data objects are intended to work when RESQML is implemented in a software package. Classes and elements are defined in the UML model.

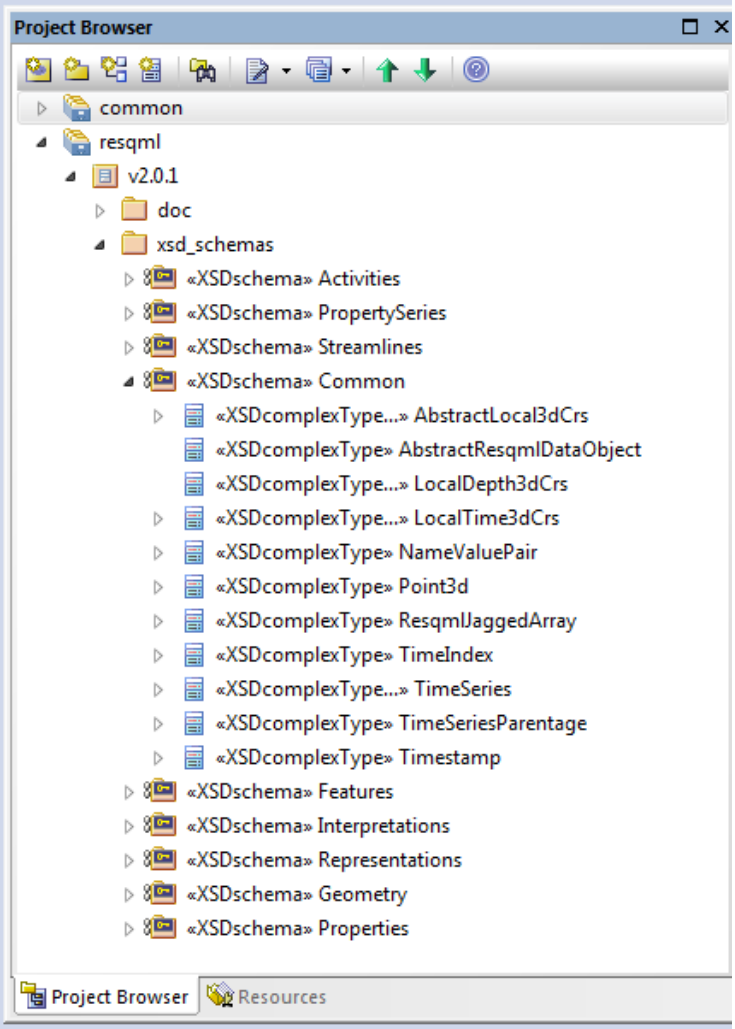


Figure 4-6—RESQML common data objects.

4.3.1 RESQML Abstract

For design consistency, all RESQML data objects inherit from AbstractResqmlDataObject, which itself inherits from AbstractCitedDataObject. AbstractCitedDataObject exists because the RESQML community considers the Citation data to be mandatory.

ResqmlPropertyKind are the enumeration of standard property kinds used in RESQML. For more information on properties and property kinds, see Chapter 8 (page 77).

4.3.1.1 Extending Data Object Definitions with NameValuePair

While most elements of a model can be extended to include proprietary extension using CustomData, RESQML also provides a simpler mechanism to transfer information that are not critical but may improve user experience. AbstractResqmlDataObject, the base class for all RESQML data objects, may include a list of string pairs, which associates a keyword with a value. For example, graphical attributes of elements such as color, could be transferred this way.

4.3.2 Local Coordinates Reference Systems

To avoid numerical issues when computing relative distance between elements of a model, it is common practice in reservoir modeling to work within a local coordinate system. In RESQML, this local coordinate system is obtained by translation of the origin and areal rotation from projected and vertical global coordinate systems. It is also common to see elements in both the depth and the time domain.

RESQML contains one abstract class, AbstractLocal3dCrs, which references the projected and vertical CRS it is based on. Because some projected and vertical CRSs can be anonymous, it also contains information such as units of measure, axis order, and orientation. Most of the time, this information is redundant with the actual projected and vertical CRS definition, but is required for an anonymous CRS and is also targeted toward applications that are not CRS aware. In any case, such information in the local CRS must match its projected and vertical CRS.

The two concrete specializations of the AbstractLocal3dCrs allow separation between the depth and time domains.

- LocalDepth3dCRS is referred by representations in the depth domain
- LocalTime3dCrs is used by the representations in the time domain. LocalTime3dCrs also provides the unit of measure for time coordinates.

NOTE: When a CRS description is based on GML, it must include gml:identifier and the identifier must follow the UUID convention, so that a reader can quickly identify which representations are in the same CRS. (For more information on GML, see Section 2.2.2.2 (page 21).)

4.3.3 Time: Time Index, Time Series, Time Stamps, and Property Series

RESQML includes several time concepts, which are listed and described here. The time usage for representations within RESQML, e.g., for properties and geometry, uses a time index into a time series (**Figure 4-7**). The use of a time series as a top-level data object allows a RESQML reader to determine all of the data times in use within a data set, without needing to interrogate individual properties or geometries. This approach also simplifies the treatment of properties in reservoir simulation where we may have computed many properties during a simulation run, but all of which share the same time series.

- Time Series. Stores an ordered list of times, for example, for time-dependent properties, geometries, or representations. It is used in conjunction with the time index to specify times for RESQML.
  - TimeSeriesParentage. Indicates that a time series has the associated time series as a parent, i.e., that the series continues from the parent time series.
- Time Index. Index into a time series. Used to specify time. (Not to be confused with time step.)
- Time Stamp. XML dateTime, with an optional year offset to capture very long time intervals (e.g., geologic time).
- Property Series. Allows us to capture the evolution of property values through time and/or multiple realizations of these values during stochastic processes (see Section C.2 (page 228)).

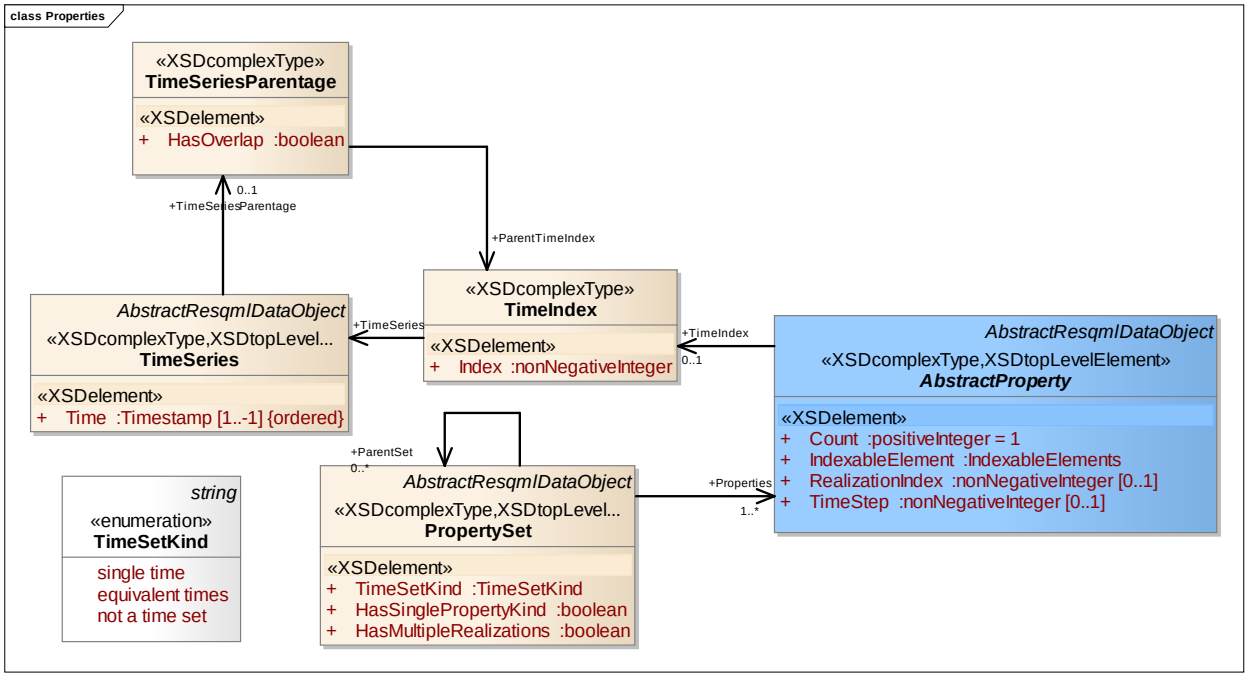


Figure 4-7—RESQML property time treatment.

4.3.3.1 Examples

Two examples of how the time series is used to support grouping of properties at identical or related times are shown in the next figure (**Figure 4-8**).

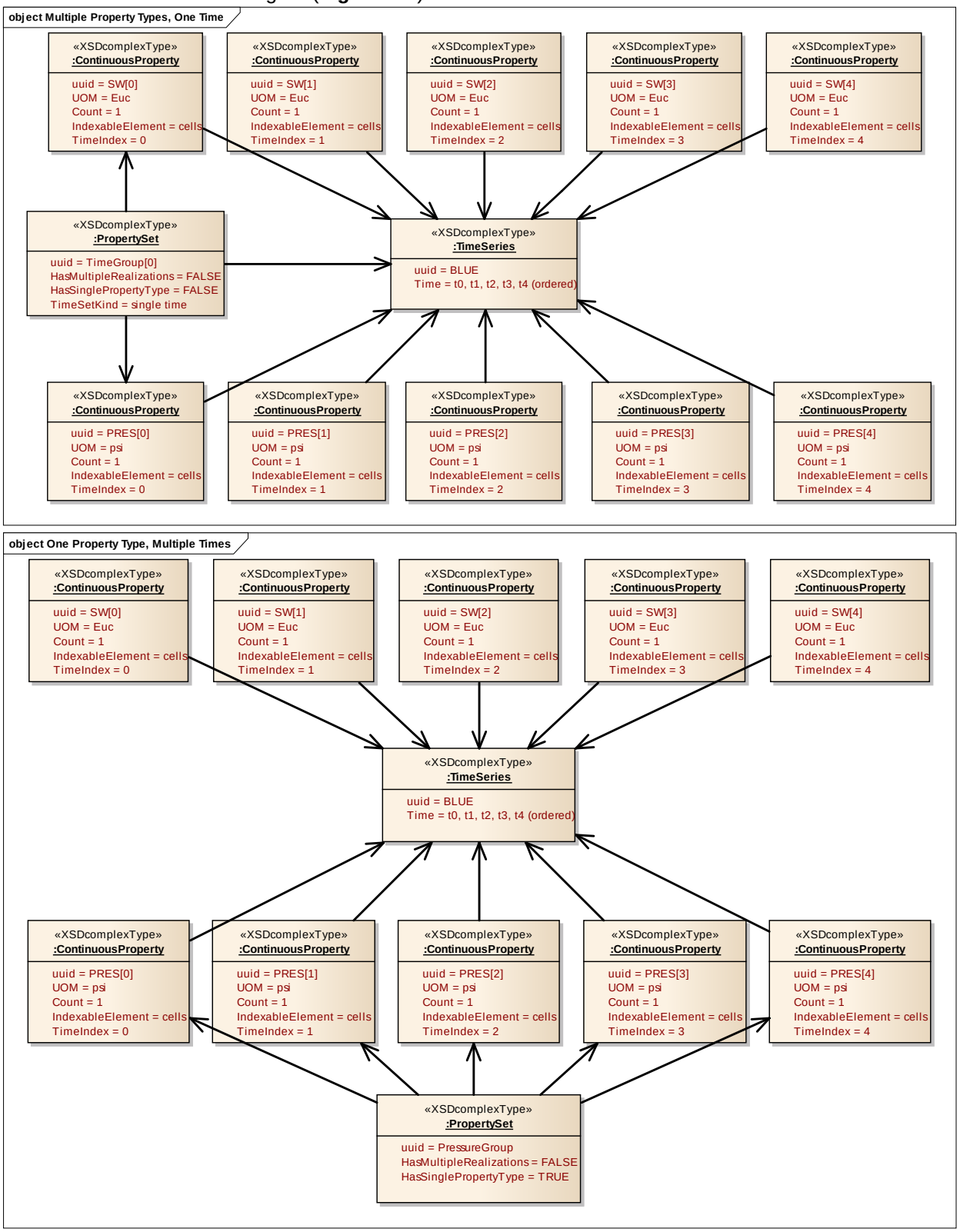


Figure 4-8—RESQML property set time group examples.

In the first example, a property set is constructed at one time from two properties. In the second, the property set is constructed from one property type at multiple times. In both of these examples, time is referenced into the time series object. The use of time series parentage allows one set of times to be appended to another, e.g., to support reservoir simulation restarts for to explore a variety of reservoir development scenarios.

The time stamp is used within features and interpretations to specify time as an XML dateTime, with an optional year offset to capture very long time intervals (**Figure 4-9**).

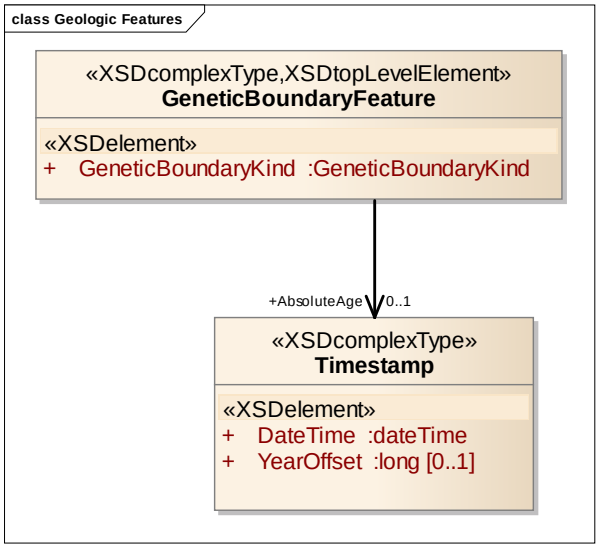


Figure 4-9—RESQML time stamp usage.

4.3.4 RESQML Jagged Array Construction

RESQML uses a “jagged array” construction to store irregular array data (**Figure 4-10**). This type of a data structure appears in many programming languages where it is sometimes called a “list of lists” or an “array of arrays”. This construction uses a pair of arrays. The “elements” of the array stores all of the values while the “cumulative length” stores the offsets. Specifically, the offset is the cumulative count of elements to the end of that portion of the array. It is implicit that the offset to the beginning of the first element is zero. The differences in offsets may also be used to determine the length of each elemental array.

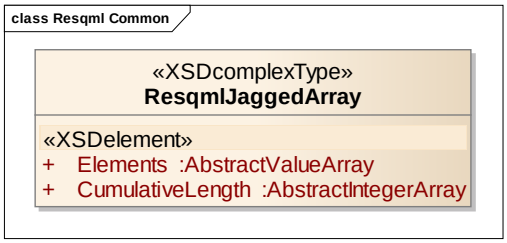


Figure 4-10—RESQML jagged array-object.

For example, to store the following three arrays as a jagged array:

(a b c)

(d e f g)

(h)

Elements = (a b c d e f g h)

Cumulative Length = (3 7 8)

5 Knowledge Hierarchy: Features, Interpretations, Representations, and Properties

As introduced earlier in Chapter 3 (page 23), RESQML v1.1 had the concept of data "versions." RESQML has now expanded the concept of "data" to include the relationships between data objects, which allows a more precise classification.

The current design now supports the transfer of abstract subsurface features, human interpretations of those features, the data representations of those interpretations, and the properties indexed onto those representations, which results in a well-defined knowledge hierarchy of feature/interpretation/representation/properties (informally referred to as "FIRP")—a key organizing concept in RESQML (**Figure 5-1**). Additionally geometry is integral to RESQML organization.

The knowledge hierarchy is set up to associate and retrieve the different levels of information on data objects exchanged between software applications, in context, which essentially allows users to monitor the progress of the related business processes.

This chapter:

- Provides definitions for features, interpretations, representations and properties concepts, and introduces topology and geometry.
- Explains how these different levels of data objects fit together into a knowledge hierarchy—a crucial new RESQML concept for more precise data organization and more efficient data exchange—and refers to specific detailed chapters, as necessary.
- Explains how to specify relationships between data objects in RESQML.

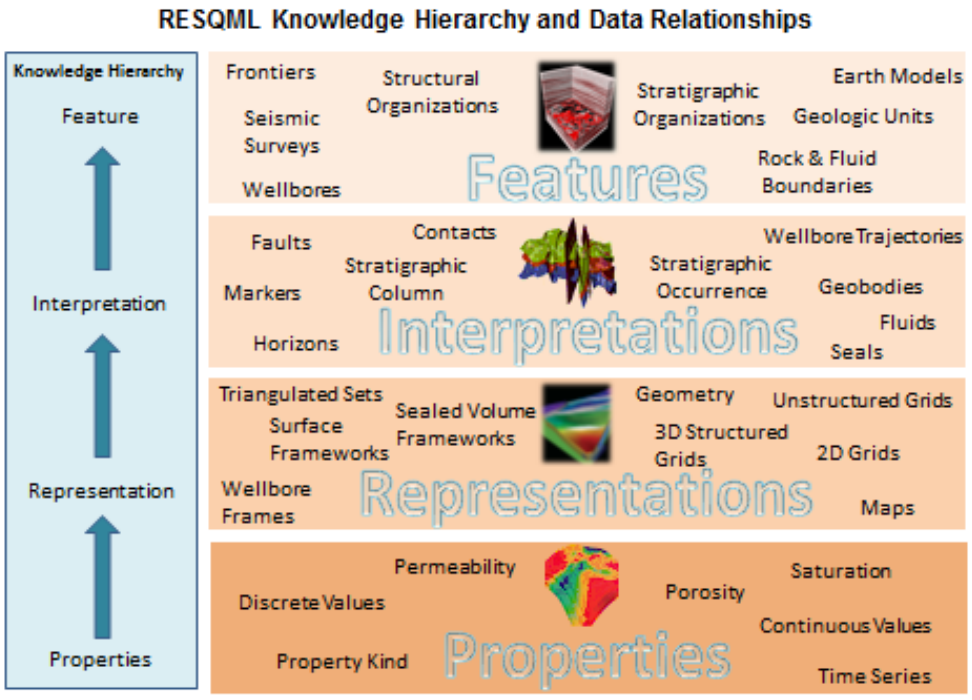


Figure 5-1—The feature/interpretation/representation/properties knowledge hierarchy (referred to informally as "FIRP") is a new concept in RESQML; it makes data organization more precise and data exchange more efficient.

5.1 Features, Interpretations, Representations, and Properties

The table below (repeated from Chapter 3 for convenience) defines these terms; each of these is a type of RESQML data object. Sections below describe additional details about each and the role of each (how it is used) in the knowledge hierarchy.

For a high-level list of RESQML data objects and their organization, see Section 3.4 (page 35).

For each of these levels, each instance of the corresponding data objects is uniquely identified with a UUID and metadata (a citation data object). The ability to uniquely identify each instance allows a user to start a business process (for example, define horizons and faults or build an earth model) by creating an instance of one feature. This begins the modeling process.

As work progresses in the business process, the user can create interpretations of the feature, and representations of the interpretations. Properties can also be added to representations and geometry defined. This process can continue (according to the requirements of the specific business process), with as many interpretations and representations as the business process requires.

Construct / Term	Definition
Feature	Something that has physical existence at some point during the exploration, development, production, or abandonment of a reservoir. For example: It can be a boundary, a rock volume, a basin area, but also extends to a drilled well, a drilling rig, an injected or produced fluid, or a 2D, 3D, or 4D seismic survey. Features are divided into these categories: geological or technical.
	Geological Feature. Objects that exist *a priori,* in the natural world, for example: the rock formations and how they are positioned with regard to each other; the fluids that are present before production; or the position of the geological intervals with respect to each other. Some of these objects are static—such as geologic intervals—while others are dynamic—such as fluids; their properties, geometries, and quantities may change over time during the course of field production.
	Technical Feature. Objects that exist by the action of humans. Examples include: wells and all they may contain, seismic data (surface, permanent water bottom), or injected fluid volumes. Because the decision to deploy such equipment is the result of studies or decisions by humans, technical features are usually not subject to the same kind of large changes in interpretation as geologic features. However, because technical features are subject to measurement error and other sources of uncertainty, they can be considered as subject to “interpretation”. In the RESQML knowledge hierarchy, technical features do not require an interpretation.
(Feature) **Interpretation**	RESQML uses the definition of David Gawith, which explains an interpretation as a single consistent description of a feature. An interpretation is subjective and very strongly tied to the intellectual activity of the project team members. The initial curiosity and reasoning of the people on the project team initiates the early pre-screening campaign (remote sensing, surveys). They make hypotheses that consist of as many interpretations as necessary to describe the features. (Gawith and Gutteridge 2007; for citation, see Section 5.5 (page 58)). A typical example of interpretation is based on the opinion of the geometry of a feature. Other specific interpretation information may include the description of the throw of a fault, the horizon classification in a sequence stratigraphic approach, or the contacts in a structural model. **NOTE:** The RESQML formal name is actually "feature-interpretation" and some of the class names use this full term. For conciseness of documentation, we use simply "Interpretation" where this usage is not confusing. Version 2 uses the term “interpretation” instead of alternative terms that were used in v1.1, such as “version” or “opinion". Most of the information contained as attributes or enumerations in individual feature interpretations or organization interpretations will help users understand

Construct / Term	Definition
	how the representations of the geologic objects should be built or have been built, if the representation is already associated to the given interpretation.
(FeatureIntepretation) **Representation**	A digital description of a feature or an interpretation. For example, currently in RESQML, a horizon interpretation may be represented by a point set, a set of triangulated surfaces, or a set of orthogonal grids. A representation contains the topology and geometry of a structural feature. **BUSINESS RULES**: Representations in RESQML must be in a single projected 2D CRS. All representations associated with the same interpretation may be in either time or in depth/elevation, but a mixture of time, depth and elevation vertical reference systems is NOT allowed. Representations may not always be associated with interpretations, although this pattern is recommended for subsurface representations for which interpretations exist. A representation contains the topology and the geometry of the data objects. These terms are defined in Section 5.2 below. **NOTE:** Like "feature interpretation" in the previous table row, this term is formally "feature interpretation representation", but we use "representation" for conciseness.
Properties	A property can be attached to any indexable element of any representation. Properties refer to semantic variables (for example, porosity, permeability, etc.) and the corresponding data values, which are recorded in arrays, which may be stored in HDF5 datasets. For more information about properties, see Chapter 8 (page 77).

5.2 Topology and Geometry

For an optimized design and to support workflow flexibility, topology, geometry, and properties are handled differently than in the hierarchical approach of RESQML v1.

To support partial model updates, the topological description of a data object has been separated from its properties. This construction is consistent with the knowledge hierarchy explained above, in which a description of a feature without properties is an interpretation, while a representation is required for property data. This construction is also similar to how seismic data is stored in SEGY, with the seismic trace headers and header information separated from the seismic trace records and data.

The table below (also repeated here from Chapter 3, for convenience) defines these terms and points to more detailed chapters.

Term	Definition
Topology	Each representation contains a topological description, which defines how to associate nodes and other “indexable elements” to represent points, lines, surfaces or volumes (like structured and unstructured grids). For complex objects like simulation grids, much of the topological description can be implicit. For more information about indexable elements, see Section 6.2 (page 60) and the *RESQML Technical Reference Guide*.
Geometry	Each representation contains its geometry, which is the spatial location of each selected indexable element, mainly nodes. This information may be provided as numerical arrays stored in HDF5 datasets, or specified implicitly. Geometry may be contained within a representation (as just described) or, if not used to define the geometry of a representation, implemented as a “point property”. For more information about geometry, see Chapter 7 (page 66)

5.3 How These Concepts are Used in the Knowledge Hierarchy

This knowledge hierarchy is set up to associate and retrieve different levels of information for data objects exchanged between applications, for each of the levels of the hierarchy defined in Section 5.1 (page 52) and shown in Figure 5-1. For more information how to specify the relationships among these different data objects, see Section 5.4 (page 56).

We have four levels of the knowledge hierarchy (informally referred to as "FIRP"):

Feature

Interpretation

Representation

Properties

5.3.1 Feature Level

A feature can be any top-level business object required by a business process, such as the individual data objects or organization data objects described above or listed in Table 2 (page 35). The creation of a feature is a declaration that this is a business object that will be further studied and developed over a span of time. As such, it must be uniquely identified and we must be able to access all data and information related to it, including future interpretations of it, future representations of those interpretations, and the properties attached to the representation. A feature may be:

- An individual data object, such as:
  - a geologic feature (e.g., a geologic unit or a geologic boundary)
  - a technical feature (e.g., a wellbore or seismic data).
- Or a complex business object of interest on which users will study, collaborate and further develop using various software applications:
  - an organization (e.g., an earth model , a structural organization, a stratigraphic organization, a reservoir, a seal, a source rock, etc.)

When beginning a series of data exchanges between software packages (or applications), the user must determine a reference feature data object that will be the entry point and the "pivot location" for identifying related interpretations and representations.

The role of the feature is to ensure a unique reference, which is why each feature has a UUID and metadata. The attached metadata (a citation element) reports the circumstances of the creation of this feature.

At the beginning of an exchange between software packages, to avoid redundancy and to ensure reliable management of the data object, the "reader" software must verify whether or not it has already imported this specific feature data object. If it has already imported the feature, it must not import it again. Instead, it should retrieve the data it has stored on that feature and determine if the new data being exchanged contains any updates or new information.

This specific feature data object must not be modified; rather, all changes to the data object are made at the interpretation, representation or property level. As data objects are exchanged back and forth among software applications, each package updates metadata (appropriately, based on the changes it made) for interpretations, representations, and properties.

For more information on features and interpretations in the context of an earth model, see Chapter 9 (page 82).

5.3.2 Interpretation Level

The interpretation level corresponds to the results of a step done by one user or software agent in a business process.

Most of the information contained in an individual interpretation or organization interpretation is as attributes or enumerations, which helps users understand how the topology and the geometry of the geological objects and organization representations should be built or have been built, if the representation is already associated with the given interpretation.

Like a feature, an interpretation is uniquely identified by a UUID and metadata. Interpretations have two additional types of information:

- **Geologic knowledge**, which describes (usually by enumerations) the hypothesis used to obtain the associated representation (embedded directly as an attribute of the interpretation):
  - Structural example: a horizon interpretation is unconformable below
  - Grid example: a reservoir organization interpretation is based on a specific stratigraphic organization interpretation
- **Link to a representation** (which could be of several types) which is obtained by applying the hypothesis declared in the interpretation using one software package (or application). We can have several representations based on the same hypothesis, for example:
  - **Structural example**: On one hypothesis: a horizon interpretation is unconformable below:
    - Surface Representation 1: a point set
    - Surface Representation 2: a triangulated surface
    - Surface Representation 3: a interval Edge in a grid (which in this case is a sub-representation of a Grid; for more information, see Section 6.3 (page 62)

    In this example, these 3 representations may come from 3 different software packages; that is, we have 3 different representation of the same interpretation.
  - **Reservoir example**: On one hypothesis, a reservoir: “rock” fluid organization interpretation is contained in an earth model interpretation based on a specific stratigraphic column we can have 3 representations of the rock volume
    - Rock Volume Representation 1: a structured explicit grid oriented north-> south with 50X50 cells and 45,000 layers
    - Rock Volume Representation2: an unstructured grid oriented northwest -> southeast with 20,000 cells
    - Rock Volume Representation 3: a structured “parametric lines” grid oriented north-> south with 50X50 cells and 45,000 layers (For more information on parametric lines, see Section 7.3 (page 69).

    Note that these three grids, which can have different orientations due to the direction of the flux (a simulation with different Injector wells), are based on the same stratigraphic organization interpretation. For more information on grids, see Chapter 11 (page 126).

5.3.3 Representation Level

The representation level corresponds to the 3D modeling expression of the feature initialized at the beginning (as described in Section 5.3.1 above).

Often, a representation contains a topological description and very often the 3D position of the “indexable elements” of this topology. Additionally, it has more concepts for organizing its data; for more information about representation concepts (including indexable elements) see Chapter 6 (page 59).

NOTE: In RESCUE (predecessor to RESQML), software packages exchanged data only at the representation level. For example, in RESCUE, software only exchanged a grid representation and we did not know how and when it was modeled, nor the horizons and faults used to construct the grid. In RESQML v1.1, horizons and faults had features and interpretations.

With the RESQML knowledge hierarchy, a representation "knows" the UUID of the interpretation on which it was based (see Section 5.1 (page 52)). With this information, a user can return to the last geomodeling process and build a new representation, based on the same principles as the previous one, but with different parameters. For example:

- **Structural example**: A user can use a triangulation to represent an horizon previously represented as a 2D grid. After more operations, he/she can come back to the original 2D grid information data for precise fitting purposes.
- **Reservoir example**: A user can create a new representation by executing a local grid refinement after having reduced the number of cells of an existing representation. The stratigraphic column attached remains the same.

5.3.4 Property Level

The property level was set up to easily transfer newly updated properties for a well-known existing representation. (For more information on properties, see Chapter 8 (page 77)

The property level corresponds to valuating the indexed elements of a representation. The properties (which can also be location properties, i.e., geometry) are in this case attached to a specific topological description. For one specific topological description—if you know the UUID of the representation to which they are attached—you can attach several properties with different time stamps and exchange these properties between different software without exchanging the representations itself--you only need to specify the representation.

For example, if a software package makes a change to a data object at the interpretation level, the software must update the data object's metadata including the "Last Change" element (date and time the data object was last changed) and the "Editor" element (the person or organization that made the change).This type of change management tracking can be used for reevaluation of models and field appraisal management.

5.4 Specifying Relationships in RESQML

RESQML uses the standard XML hierarchical relationship, for example, where one data object is contained inside another. However, the nature of subsurface description means there are many possible hierarchies in a reservoir model with more complex relationships between RESQML data objects, which cannot be modeled in a single hierarchical fashion. For example:

- Relationships between feature, interpretations, representations, and properties that create the knowledge hierarchy defined above (which is informally referred to as "FIRP").
- Relationship between data objects of the "same level" of the knowledge hierarchy, such as two horizon features that intersect to form a contact feature, and which may be combined to form a part of a structural framework.

To address these more complex relationships, RESQML uses a data object reference, which is explained in Section 5.4.1 below. Section 5.4.2 (page 57) shows an example of how it works.

Additionally, relationships are specified in the context of an Energistics Package, which is explained in Section 3.2.6 (page 30).

5.4.1 Relationship Mechanisms: Data Object Reference

The data object reference is a special mechanism in the schema (DataObjectReference in the Energistics common package of the schema/EA model) that is used to specify relationships between and among RESQML data objects. The reference mechanism is specified in the data object schema and includes:

- The UUID(s) that the data object references.
- The nature of the reference relationship. For example, one data object may "interpret" another data object or one data object may "represent" another data object. Possible relation types include:
  - Interprets

- Represents
- IsSupportedBy
- isbasedOn

  Because these relationships are specific, they are entered as relation names in the UML model in the EA project.

5.4.1.1 "Direction" of Data Object References

The feature/interpretation/representation/properties knowledge hierarchy creates some special considerations for which data object specifies (or "holds") the reference. During the reservoir lifecycle, a feature can have many interpretations, an interpretation can have many representations, and a representation may have many properties. However, an interpretation cannot "know" how many future representations will be created, or their UUIDs. In contrast, when a user creates a representation, the user must know and specify which interpretation it "represents." For this reason, the child data object must specify (or hold) the relationship.

Here are the general rules on direction in data object references:

- Parent-child:
  - In a one-to-one parent-child relationship, the data object reference is from the parent to the child.
  - In a one-to-many parent-child relationship—and always for the "FIRP" relationship (see the example in Section 5.4.2 (below))—the data object reference is from the child to the parent.
- *isbasedOn,* where one data object is based on another data object defined at the same level. The data object reference goes from one class to another to express that the source object which is BasedOn a target object needed to collect all the information gathered by the target object.

5.4.2 Example: "FIRP" Relationships

The relationships between features, interpretations, representations and properties are parent-child relationships held by the child(ren). **Figure 5-2** shows an example, which is further explained in the text below. As explained in the previous section, the child data objects specify the relationship.

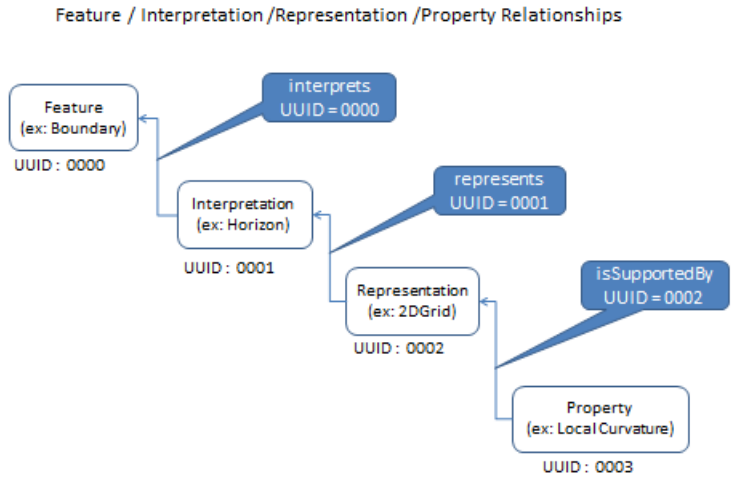


Figure 5-2—Example of relationships in RESQML for FIRP. Property "is supported by" (or provides values for) a representation; a representation "represents" an interpretation; an interpretation "interprets" a feature.

Each data object (except the feature) has a data object reference, which includes the UUID of the data object it references and the type of relationship. The relationships can be described as follows:

- Horizon 1 Interpretation *interprets* a genetic boundary feature of UUID= 0000.
- 2D Grid *represents* a horizon interpretation of UUID= 0001.
- A Local Curvature *isSupportedBy* (i.e., has numeric *values and is described within)* a 2D grid representation of UUID= 0002.

Figure 5-3 shows the addition of several children, which include a new interpretation, representation and property.

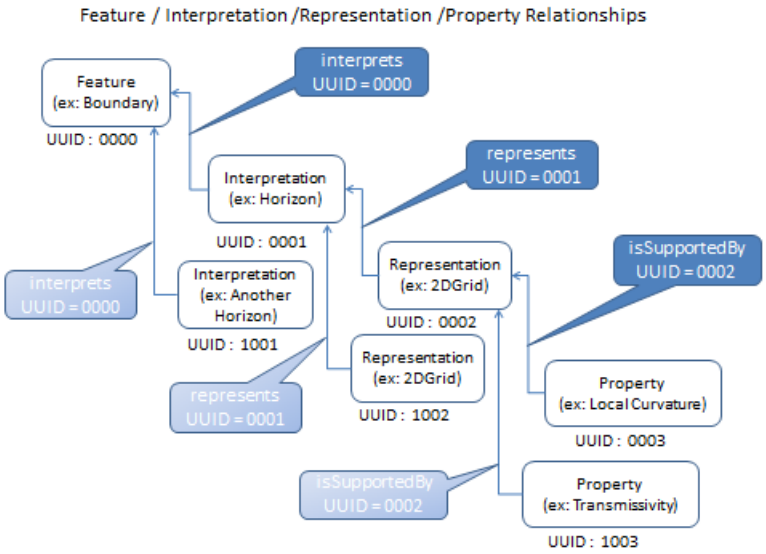


Figure 5-3—The previous example is extended to show multiple children with the addition of: another interpretation of the boundary feature (UUID 1001), another representation of the horizon interpretation (UUID 2002), and another property on the first representation (UUID 1003).

5.5 References

Gawith, D and Gutteridge, P. (2007). Redefining what we mean by shared earth model. *First Break*, 25:10. EAGE http://www.earthdoc.org/publication/publicationdetails/?publication=27669

6 Representations (Shared Concepts)

A representation has two distinct and complementary roles in RESQML:

- It is an important component of the feature/interpretation/representation/property knowledge hierarchy where it corresponds to a 3D modeling expression of a feature that was initialized at the beginning of a business process (as explained in Section 5.1 (page 52)). For example, the same horizon feature-interpretation can have a 2D grid representation or a triangulated set representation.
- It supports the geometry and properties of data objects in RESQML. The geometry of a representation is contained within the representation, while properties may be attached to the representation. Each property is "attached" to the indexable elements of a representation, which may be as simple as the nodes on a single triangulated surface or as complex as the cell, nodes, faces, pillars, coordinate lines, columns, etc., for a 3D grid.

All representations share some key concepts, which are explained in this chapter. For more information on these related topics, see the indicated chapter:

- For geometry, see Chapter 7 (page 66).
- For properties, see Chapter 8 (page 77).
- For structural/stratigraphic representations, see Chapter 10 (page 107).
- For grids, see Chapter 11 (page 126).
- For wells, see Chapter 12 (page 197).
- For seismic, see Chapter 13 (page 212).

6.1 Representations Overview

Representations of different business objects (e.g., a horizon versus a reservoir versus a seismic survey) have different requirements and elements. However, all RESQML representations share several common concepts. This chapter explains these shared concepts, which include:

- **Patches** (see Section 6.3 (page 62). A Patch is a mechanism in RESQML that provides a clear way of ordering indices to avoid ambiguity in their definition. For example, the representation of a horizon may consist of 10 triangulated surfaces. To correctly order the geometry or properties on this representation, the software importing or reading that horizon must know the indices within each of the 10 triangulated surfaces AND how the 10 triangulated surfaces are sequenced.

  All classes with "patch" in their name (e.g. NodePatch, PolylineSetPatch, Grid2DPatch, etc.) have a patch index, which is explicitly defined by the patch index inherited from the Patch object. Recommended usage is for the patch index to be identical to the order in which that patch object appears in a RESQML file. For instance, the first NodePatch would have a patch index of 0, the second a patch index of 1, etc. This order is used to uniquely sequence the elements of the patches. (The use of an explicit patch index definition is expected to be replaced by an implicit definition based on the object order in a future version of RESQML.)
- **Indexable elements** (see Section 6.2 (page 60). Geometric or topological elements in a representation that can be enumerated by a contiguous set of integral numbers, which are called indices. The indices are used to uniquely specify how properties and geometry are associated with elements in a representation. A subset of indexable elements can be identified by an ordered subset of indices. Indices can be multi-dimensional.
- **Subrepresentations** (see Section 6.3 (page 62). A subrepresentation is a logical and ordered subset of an existing representation. It is itself a representation. Subrepresentations are used to define the topological elements of new representations that get their geometry from the previously defined existing representation.
- **Representation identities** (see Section 6.5 (page 63). Relationships (or semantics) between nodes of representation or subrepresentations.

In RESQML v1.1, gridding information was exchanged at the representation level only. Now, a grid representation (and all the other representations) is associated with the UUID of an interpretation of a geologic feature, so that a user can revisit the last geomodeling process and build a new representation that preserves the interpretation. For example:

- For structural modeling, the user can use a triangulation to represent a horizon that was previously represented by a 2D grid. After more operations, the user can go back to the original 2D grid representation for precise fitting purposes. He can do this because these two representations are linked to the same interpretation.
- For reservoir grids, the user can create a new representation by specifying a local refinement of an existing grid after having reduced the number of cells of an existing representation. The stratigraphic column, which is a stratigraphic organization interpretation, attached remains the same. He can do this because the two grid representations are linked to the same interpretation.

6.2 Indexing

RESQML now makes extensive use of the concept of indexing to order and reference the indexable elements of a representation. RESQML uses both one-dimensional and multi-dimensional arrays of elements. So that all elements may be referenced in a consistent and uniform fashion, each multi-dimensional index must have a well-defined 1D index.

6.2.1 Indexable Elements

Table 4 shows the RESQML indexable elements and indicates for which representation or representations these elements are defined. This list of indexable elements is used to:

- Contain geometry within a representation
- Attach properties to a representation
- Identify portions of a representation when expressing a representation identity
- Construct a subrepresentation from an existing representation

Several specialized indexable elements, e.g., hinge node faces, have been included to add higher order geometry to a grid representation, and are not available for other purposes.

Table 4—RESQML Indexable Elements and Applicable Representations

Indexable Elements	Applicable Representation(s)
cells	grids, wellbore frames
column edges	column-layer grids
columns	column-layer grids
contacts	surface frameworks
coordinate lines	column-layer grids
edges	triangulated sets, grids
edges per column	column-layer grids
enumerated elements	subrepresentations
faces	sealed volume frameworks, grids
faces per cell	grids
hinge node faces	grids (geometry only)
intervals	wellbore frames, column-layer grids
interval edges	column-layer grids

Table 4—RESQML Indexable Elements and Applicable Representations	
I0	IJK grids
I0 edges	IJK grids
J0	IJK grids
J0 edges	IJK grids
layers	column-layer grids
nodes	all representations
nodes per cell	grids
nodes per edge	grids
nodes per face	grids
patches	all representations
pillars	column-layer grids
radial origin polyline	IJK grid (geometry only)
regions	all representations
representation	all representations
subnodes	grids
triangles	triangulated sets

6.2.2 Multi-Dimensional Arrays and HDF5 Data Storage

Each element of a multi-dimensional array within a representation must have a well-defined 1D index, to allow elements to be uniquely referenced for properties, geometry, data storage or any other purposes, e.g., subrepresentations. The data ordering is uniquely specified at the representation level and this ordering is inherited by the array constructions for points and geometry.

For example:

- For a 2D array (N1 x N2) with indices I1=0,…,N1-1 and I2=0,…,N2-1, then the 1D index is I1+N1*I2.
- For a 3D array (N1 x N2 x N3) with indices I1=0,…,N1-1, I2=0,…,N2-1 and I3=0,…,N3-1, then the 1D index is I1+N1*I2+N1*N2*I3.

This ordering choice is sometimes called “fastest to slowest”, with the first index in the equation varying the fastest, and the last index varying the slowest. RESQML is not restricted to 3D arrays, for example, the “faces per cell” on an IJK grid follow a 4D (6 x NI x NJ x NK) array indexing.

HDF5 Data Storage. When stored in HDF5, the data storage order is the RESQML index order. It is very important to understand this relationship between indexing and data storage within RESQML. Index order for the elements within a representation is specified by the schema documentation, and this data order is preserved in the HDF5 data storage. However, because of how the HDF5 array storage works, this means that an N1 x N2 RESQML array is stored as a N2*N1 HDF5 array (N1 fastest, N2 slowest). To avoid confusion, use of the words “first” and “last” needs to clearly distinguish between the RESQML index calculation and the HDF5 data storage context. The important point: when viewed as an equivalent 1D array, the HDF5 data storage ordering and the RESQML index ordering are identical.

NOTE: For a brief introduction on implementing HDF5 in RESQML, see Appendix D (page 237).

Lattice Offsets. Geometry and properties use multi-dimensional lattice offset constructions for points and values, respectively. The ordering of the offsets follows the ordering of the indices in the multi-dimensional index calculation and hence is opposite to the ordering of the HDF5 data storage.

An example of the use of multi-dimensional arrays. The coordinate line nodes on a faulted grid, where N1=coordinateLineCount and N2=NKL. However, the dimensionality of an array may vary with context; for example, the coordinate lines themselves may be either a 1D or a 2D array. In the special case of an unfaulted grid, the coordinate lines are a 2D array indexed by NIL x NJL, and the coordinate line nodes are a 3D array indexed by NIL x NJL x NKL.

Lists. When points or multi-dimensional (count>1) property values are stored in HDF5, this introduces an additional dimension, which is always the fastest. For example:

- An N dimensional array of points3d is stored as an N*3 HDF5 array of coordinates.
- Alternatively, an N dimensional array of points2d, is stored as an N*2 HDF5 array of coordinates.
- An array of facies proportion curves, (count>1), is stored as an N*count HDF5 array of values.

BUSINESS RULE: To facilitate data validation and hyper-slabbing of the data, RESQML requires that data be stored with the maximum dimensionality possible. For the example of coordinate line nodes given earlier, this rule implies that instead of always using a 2D array format, which is possible, that a 3D array format is used for an unfaulted grid.

6.3 atches

A Patch is a mechanism in RESQML that provides a clear way of ordering indices to avoid ambiguity. For example, the representation of a horizon consists of 10 triangulated surfaces, to correctly represent the same horizon, the software importing or reading that horizon must know the indices within each of the 10 triangulated surfaces AND how the 10 triangulated surfaces are sequenced.

6.3.1 When to Use a Patch

Representations with unique indexing of their elements DO NOT require Patches. For example, a (lower order) corner-point grid has an indexing scheme that can be defined without using Patches. However, a RESQML general purpose (GP) grid (an unconstrained hybrid of any of the other RESQML grid types) is much more complex and variable, with no “natural” sequence. For a reader to correctly interpret a GP grid, the software that created the GP grid must:

- Explicitly define each Patch (specify the indices) that comprise the grid.
- Designate the correct order of the Patches.

If a representation includes indexable elements both specified within patches and external to patches, then Patch Index = 0 is defined to be the representation itself.

6.3.2 Characteristics of Patches

Patches have these characteristics, which must be followed by the software that creates the Patches (the “writer”):

- RESQML defines many types of Patches. Each Patch data object includes the word “patch” in its name, e.g., TrianglePatch.
- Each Patch must itself have a range of indexable elements.

6.4 Subrepresentations

A subrepresentation is a logical and ordered subset of an existing representation. It is itself a representation. Because RESQML has separated the representation concepts of topology, geometry, and property values, we can select a range of nodes, edges, faces, volumes, or any of the indexable elements from the topological support of a representation. By extracting such a list of simple topological element indices, we define a subrepresentation.

A subrepresentation may describe a different feature-interpretation using the same geometry or property as the "parent" representation. In this case, the only information exchanged is a set of potentially non-consecutive indices of the topological support of the representation.

6.5 Representation Identities

It is also possible to add semantics about the relationships between subrepresentations, even if they come from different representations. The table below describes different identity relationships. This type of relationship is commonly used to identify the contacts between representations in model description, but may also be used to relate the components of a grid (pillars) to those of a structural framework (faults).

Concept	Definition: A set of subrepresentations or representations):
Collocated (Sub)Representations	Is **Collocated** if there is bijection between the simple elements of all of the participating (sub)representations. This implies there is the same number of simple elements. The geometric location of each set of simple elements mapped through the bijection is intended to be identical *even if the numeric values of the associated geometries differ, i.e., due to loss of spatial resolution*.
Equivalent (Sub)Representations	Is **Equivalent** if there is a map giving an association between some of the simple topological elements of the participating (Sub)Representations.
Previously Collocated (Sub)Representations	Were **collocated** at some time in the geologic **past**, but not necessarily in the present day earth model.
Previously Equivalent (Sub)Representations	Were **equivalent** at some time in the geologic **past**, but not necessarily in the present day earth model.

6.6 Redefined Geometry Representations

RESQML provides us with the ability to modify the geometry of a representation. However, because geometry is central to the definition of a representation, we can only do this by creating a new representation based upon the existing representation. This capability supports a number of very useful cases:

- Time dependent geometry for structures that evolve in time (geomechanics, basin evolution)
- Related representations with one in depth and one in time
- Related representations with one in one coordinate reference system and one in another

Figure 6-1 shows the construction. Any representation with geometry may be selected as the supporting representation. The use of a “patch of geometry” construction allows grids with additional grid geometry to have all patches of their grid geometry redefined.

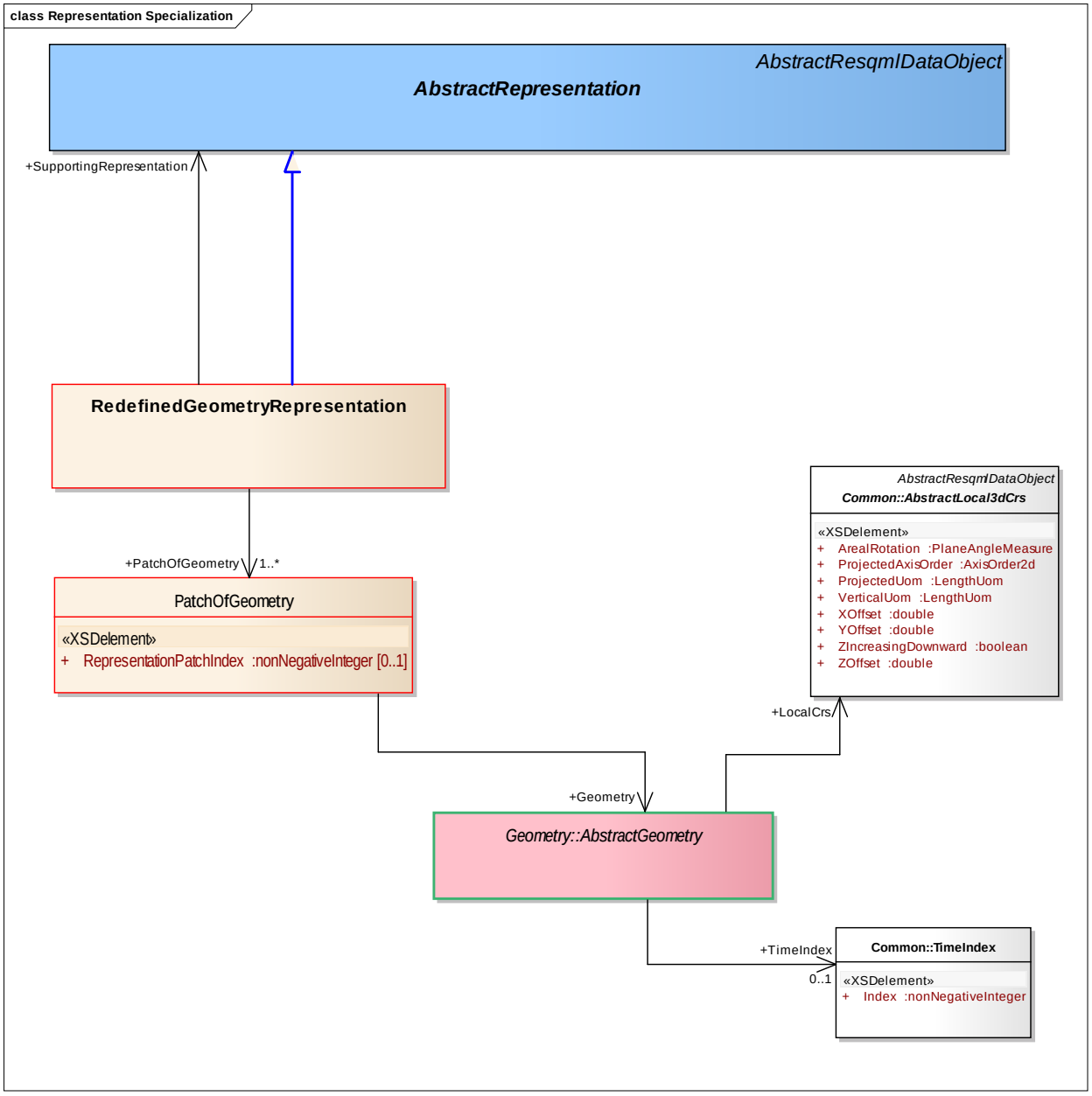


Figure 6-1—Redefined geometry representation.

6.7 Representation Set Representation

Representation set representations (**Figure 6-2**) are an indexed assemblage of individual representations. The representation index given is internal and defined in the context of a particular representation set interpretation instance. This representation index is implicit. It follows the order on which the representations are given in the XML instance by the software writer. This representation index is used in the non-sealed surface framework, sealed surface framework, and sealed volume framework.

Representation set representations are used to group together individual representations into a “bag” of representations. These “bags” do not imply any geologic consistency. For example, you can define a set of wellbore frames, a set of wellbore trajectories, and a set of blocked wellbores.

If the bag contains homogeneous individual representations, the "isHomogenous" Boolean may be set, and then the reader software need only read the first individual representation to understand the kinds of individual representations that are gathered in the set.

The representation set representation is also the parent class of the framework representations. Because the framework representations inherit from this class, they inherit the capability to gather individual representations into sealed and non-sealed surface framework representations, or sealed volume framework representations. The representation index is used to define the contact patches.

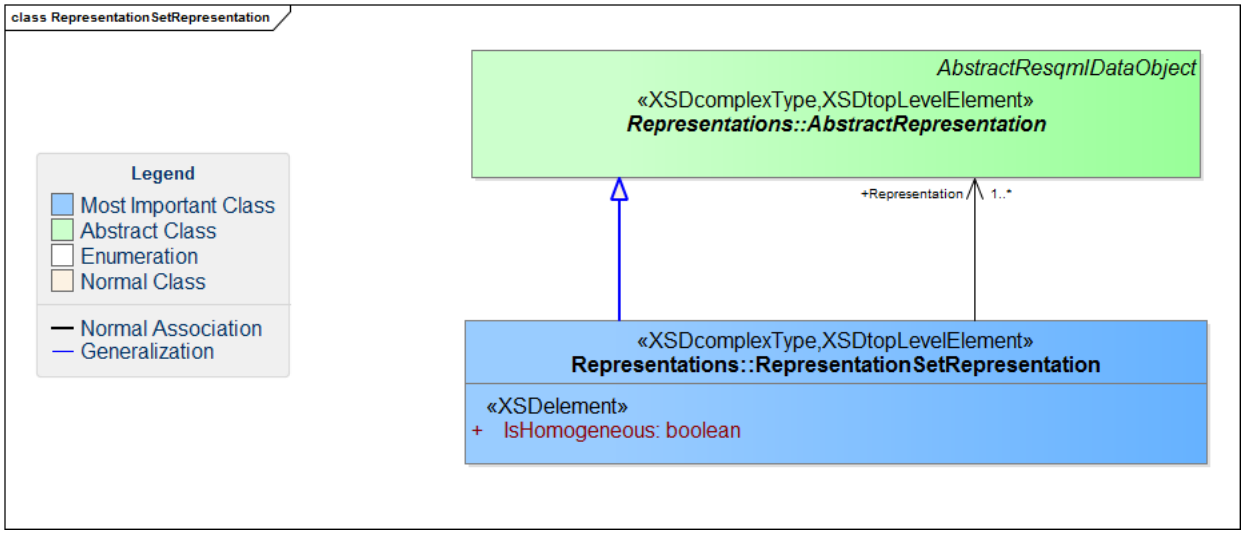


Figure 6-2—Representation set representation.

7 Geometry

RESQML has two main ways of implementing geometry:

- When geometry applies to the specification of a representation, then the methods described in this section are used.
- When geometry valued point properties are to be attached to an existing representation, then a particular type of property (points property) is used. For more information, see Section 8.3 (page 80).

This chapter describes general methods. For details on how geometry is applied to specific representations or data objects, refer to these chapters:

- For earth models, see Chapter 9 (page 82).
- For structural and stratigraphic representations, see Chapter 10 (page 107).
- For grids, see Chapter 11 (page 126).
- For wellbores, see Chapter 12 (page 197).
- For seismic, see Chapter 13 (page 212).

7.1 Overview

RESQML provides descriptions for the geometries of points, lines, and planes (**Figure 7-1**). These descriptions are in the context of a local depth or time 3D coordinate reference system, and to support time varying geometries, a time index. In the following text references to a Z coordinate are appropriate for use in a depth 3D coordinate reference system. If working in time, then Z is replaced by T.

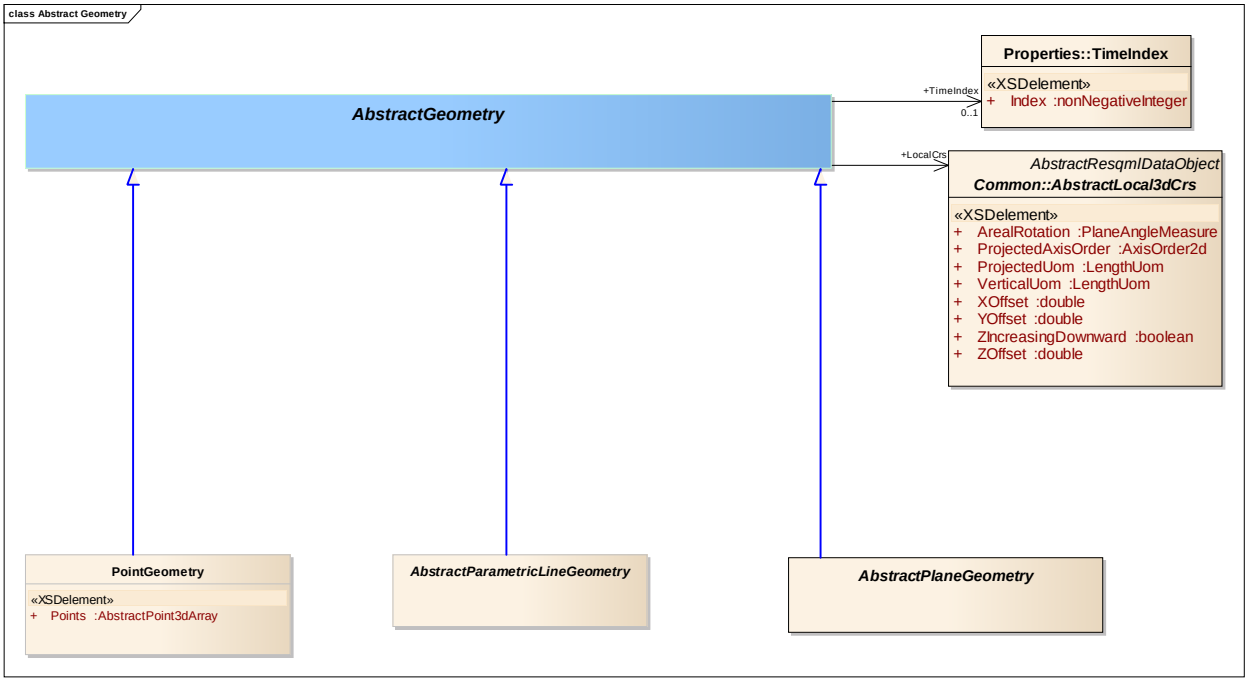


Figure 7-1—Class diagram showing geometries of points, lines, and planes.

Points are organized into arrays of 3D points, line geometry is parametric, and there are simple descriptions for horizontal or tilted plane geometry.

RESQML provides implicit geometric descriptions for the parametric points on a parametric line. A familiar example from the grid domain is the COORD/ZCORN description of an Eclipse grid coordinate line (**Figure 7-2**), in which a value for Z may be used to infer values for X and Y. RESQML includes vertical, piecewise linear, cubic and minimum-curvature spline parametric lines. Unlike the COORD/ZCORN

description, RESQML does not restrict the spline parameter to be depth. This allows support for over-turned geologic structures or for more general relationships.

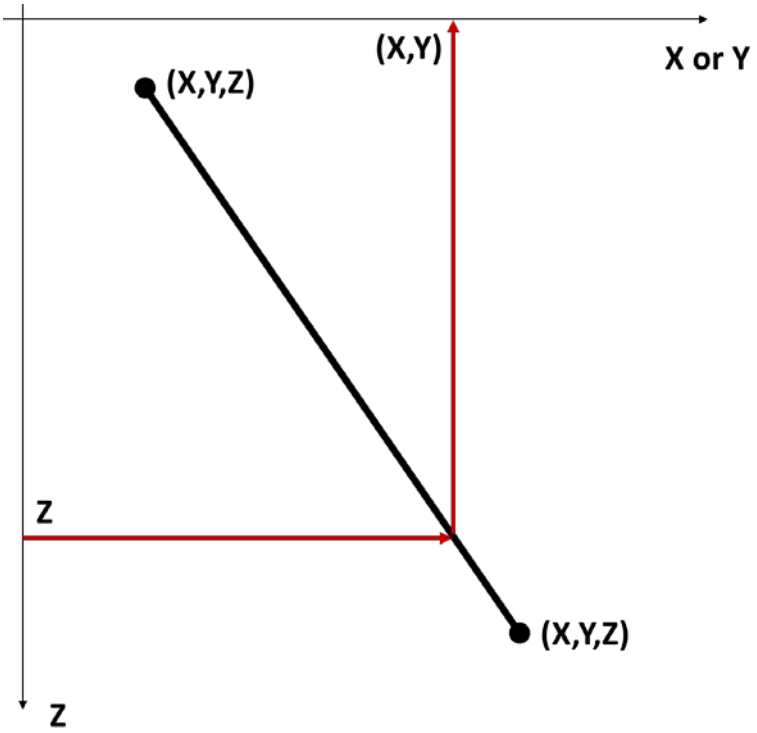


Figure 7-2—Eclipse COORD/ZCORN construction in which two (X,Y,Z) control points and a value for Z may be used to infer values for (X,Y).

The use of arrays for points and parametric lines is very similar to that of the RESQML property values. However, unlike properties, which are top-level data objects, geometry only occurs within a representation. As with the property arrays, the dimensions of these arrays are not specified within the schema geometry, but are inherited from their context within a representation.

7.2 Points, Lines, and Planes

Table 5 summarizes the different construction types available for the geometry of points, lines, and planes. Changes for this latest version of RESQML include a much richer list of construction types and a simplified (restricted) design that supports only HDF5 for explicit point arrays (previously both XML and HDF5 arrays were supported).

Table 5—Point, Line and Plane Geometry	
Construction Type	**Definition / Explanation**
Point Geometry	
Point3d HDF5 Array	Explicit HDF5 array of N*3 coordinates, (X,Y,Z)
Point2d HDF5 Array	Explicit HDF5 array of N*2 coordinates (X,Y) for a 3D point (X,Y,0)
Point3d ZValue Array	Points extracted from another representation, and then modified to have new Z coordinate values
Point3d Lattice Array	Points in a lattice created from a start point and offset vectors
Point3d From Representation Lattice Array	Points extracted from a representation, using a lattice of indices to space the sampling
Point3d Parametric Array	Points defined parametrically using parametric lines

Table 5—Point, Line and Plane Geometry	
Construction Type	**Definition / Explanation**
Line Geometry	
Parametric Line Geometry	Parametric line geometries are described in more detail in the next table
Parametric Line From Representation Geometry	Parametric line extracted from a representation
Plane Geometry	
Horizontal Plane Geometry	Definition of the infinite geometry of a horizontal plane provided by giving its unique Z value.
Titled Plane Geometry	Used to describe the infinite geometry of a potentially tilted plane from three points.

Point, line, and plane geometry are described in the following figures (**Figure 7-3, Figure 7-4, Figure 7-5**). Each individual construction is also described in the *RESQML Technical Reference Guide* (For a link to this document, see Section 1.4 (page 13).

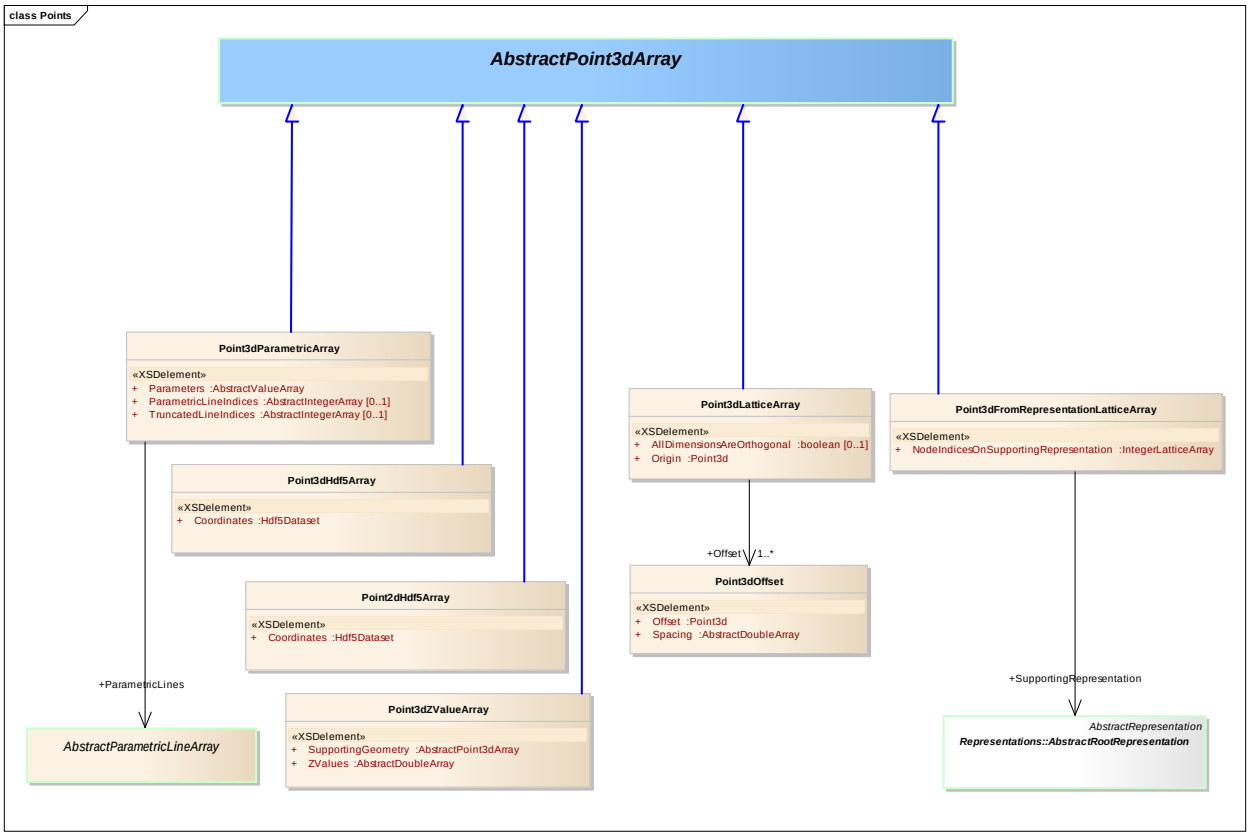


Figure 7-3—Class diagram showing the specification of point geometry organized into an array of 3D points.

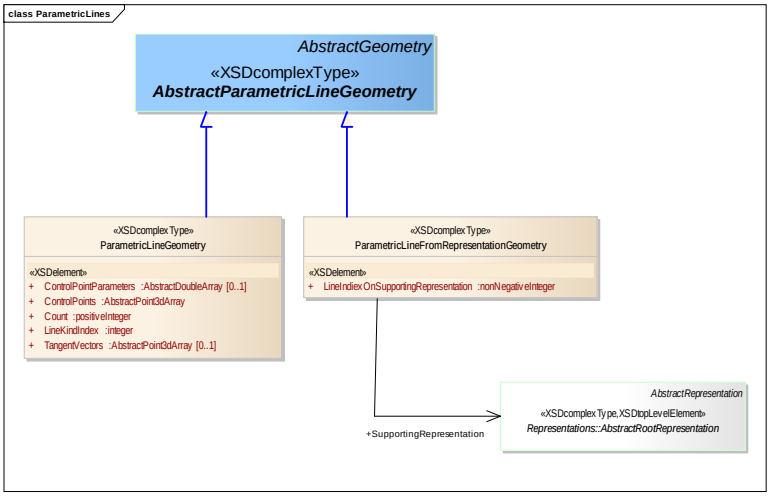


Figure 7-4—Class diagram showing the specification of parametric line geometry.

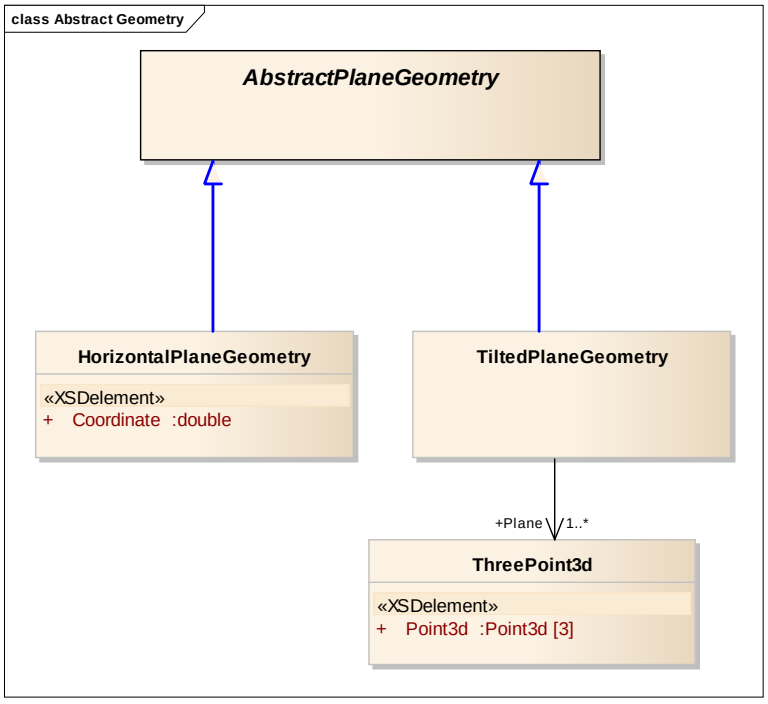


Figure 7-5—Class diagram showing the specification of plane geometry as horizontal or multiple tilted planes.

7.3 Parametric Points and Lines

A parametric line is essentially a vector-valued function. Given a parametric value *P* and the specification of a parametric line, what are the resulting values of X(P), Y(P), and Z(P) (or T(P)) in the Local 3D CRS?

This is a parametric description of the points on the line. The use of a parametric line provides a more compact means of specifying point geometry. As importantly, it provides interpolated geometric information at higher resolution than the spacing of the control points on a piecewise linear line, which supports more accurate intersection calculations and geometric refinement.

Table 6 lists and describes the available types of parametric lines and the control points needed for each type of line.

Table 6—Description of RESQML Parametric Lines		
Parametric Line	**No. of Control Point(s)**	**Description**
Vertical	One control point: (*X,Y,-*)	Parametric value is *Z* => *(X,Y,Z).*
Linear Spline 1 or more intervals	Two or more knots, each with a control point: $(P,X,Y,Z)_i$, *i=1,2,…*	Piecewise linear interpolation in (*X,Y,Z*) as a function of the parametric value *P.*
Natural Cubic Spline 1 or more intervals	Two or more knots, each with a control point: $(P,X,Y,Z)_i$, *i=1,2,…*	Piecewise cubic interpolation in *(X,Y,Z)* as a function of the parametric value P, subject to the additional constraints of continuous first and second derivatives at the knots, and vanishing second derivative at the edge knots.
Cubic Spline 1 or more intervals	Two or more knots, each with a control point and a tangent vector. Tangent vectors are defined as the derivative of position with respect to the parameter *P*.	Piecewise cubic interpolation in *(X,Y,Z)* as a function of the parametric value *P*, given the additional constraint of specified tangent vectors at the knots.
Z Linear Cubic Spline 1 or more intervals	Two or more knots, each with a control point: $(P,X,Y,Z)_i$, *i=1,2,…*	Linear spline interpolation in *Z* as a function of the parametric value *P.* Natural cubic spline interpolation in *(X,Y)* as a function of the parametric value *P.*
Minimum-Curvature Spline 1 or more intervals (knots = stations)	One control point for the first knot. Two or more knots, each with a tangent vector. Tangent vectors are defined as the derivative of position with respect to the parameter *P*.	Piecewise minimum curvature interpolation in *(X,Y,Z)* as a function of the parametric value *P*, given the constraint of specified tangent vectors at the knots. Curvature is defined in the units of measure of the local 3d CRS, without unit conversion, so care must be taken when using mixed units.

With the exception of the vertical parametric line, the parameter itself has no specific interpretation, nor is there any requirement that the same parametric values be used along different lines in a parametric line array. However, it is important that the parametric values associated with the control points and the parametric values used for interpolation are consistent. When used to describe the geometry of a wellbore trajectory, the parameter is interpreted as the measured depth along the wellbore. In this case, the specification of the measured depth units of measure and datum location are part of the wellbore trajectory representation, and not the geometry itself.

NOTE: As a companion to this documentation on cubic splines, a spreadsheet (titled *20131223 RESQML Cubic Splines.xslx*) is included with the download of the RESQML standard. The spreadsheet allows you to see the equations described here and experiment with different input values and examine the results.

7.3.1 Cubic Splines

There are many ways to describe a cubic spline. The current description draws heavily upon the description in *Numerical Recipes* (Press et al. 1992), but with some variations that are in use within our domain. For a spline, each interval $(i = 1, \ldots, N)$ is parameterized in terms of a parameter *p*, or equivalently a normalized parameter ξ, $\xi = (p - p_{i-1})/\Delta p$, $\Delta p = p_i - p_{i-1}$. The parameter takes on the values of ξ*=0* and ξ*=1* at the two knots that bound the interval. We may express a cubic spline in terms of its function values and *second* derivatives, specified at the two knots. Spline derivatives are specified with respect to the parameter *p*, but need to be converted to a derivative with respect to ξ within an interval,

$\frac{d\vec{x}}{d\xi} = \Delta p \frac{d\vec{x}}{dp}$ and $\frac{d^2\vec{x}}{d\xi^2} = (\Delta p)^2 \frac{d^2\vec{x}}{dp^2}$, when using the following table of basis functions. Although the derivatives with respect to the parameter *p* may be continuous at the knots, because of the scaling by Δp, the normalized derivatives with respect to ξ need not be. The interpolant for a cubic spline can then be written as a superposition of four basis functions (**Figure 7-6**).

Basis	$\phi(\xi)$	$\phi(0)$	$\phi(1)$	$\phi''(0)$	$\phi''(1)$
1	$1-\xi$	1	0	0	0
2	ξ	0	1	0	0
3	$-\frac{1}{6}\xi(1-\xi)(2-\xi)$	0	0	1	0
4	$-\frac{1}{6}\xi(1-\xi^2)$	0	0	0	1

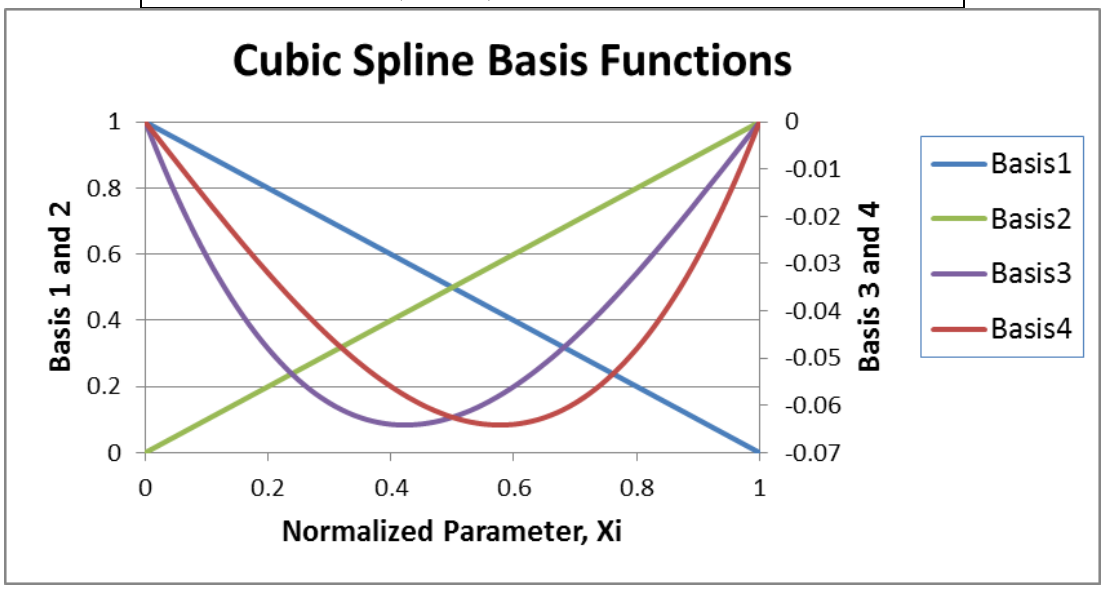


Figure 7-6—Cubic Spline Basis Functions.

Specifically, within an interval we have:

$$\vec{x}(\xi) = \vec{x}_0 \cdot \phi_1(\xi) + \vec{x}_1 \cdot \phi_2(\xi) + \left(\frac{d^2\vec{x}}{d\xi^2}\right)_0 \cdot \phi_3(\xi) + \left(\frac{d^2\vec{x}}{d\xi^2}\right)_1 \cdot \phi_4(\xi)$$

$$= \vec{x}_0 \cdot (1-\xi) + \vec{x}_1 \cdot (\xi) - \frac{1}{6}(\xi)(1-\xi) \cdot \left\{ \left(\frac{d^2\vec{x}}{d\xi^2}\right)_0 \cdot (2-\xi) + \left(\frac{d^2\vec{x}}{d\xi^2}\right)_1 \cdot (1+\xi) \right\}$$

For instance, a function that takes on the values of *a* and *b* at the interval knots but with vanishing second derivatives would be given by $a \cdot (1-\xi) + b \cdot (\xi) = a + (b-a) \cdot \xi$. With non-zero second derivatives, a cubic equation would arise. Any cubic spline may be expressed in this fashion, and all cubic splines rely upon the specification of the control points at the knots. However, different cubic spline implementations arise depending upon the specification of the derivatives at the knots.

7.3.2 Tangential Cubic Splines

For tangential cubic splines, the control points and the tangential derivatives, $\frac{d\vec{x}}{dp}$ are specified at each knot. The function is everywhere continuous and differentiable, but the second derivatives may be discontinuous at the knots. Using the cubic functional form within an interval, these four constraints may be used to determine the second derivatives at the interval edges.

$$\left(\frac{d^2\vec{x}}{d\xi^2}\right)_0 = (6\Delta p)\cdot\left\{\frac{(\vec{x}_1-\vec{x}_0)}{\Delta p}-\frac{2}{3}\left(\frac{d\vec{x}}{dp}\right)_0-\frac{1}{3}\left(\frac{d\vec{x}}{dp}\right)_1\right\}$$

$$\left(\frac{d^2\vec{x}}{d\xi^2}\right)_1 = (-6\Delta p)\cdot\left\{\frac{(\vec{x}_1-\vec{x}_0)}{\Delta p}-\frac{1}{3}\left(\frac{d\vec{x}}{dp}\right)_0-\frac{2}{3}\left(\frac{d\vec{x}}{dp}\right)_1\right\}$$

Hence:

$$\left\{\left(\frac{d^2\vec{x}}{d\xi^2}\right)_0\cdot(2-\xi)+\left(\frac{d^2\vec{x}}{d\xi^2}\right)_1\cdot(1+\xi)\right\}$$

$$=6\cdot(1-\xi)\cdot\left\{(\vec{x}_1-\vec{x}_0)-\Delta p\cdot\left(\frac{d\vec{x}}{dp}\right)_0\right\}-6\cdot(\xi)\cdot\left\{(\vec{x}_1-\vec{x}_0)-\Delta p\cdot\left(\frac{d\vec{x}}{dp}\right)_1\right\}$$

Notice that when written in this form, that zero values for Δp are permitted. This type of spline appears in many interactive graphics packages to provide a smooth interpolant with specified slopes at the knots.

7.3.3 Natural Cubic Splines

For a natural cubic spline, only the control points are specified at each knot. The function is everywhere continuous and differentiable, with continuous second derivatives at the knots. The requirement of a continuous second derivative is sufficient to uniquely define the derivatives. For the edge knots, by definition, the second derivative vanishes. For the internal knots, the second derivative is determined from a quadratic fit through each triple of knots, as shown in **Figure 7-7**.

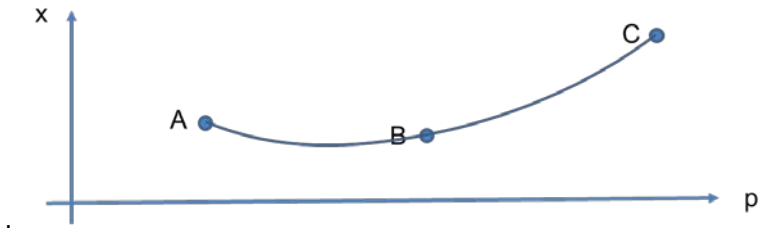


Figure 7-7—Second derivative at a knot.

The quadratic functional form that is used in the derivation, and the first and second derivatives at the center knot are as follows.

$$\vec{x}(p)=\vec{x}_B+(\vec{x}_A-\vec{x}_B)\frac{(p_B-p)(p_C-p)}{(p_B-p_A)(p_C-p_A)}+(\vec{x}_C-\vec{x}_B)\frac{(p-p_A)(p-p_B)}{(p_C-p_A)(p_C-p_B)}$$

$$\frac{d\vec{x}}{dp}(p_B)=\frac{(\vec{x}_B-\vec{x}_A)}{(p_B-p_A)}\cdot\frac{(p_C-p_B)}{(p_C-p_A)}+\frac{(\vec{x}_C-\vec{x}_B)}{(p_C-p_B)}\cdot\frac{(p_B-p_A)}{(p_C-p_A)}$$

$$\frac{d^2\vec{x}}{dp^2}(p_B)=\frac{2}{(p_C-p_A)}\left(\frac{(\vec{x}_C-\vec{x}_B)}{(p_C-p_B)}-\frac{(\vec{x}_B-\vec{x}_A)}{(p_B-p_A)}\right)$$

The quadratic fit shows that the best estimate of the slope at the intermediate knot is a weighted average of forward and backward differences, which reduces to a central difference for evenly spaced data. The last of these equations is used in the calculation of the interpolant for the natural cubic spline. Again, care must be taken in their normalization before using the table of basis functions.

7.3.4 Z Linear Cubic Splines

There is one interesting variation on the cubic spline in use in our domain: the so-called *Z Linear Cubic Spline*. As shown in **Figure 7-8**, the resulting interpolant is bounded in Z where a cubic spline need not be.

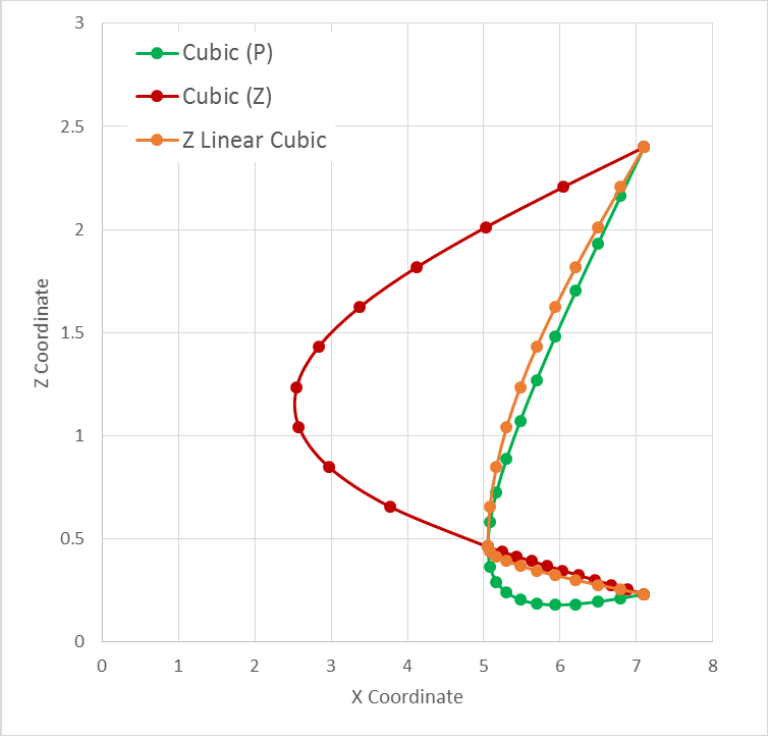


Figure 7-8—Z Linear Cubic and cubic splines over two intervals.

This variation mixes a linear spline interpolant in Z with a natural cubic spline interpolant in (X,Y). It always appears as a natural cubic spline. The figure also include two variations on the cubic splines. The green curve corresponds to the standard natural cubic spline interpolation from Numerical Recipes. The red curve is a cubic spline as a function of the Z coordinate. The Z Linear Cubic Spline is a function of the parameter P, and has continuous derivatives at the knots when expressed as a function of P, but not as a function of Z.

7.3.5 Minimum-Curvature Splines

The minimum-curvature interpolation method, also known as the circular arc method, is used to describe the shape of a wellbore trajectory interpolated between stations (knots) on which the dip and azimuth are specified. The current exposition largely follows that of Taylor and Mason (1972), Zaremba (1973) and the more recent discussions by Sarawyn and Thorogood (2005), suitably generalized beyond the wellbore trajectory domain. There are a number of differences between this mathematical exposition and industry practice:

- The current calculation is performed in the local 3D projected CRS, and ignores curvature effects which may be important, especially for extended reach wells.
- The current calculation does not assume that the parameterization of the spline is with respect to the measured depth along the trajectory. As a consequence, just as with all of the other RESQML

splines, the tangent vectors (derivative of position with respect to parameter) must be specified in the local 3D CRS, and need not be unit vectors specified solely by dip and azimuth.

  - In the context of a well trajectory representation, the local 3D CRS is usually not rotated with respect to the projected CRS. As a consequence, the local Y axis is aligned with the projected North direction.

- This generalization allows an interpolant to be defined with mixed units of measure. However, no unit conversions are implied so care must be taken in such cases.

The algorithm is posed as follows. Given an initial station for which we know position, measured depth (arc length), and tangent vector, and a next station for which we know measured depth and tangent vector, what is the position of the next station based upon a minimum-curvature interpolant? Translating from station to spline knot, from measured depth to parameter values, and from dip and azimuth angles to tangent vectors, we have the following expression for the minimum-curvature trajectory.

$$\vec{x}(\xi) = \vec{x}_0 + \Delta p \cdot \left\{ \left(\frac{d\vec{x}}{dp} \right)_0 \frac{(1-\cos(\xi\psi))}{\psi \sin\psi} + \left(\frac{d\vec{x}}{dp} \right)_1 \frac{(\cos((1-\xi)\psi) - \cos\psi)}{\psi \sin\psi} \right\}$$

Here, ψ is defined by $\cos\psi = \left(\frac{d\vec{x}}{dp} \right)_0 \bullet \left(\frac{d\vec{x}}{dp} \right)_1 \Big/ \left\| \left(\frac{d\vec{x}}{dp} \right)_0 \right\| \left\| \left(\frac{d\vec{x}}{dp} \right)_1 \right\|$. The next position is given by $\xi = 1$:

$$\vec{x}_1 = \vec{x}_0 + \Delta p \frac{(1-\cos\psi)}{\psi \sin\psi} \left\{ \left(\frac{d\vec{x}}{dp} \right)_0 + \left(\frac{d\vec{x}}{dp} \right)_1 \right\}.$$

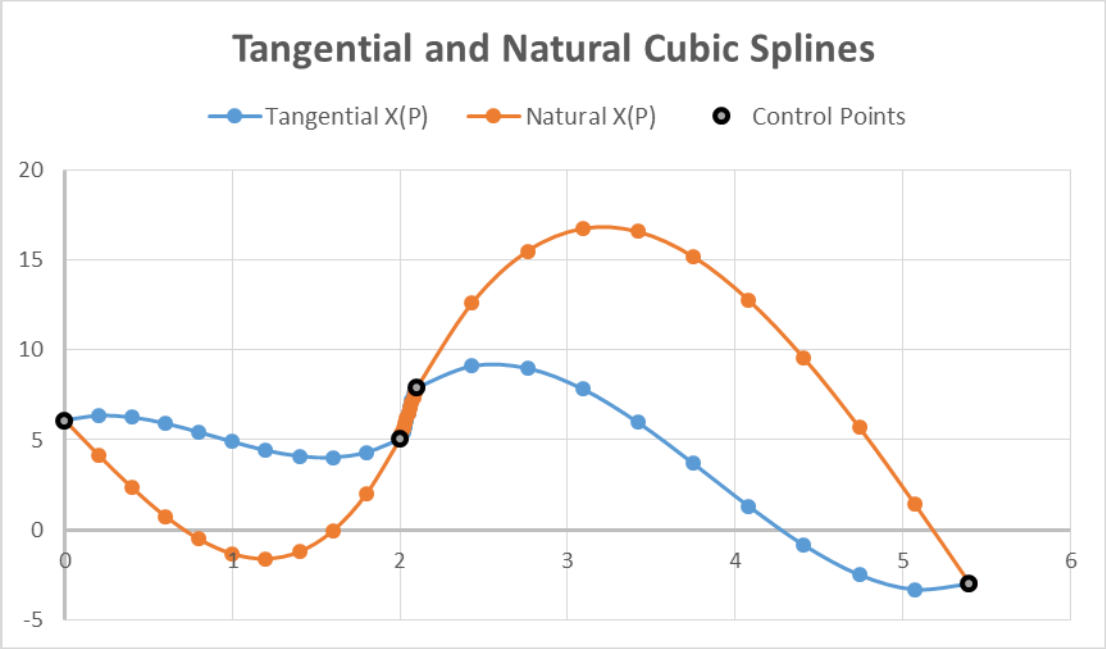
If the two tangents vectors are close to parallel then ψ will be close to 0, and some care has to be taken when evaluating these expressions. In that limit:

$$\frac{(1-\cos(\xi\psi))}{\psi \sin\psi} \to \frac{\xi^2}{2} \quad \frac{(\cos((1-\xi)\psi) - \cos\psi)}{\psi \sin\psi} \to \frac{1-(1-\xi)^2}{2} \quad \frac{(1-\cos\psi)}{\psi \sin\psi} \to \frac{1}{2}$$

Additional higher order terms in ψ may also be included to improve upon this approximation. Again, in the context of a wellbore trajectory representation, *p* is interpreted as the measured depth, Δp as the incremental measured depth, and the tangent vectors will be unit vectors.

7.3.6 Example: Tangential and Natural Cubic Splines

INPUT		
P	X	dX/dP
0	6.1	2.3
2	5.05	5
2.1	7.9	6
5.4	-3	3



Left (Xi=0)			Natural	Right (Xi=1)			Natural							Tangential	Natural
P	X	d2X/dXi2	d2X/dXi2	P	X	d2X/dXi2	d2X/dXi2	Xi	P	BASIS1	BASIS2	BASIS3	BASIS4	X(P)	X(P)
0	6.1	-44.7	0	2	5.05	55.5	110.5714	0	0	1	0	0	0	6.1	6.1
0	6.1	-44.7	0	2	5.05	55.5	110.5714	0.1	0.2	0.9	0.1	-0.0285	-0.0165	6.3532	4.170571
0	6.1	-44.7	0	2	5.05	55.5	110.5714	0.2	0.4	0.8	0.2	-0.048	-0.032	6.2596	2.351714
0	6.1	-44.7	0	2	5.05	55.5	110.5714	0.3	0.6	0.7	0.3	-0.0595	-0.0455	5.9194	0.754
0	6.1	-44.7	0	2	5.05	55.5	110.5714	0.4	0.8	0.6	0.4	-0.064	-0.056	5.4328	-0.512
0	6.1	-44.7	0	2	5.05	55.5	110.5714	0.5	1	0.5	0.5	-0.0625	-0.0625	4.9	-1.33571
0	6.1	-44.7	0	2	5.05	55.5	110.5714	0.6	1.2	0.4	0.6	-0.056	-0.064	4.4212	-1.60657
0	6.1	-44.7	0	2	5.05	55.5	110.5714	0.7	1.4	0.3	0.7	-0.0455	-0.0595	4.0966	-1.214
0	6.1	-44.7	0	2	5.05	55.5	110.5714	0.8	1.6	0.2	0.8	-0.032	-0.048	4.0264	-0.04743
0	6.1	-44.7	0	2	5.05	55.5	110.5714	0.9	1.8	0.1	0.9	-0.0165	-0.0285	4.3108	2.003714
0	6.1	-44.7	0	2	5.05	55.5	110.5714	1	2	0	1	0	0	5.05	5.05
2	5.05	13.9	0.276429	2.1	7.9	-13.7	-0.18708	0	2	1	0	0	0	5.05	5.05
2	5.05	13.9	0.276429	2.1	7.9	-13.7	-0.18708	0.1	2.01	0.9	0.1	-0.0285	-0.0165	5.1649	5.330209
2	5.05	13.9	0.276429	2.1	7.9	-13.7	-0.18708	0.2	2.02	0.8	0.2	-0.048	-0.032	5.3912	5.612718
2	5.05	13.9	0.276429	2.1	7.9	-13.7	-0.18708	0.3	2.03	0.7	0.3	-0.0595	-0.0455	5.7013	5.897064
2	5.05	13.9	0.276429	2.1	7.9	-13.7	-0.18708	0.4	2.04	0.6	0.4	-0.064	-0.056	6.0676	6.182785
2	5.05	13.9	0.276429	2.1	7.9	-13.7	-0.18708	0.5	2.05	0.5	0.5	-0.0625	-0.0625	6.4625	6.469416
2	5.05	13.9	0.276429	2.1	7.9	-13.7	-0.18708	0.6	2.06	0.4	0.6	-0.056	-0.064	6.8584	6.756493
2	5.05	13.9	0.276429	2.1	7.9	-13.7	-0.18708	0.7	2.07	0.3	0.7	-0.0455	-0.0595	7.2277	7.043554
2	5.05	13.9	0.276429	2.1	7.9	-13.7	-0.18708	0.8	2.08	0.2	0.8	-0.032	-0.048	7.5428	7.330134
2	5.05	13.9	0.276429	2.1	7.9	-13.7	-0.18708	0.9	2.09	0.1	0.9	-0.0165	-0.0285	7.7761	7.615771
2	5.05	13.9	0.276429	2.1	7.9	-13.7	-0.18708	1	2.1	0	1	0	0	7.9	7.9
2.1	7.9	-164.4	-203.726	5.4	-3	144.6	0	0	2.1	1	0	0	0	7.9	7.9
2.1	7.9	-164.4	-203.726	5.4	-3	144.6	0	0.1	2.43	0.9	0.1	-0.0285	-0.0165	9.1095	12.6162
2.1	7.9	-164.4	-203.726	5.4	-3	144.6	0	0.2	2.76	0.8	0.2	-0.048	-0.032	8.984	15.49887
2.1	7.9	-164.4	-203.726	5.4	-3	144.6	0	0.3	3.09	0.7	0.3	-0.0595	-0.0455	7.8325	16.75173
2.1	7.9	-164.4	-203.726	5.4	-3	144.6	0	0.4	3.42	0.6	0.4	-0.064	-0.056	5.964	16.57849
2.1	7.9	-164.4	-203.726	5.4	-3	144.6	0	0.5	3.75	0.5	0.5	-0.0625	-0.0625	3.6875	15.1829
2.1	7.9	-164.4	-203.726	5.4	-3	144.6	0	0.6	4.08	0.4	0.6	-0.056	-0.064	1.312	12.76868
2.1	7.9	-164.4	-203.726	5.4	-3	144.6	0	0.7	4.41	0.3	0.7	-0.0455	-0.0595	-0.8535	9.539554
2.1	7.9	-164.4	-203.726	5.4	-3	144.6	0	0.8	4.74	0.2	0.8	-0.032	-0.048	-2.5	5.699247
2.1	7.9	-164.4	-203.726	5.4	-3	144.6	0	0.9	5.07	0.1	0.9	-0.0165	-0.0285	-3.3185	1.451487
2.1	7.9	-164.4	-203.726	5.4	-3	144.6	0	1	5.4	0	1	0	0	-3	-3

Figure 7-9—Example tangential and natural cubic splines over three intervals.

7.4 References

Press, W.H., Teukolsky, S.A., Vetterling, W.T. & Flannery, B.P. (1992). Numerical Recipes, Cambridge University Press

Sawaryn, S. J., & Thorogood, J. L. (2005). A Compendium of Directional Calculations Based on the Minimum Curvature Method. Society of Petroleum Engineers. doi: http://dx.doi.org/10.2118/84246-PA

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Zaremba, W. A. (1973). Directional Survey by the Circular Arc Method. Society of Petroleum Engineers. doi: http://dx.doi.org/10.2118/3664-PA

8 Properties

This chapter provides an overview of how properties are attached to representations, and in one particular case, how geometry is attached. **Figure 8-1** below shows the Properties class diagram.

8.1 Overview of How it Works

A **property** is a group of values (array of values) at different locations in the model. Inside a single property, each individual value is attached to a single type of element in the representation—either its topological elements, such as nodes or cells, or bigger elements such as the entire representation or large parts of it, through subrepresentations. For more information on representations, see Chapter 6 (page 59).

Each property is also associated with a single **property kind**, which provides global semantics about the meaning of these values (for example, porosity, permeability, saturation, etc.). Properties can also be associated with **facets**, which provide additional context for the values. For example, RESQML has a facet for condition of acquisition, indicating if a temperature or pressure value is a surface reading or a reservoir reading (for more information, see Section 8.2.2 (page 80)).

It is common in subsurface/earth modeling workflows to follow the evolution of some properties through time or to consider them together as a group of properties. Each property inside the group can be attached to the same or different representations and the same or different property kinds. To capture this information, RESQML provides the notion of:

- time series (Section 8.5 (page 81))
- property sets (Section 8.4 (page 81))

Each continuous property is associated with a unit of measure (UOM) providing the context for individual values. However, a property's UOM must be compatible with the UOM of its corresponding property kind (see 8.2.1 (page 79)). Each property kind should be derived from a given **quantity class** (in the Energistics common schema; see Section 4.2 (page 40)).

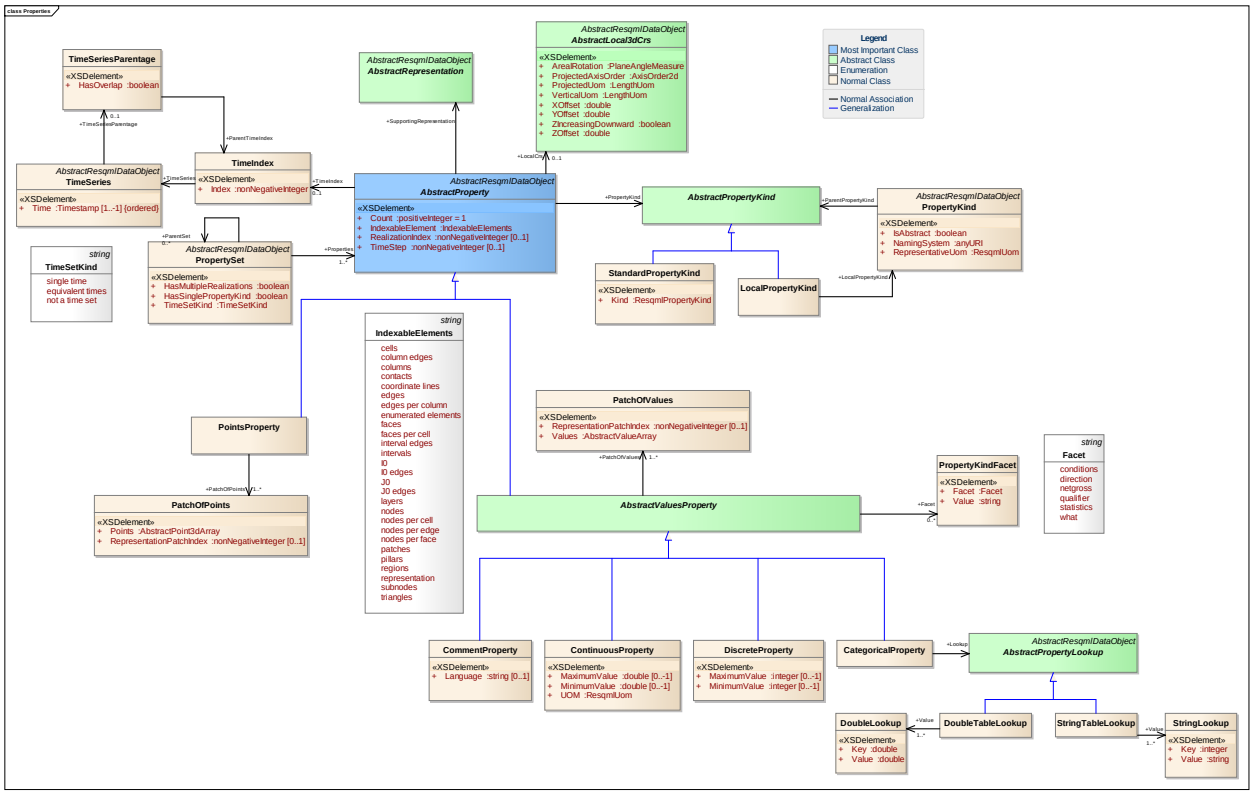


Figure 8-1—Properties class diagram.

8.2 Property

In RESQML, all subsurface or surface values tied to specific topological locations (or indexable elements) in a model are carried by any concrete data object that derives from abstract property (contained in the properties package) attached to one or more representations. A representation can have several properties and provides the indexable elements for these lists of values (for more information on indexable elements, see Section 6.2 (page 60).

In some cases, geometric information also must be "attached" to a specific location in a model, but the treatment of geometric points is almost identical to that of property values. For more information, see Section 8.2.3 (page 80).

This section provides an overview of how properties and geometric information are attached to RESQML models.

The value locations are based on three elements:

- The representation supporting the property values.
- The type of elements on which the values are stored.
- One index that uniquely specifies a given element. For a given representation type, each element type is associated with an indexing scheme that allows you to identify any particular element in the representation. The indexing scheme provides a range (0… number of elements) that defines the order inside an array (for more information, see Section 6.2.2 (page 61).
  - When local values are scalar, the array is 1D.
  - Else, the array is 2D and (1) the slowest (first) array dimension is the number of elements in the representation, while (2) the fastest (last) dimension is the number of values per element. The list of element types available is given as a finite list, but this list may be restricted according to the type of representation.

The storage of the value array can be fully explicit inside an HDF5 file, or implicit. Implicit storage can use constant or linear equations based on indexing. The list of values is separated in a patch of values for each patch of the representation. The patch of values contains an index allowing the mapping to the corresponding representation patch.

The stored values are either of type double, integer, character, Boolean or an index that maps to either a string or a table. Each data type corresponds to a specific XML type (**Table 7**) based on the abstract property value type.

Table 7—XML Types Corresponding to Data Types

Type	Corresponding Data Type / Description
ContinuousProperty	Contains double values; most common type of property used for storing rock or fluid attributes. Stores min and max values so that the value range can be known before accessing all values. Also contains a unit of measure that can be different from the unit of measure of their property type, but must be convertible into this unit.
DiscreteProperty	Contains discrete integer values; typically used to store any type of index. Stores min and max so that the value range can be known before accessing all values.
CategoricalProperty	Contains discrete integer values. However these index values are just a proxy for the most complex types, such as string or table. Associated with a lookup structure: String lookup associates indices to a string in a table of strings. Example of use: storage of facies properties, where a facies index is associated with a facies name. Table lookup associates indices to a cell inside a table of values. Example of use: storage of indices associated with empirical tables, such as PVT table.
CommentProperty	Contains strings of character. Used to capture comments or annotations associated with a given element type in a data object, for example, including comments on specific location on a well path. The language (e.g., English, French, etc.) used in the comment is included in property values.

8.2.1 Property Kind

Property kinds carry the semantics of the list of values. They are used to identify if the values are, for example, representing porosity, length, stress tensor, etc. RESQML includes a list of standard property names that represent the basis for the commonly used properties in the E&P subsurface workflow.

RESQML has these property kinds:

- **RESQML "well-known" kinds**. A finite list of well-known kinds (for example, length, volume, and permeability). During a RESQML-enabled data exchange, each property kind MUST be derived (either directly or indirectly) from the names listed in the RESQML property kind enumerations, which are included in the properties package (ResqmlPropertyKind). This enumeration has been generated from the ResqmlPropertyKind enumList contained in the enumValuesResqml.xml file located in the energyml\data\resqmlv2\v2.0.1\ancillary folder of the XML schemas. In this XML file, you can find out deprecated information about the RESQML "well-known" kinds" such as the respective representative units of measure of these property kinds. NOTE: This information should not be used in any validation process because it may contradict the quantity class information provided by the schema.

Use of well-known kinds allows programmers implementing RESQML to map their software property names to the RESQML standard property software names, which makes it possible for RESQML-enabled software to translate property names between each other.

For example, if *Software A* names “porosity” as POR and *Software B* names it PORO, and both *A* and *B* are RESQML enabled, then the software can recognize that these properties are equivalent because they refer to the same RESQML parent property, e.g., "porosity". They can also exchange without ambiguity the numerical values that are recorded because those values will be in the same unit of measure.

- **Company- or user-specific kinds**. Companies or organizations may specify their own property kinds. When specifying your own property kinds, you MUST observe these conventions:
  - The user-specified name must always be based on another property kind, well-known or not (e.g., a custom kind may be based on another custom kind, which is ultimately based on a well-known kind).
  - To identify the company or group that defines the property kind, a naming system must be used. For example, urn:resqml:mycompany.com:myproduct
  - A reference unit must be provided and requires the associated property value units to be compatible through conversion.
  - All of this information must be explicitly defined in the files being transferred.

8.2.2 Facets

In addition to property kind to define semantics, a facet is a mechanism that gives some context about the nature of the property. Each property kind can be associated with as many property kind facets as needed. Facets can represent any of the following:

- *Conditions* of acquisition, which, for example, allows distinguishing between surface conditions and reservoir conditions.
- *Direction*, which, for example, can indicate vertical or horizontal permeability.
- *NetGross*, which, for example, indicates the difference between net and gross volumes.
- *Statistics* can be used to indicate if values are minimum, maximum, average, etc.
- *What,* which indicates the element that is measured, for example, in a mineral concentration measurement, the mineral name.
- *Qualifier* is used to capture any other context, that doesn’t' fit into one of the above types.

8.2.3 Units of Measure

The RESQML-recognized units of measure are listed in the Properties package in the Resqmluom enumeration. Both property and property kind are associated with a UOM. The representative UOM of a property kind is a typical UOM associated with a property kind; it is constrained by the measure class that the property kind is based on. Often, it corresponds with SI units, but it's not required. The UOM of a given property must be consistent with the representative UOM of its property kind.

8.3 Geometrical Information Stored as a Property

Sometimes it is necessary to store geometrical information about the elements of a representation, for example, for former locations, height, distance, etc. Specific examples include descriptions such as a depth of the oil-water contact, or throw of a fault from the footwall to the hanging wall.

To use property capabilities for this type of data requires a coordinate system, which is why an optional link between properties and a local coordinate system is available in the data model.

When spatial locations need to be stored, a specific kind of property is used: points property, which is based on an array of points instead of an array of values.

8.4 Property Set

Property values are often collected to indicate that they should be considered together as a set, for example, to show they are part of the same simulator output. To provide this type of grouping, RESQML has a property set.

Property sets have these characteristics:

- Sets are not exclusive; a property (group of values) can belong to several sets.
- Sets can be related through a parenting relationship. For example, a parent group representing the entire simulator output can be made up of several smaller groups corresponding to each time step.
- Sets can contain semantic information; for example, you can specify if all the contained property values correspond to a single property kind, or if they correspond to multiple realizations, at similar or equivalent times.

8.5 Time Information: Time Step and Time Series

Properties can be associated with optional time information. These types of time information are available:

- **Time Step.** Directly related to the time step of a flow simulator, which is an index that is only defined in the context of a specific simulation data set.
- **Time Series.** A series of ordered time stamps (a time produced by software when something significant happens, such as saving a file). A series can itself be the continuation of another parent time series, with which it can overlap. A property value references an entry in a time series through its time index.

9 Earth Model

This chapter provides an overview of earth model features and earth model interpretations and how they may be used and constructed using RESQML.

This chapter explains some basic concepts and provides some examples for creating and updating an earth model interpretation—following the feature/interpretation/representation/property knowledge hierarchy defined in Chapter 5 (page 51)—beginning with structural and stratigraphic features, then adding related interpretations and representations, including related geometry.

This concept of earth model interpretation is the most important to ensure an update of the earth model when more information (new data) are acquired during the lifecycle of a prospect.

The goal is to transfer the information built up from each step of the modeling process, which includes the semantic and numeric information necessary to describe a subsurface area for development and/or reservoir management activities.

9.1 What is a RESQML Earth Model and how can it be Used?

The RESQML earth model has two main parts:

- earth model feature
- earth model interpretation (formally, a *feature-interpretation*, but referred to as *interpretation* for brevity)

9.1.1 Earth Model Feature

An earth model feature is a RESQML geologic feature organization, which is the entry point from which a software reader can get access to all the information about the raw data acquired, the interpretations of these raw data, and all the organization interpretations built on them.

To be used in an effective manner along a multi-software workflow, it is strongly recommended that an earth model organization (like other RESQML features) be declared at the beginning of any transfer. This creation drives the user to begin thinking about how to organize information for data exchange and "initializes" the flow of information.

So, the first (and more important) usage of the earth model feature is to create a UUID reference on which all the results of operations relative to one prospect can be furthermore “linked” and retrieved independently of software files, databases releases, or proprietary and legacy data stores.

This means that, at the very beginning of a prospect life cycle, it might be useful (though not mandatory) for an asset team to create a geologic organization feature of type earth model, which can be the "container" (organizing basis) for a consistent set of information (NOTE: The earth model does not actually "contain" its contents, but is referenced to them using data object references (for more information, see Section 5.4 (page 56)). The individual features of the earth model can also be exchanged individually, during prospect appraisal and development.

9.1.2 Earth Model Interpretation

An earth model interpretation is an organized collection of subsurface feature-interpretations, which are integrated in their mutual relationships.

As is the case for all RESQML data objects, a given earth model feature can have many associated earth model interpretations.

BUSINESS RULE: Each earth model interpretation may consist of only one each of these three interpretation types: structural organization interpretation, stratigraphic organization interpretation, and/or fluid organization interpretation. These interpretations must be consistent with one another. (NOTE: Currently, this business rule cannot be enforced in the schema so the reading software must "trust" that the writing software has followed this rule.)

Each of the component feature interpretations that make up the organization interpretations (for example, horizon interpretations, fault interpretations, geologic unit interpretations, and contact interpretations) may also be associated together, which is explained in Section 9.2 (page 84).

9.1.3 Use of Earth Model Interpretations

An earth model has these main uses:

- To take a “snap shot” at a given time stamp to capture a consistent set of information at a specific step of the geomodelling/simulation business process. The objective is to mark this step or to transfer a complete and consistent set of information from one software package to another after a specific step.
- To be able to consistently update—stage by stage—this consistent model (from the snap shot forward) with new data and information about the prospect.
- To archive one given step or the global history of the prospect creation and its evaluation.

From an IT perspective, an earth model interpretation can be considered an instance of one earth model feature (**Figure 9-1**).

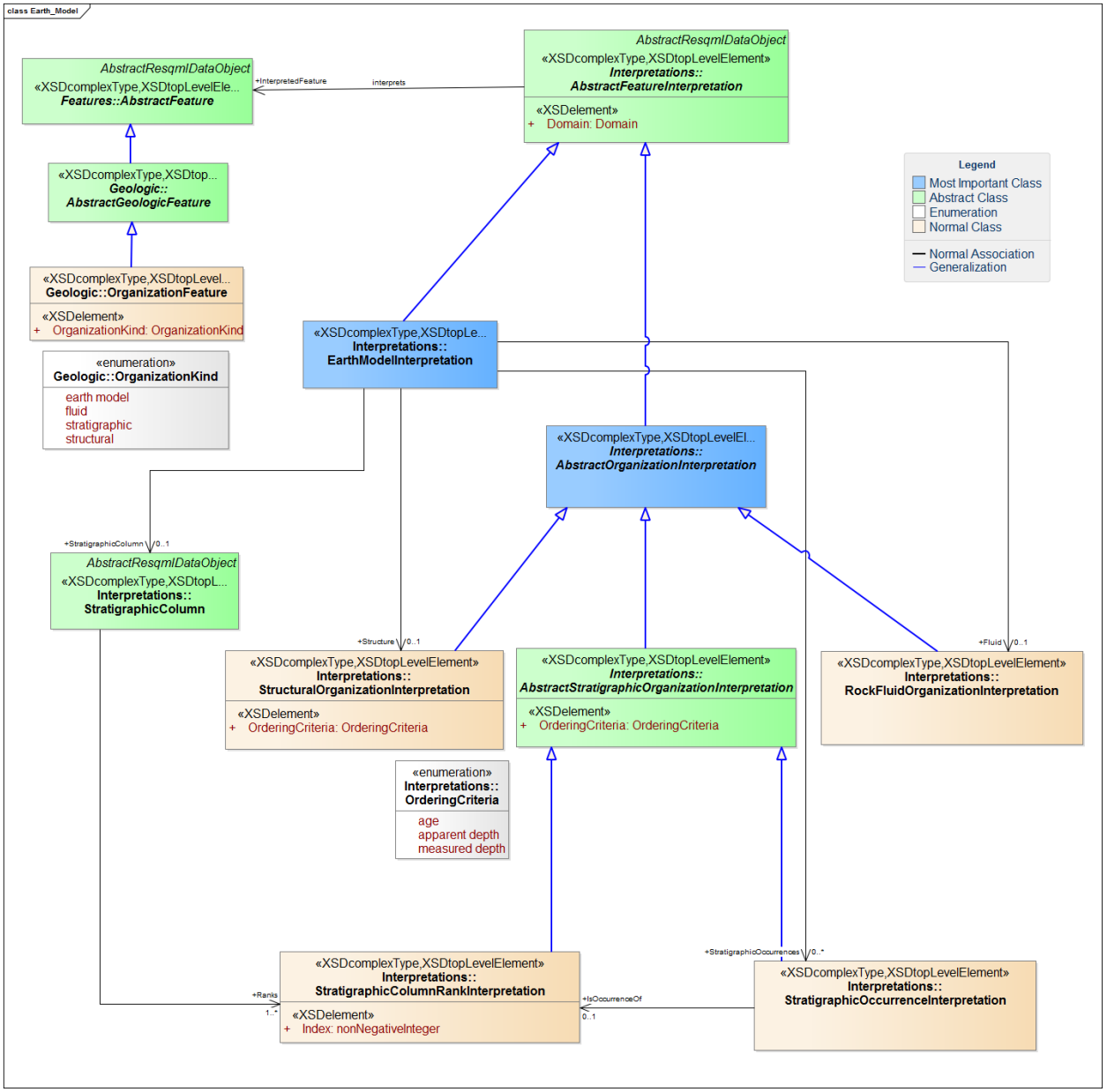


Figure 9-1—Earth model feature and interpretation in the RESQML UML model.

9.2 Components of Earth Model Organizations

This section describes the features and feature-interpretations that can be used to build an earth model.

9.2.1 Features

The abstract feature is the parent class of all the features used for exchanging structural and stratigraphic information; it includes geologic, technical, and organization features as defined above (see Section 5.1 (page 52)).

The main categories of individual geologic features include (**Figure 9-2**):

- Boundary features, such as tectonic (fault or fracture), genetic (geobody boundary or horizon), and fluid boundaries (free water, gas-oil, gas-water, and water-oil contacts plus seal)
- Geological unit features (rock fluid feature, stratigraphic units, and geobodies)

- Rock fluid phase units, which describe either gases or liquids (aquifer, gas cap, oil column and seal)

Both stratigraphic and rock phase units are naturally bordered by genetic and fluid flow boundaries.

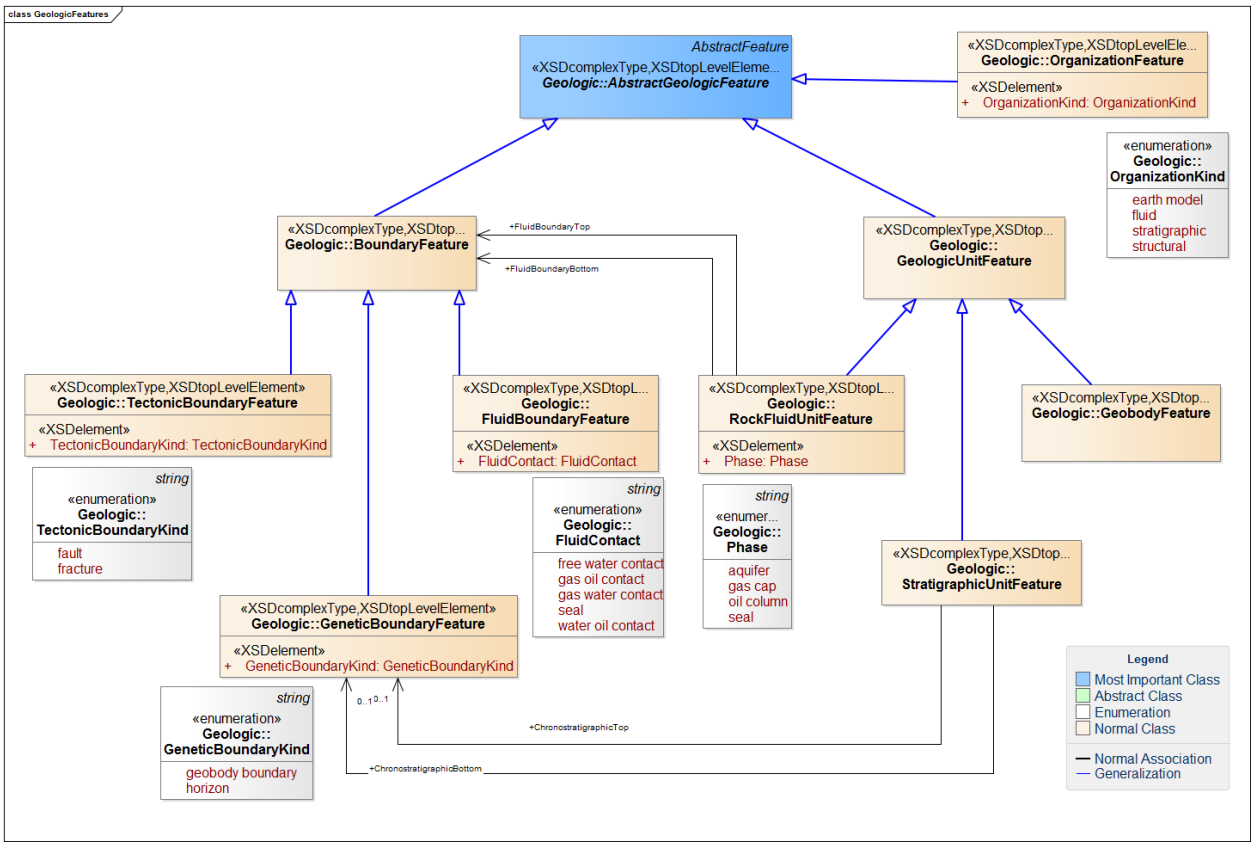


Figure 9-2—Geologic features.

Technical features include (**Figure 9-3**):

- Seismic features, which can be defined as a set of seismic lattices to describe multiple seismic3D surveys or as a set of seismic 2D lines to characterize 2D seismic sections. For more information on seismic data, see Chapter 13 (page 212).
- Frontier feature of the studied domain used to build the volume of interest for the model area.
- Wellbore features, which describe wells in three dimensions and associated WITSML wellbore references. For more information on wells, see Chapter 12 (page 197).

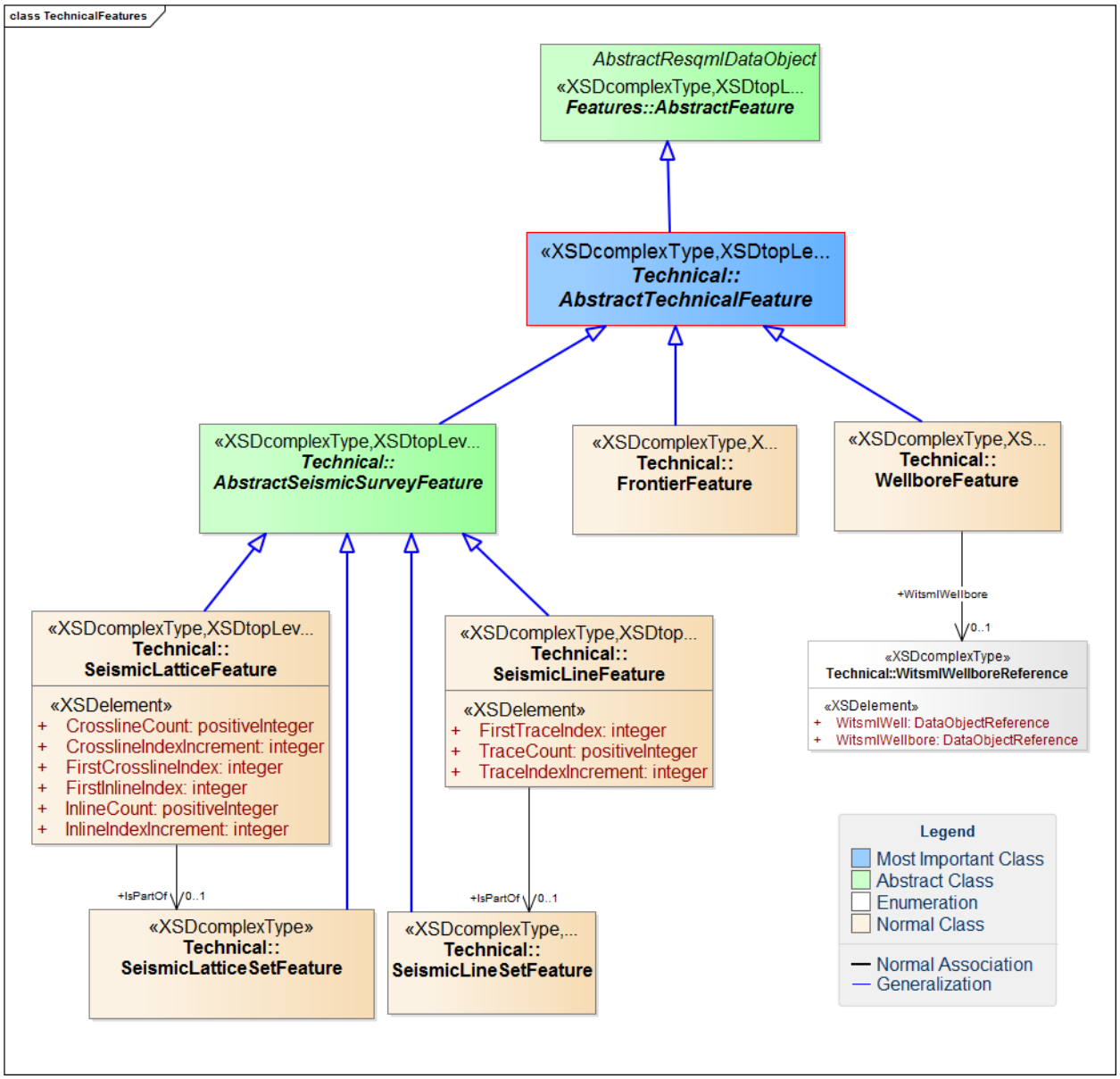


Figure 9-3—Technical features.

In RESQML, these features (geologic and technical) can be assembled into these types of organization features:

- Structural organization (surface)
- Stratigraphic (volume)
- Fluid (volume)
- Earth model (association of the previous organization features)

9.2.2 Structural and Stratigraphic Interpretations

Most of the information contained as attributes or enumerations in individual interpretations or organization interpretations can help users to understand how the topology and the geometry of the geological objects and organization representations should be built, or have been built if a representation is already associated with a given interpretation.

An abstract interpretation is the parent class of all specialized interpretations of a linear, surface, or volume of geologic data objects. In an interpretation, we must find all the necessary information needed to build up a realization of a representation of these data objects.

9.2.2.1 Individual Feature Interpretations

RESQML has these categories of individual interpretation features (**Figure 9-4**):

- **Wellbore interpretation (line).** A wellbore feature can contain different wellbore interpretations, which correspond to planned and/or drilled trajectories. A Boolean attribute "isDrilled" is used to indicate drilled versus planned wellbores.
- **Boundary interpretation (surface).** A boundary interpretation may be one of these kinds: fault, horizon, or geobody boundary. Each of these has characteristics (enumerations) which may influence how its representation is built.
- **Geologic unit interpretation (volume).** A geologic unit interpretation can be allochtonous or autochtonous and knowledge of its composition can help the user determine how to model it. RESQML geologic units have these two main categories and the following specific values:
  - **Geobody interpretation**, which can have these 3D shapes: dyke, silt, dome, sheeth, diaper, batholith, channel, delta, dune, fan, reef, wedge
  - **Stratigraphic unit**, which can have these deposition modes:
    - Proportional between top and bottom
    - Parallel to bottom
    - Parallel to top
    - Parallel to another boundary

These individual feature interpretations are the base of the constitution of the contact interpretations (Section 9.2.2.2 (page 88)) and of the organization interpretation (Section 9.2.2.3 (page 90)).

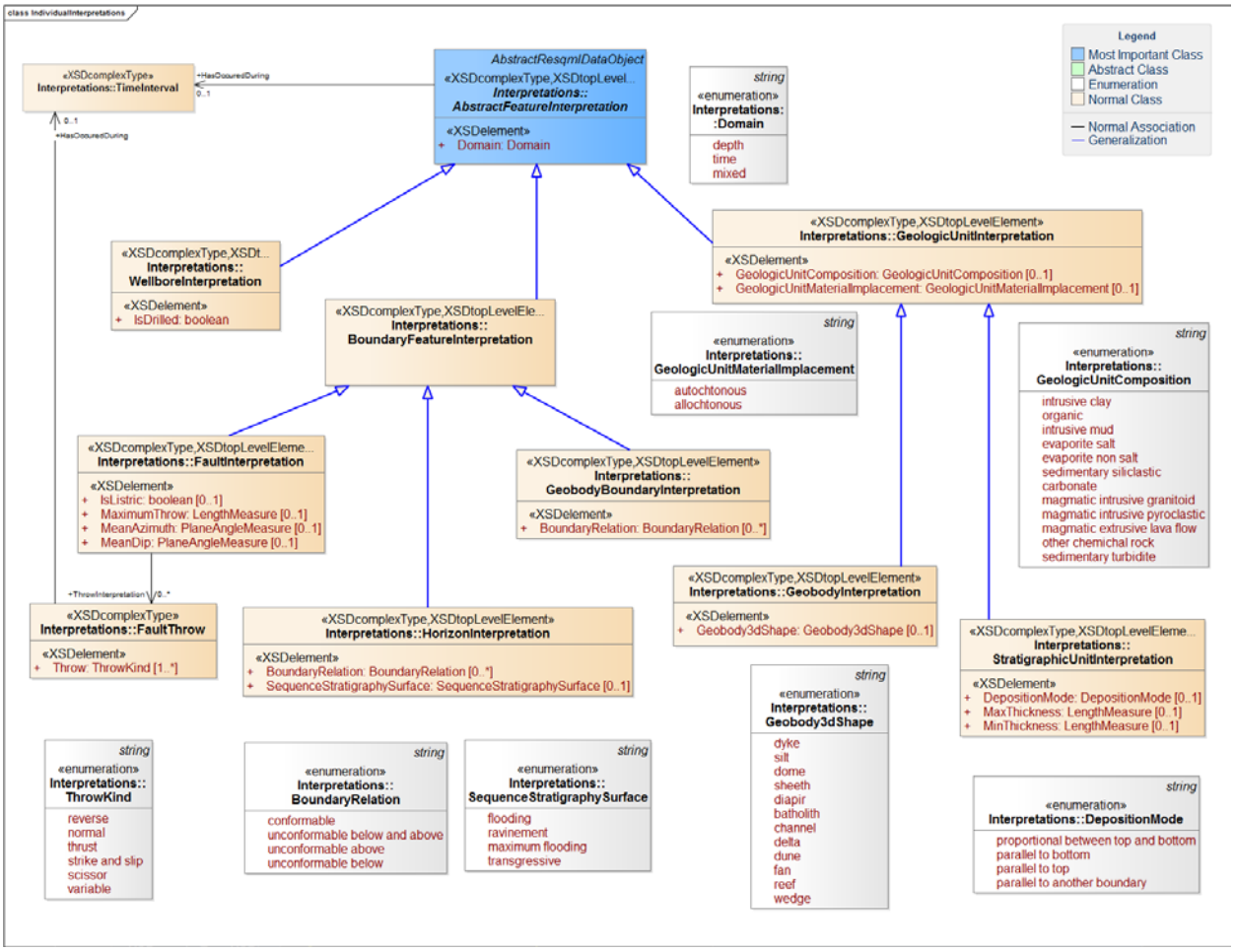


Figure 9-4—Individual Interpretations.

9.2.2.2 Contact Interpretations

To develop consistent organizations, the previously defined individual interpretations must be linked together. In the subsurface, these links occur as geological contacts. These contacts are mainly surface contacts (between two units), linear contacts (between two boundaries), and can be also nodal contacts (between linear contacts) (**Figure 9-5**).

The organization interpretation (Section 9.2.2.3 (page 90)) gathers the individual representations and the contact interpretations, but a preliminary step is required to define these contacts.

Contact interpretations exist only in the context of an organization interpretation. This means that each contact interpretation has a unique index in the context of only one organization interpretation but not in "the universe" (no UUID). Therefore, contact interpretations cannot be shared by organization interpretations.

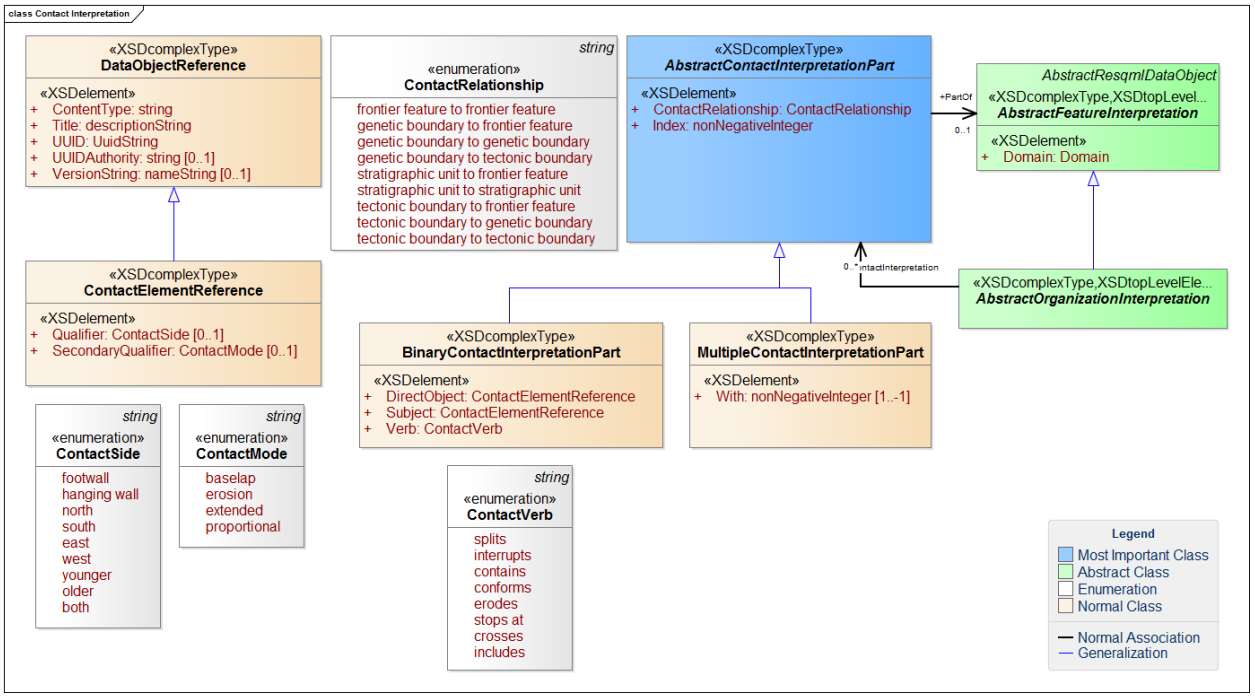


Figure 9-5—Contact Interpretations.

9.2.2.2.1 Contact Interpretation Part

A contact interpretation part is built on relationships between two interpretation features or between two already existing contact interpretation parts.

To characterize the business side of these contact relationships, the writer must specify a relationship from the following list.

Kinds of contact relationships:

- frontier feature to frontier feature
- genetic boundary to frontier feature
- genetic boundary to genetic boundary
- genetic boundary to tectonic boundary
- stratigraphic unit to frontier feature
- stratigraphic unit to stratigraphic unit
- tectonic boundary to frontier feature
- tectonic boundary to genetic boundary
- tectonic boundary to tectonic feature

A contact interpretation part is defined by its binary contact interpretation part. This class allows you to build a formal sentence with the following pattern:

SUBJECT Subject Qualifier VERB DIRECT-OBJECT Direct-Object Qualifier

This sentence describes the construction of a nodal, linear, or surface contact. It is possible to attach a primary and a secondary qualifier to the subject and to the direct object as a contact element reference attribute.

For example, one contact interpretation can be described by a sentence such as:

The interpreted fault named *F1 interp* on its hanging wall side SPLITS the interpreted horizon named *H1 Interp* on both its sides.

SUBJECT = *F1 Interp*, with qualifier "hanging wall side"

VERB = *splits*

DIRECT-OBJECT = *H1 Interp*, with qualifier "on both sides"

We must use the individual representation elements to describe how these contacts were built (what modeling business rules were used) for the construction of the binary contact interpretation. Practically, these individual representations are known by their contact element references. This is a way to define which boundary or geologic unit you want to use to define the contact interpretation (the SUBJECT and the DIRECT-OBJECT).

The contact element reference is used to reference the interpretation of a geological boundary or a geological unit. Its primary qualifier is used to define the contact side, which includes these options:

- foot wall
- hanging wall
- north
- south
- east
- west
- younger
- older
- both

Its second qualifier is used to define contact mode, which includes these options:

- baselap
- erosion
- extended
- proportional

The verbs correspond to a topological/geometrical action that must be realized to calculate the corresponding contact representation; verb options include: splits, interrupts, contains, conforms, erodes, stops at, crosses, includes.

9.2.2.3 Organization Interpretations

Technically, an organization interpretation:

- Is typically composed by one stack of its contained elements.
- Typically contains:
  - contacts between the elements of this stack among themselves
  - contacts between the stack elements and other organization elements
- May be built on other organization interpretations.

The feature interpretation set is used to specify collections of unordered interpretation features. For example, this class can be used to specify fault sets in a structural organization interpretation.

RESQML distinguishes these types of organization feature-interpretations, which are described further below: structural, stratigraphic, rock fluid, and earth model.

- A **structural organization** (**Figure 9-6**) contains the boundary interpretations (and the frontiers) that are present in a given volume or rock and their contact interpretations, which includes the contact kinds listed Section 9.2.2.2 (page 88).

  A structural organization interpretation instance corresponds to a complete description of the architecture of an earth volume. It includes an ordered list of horizon interpretation indices and a list

of fault interpretations. Note that to define a fault network, we used a list of fault interpretations plus a "tectonic boundary to tectonic boundary" contact interpretation.

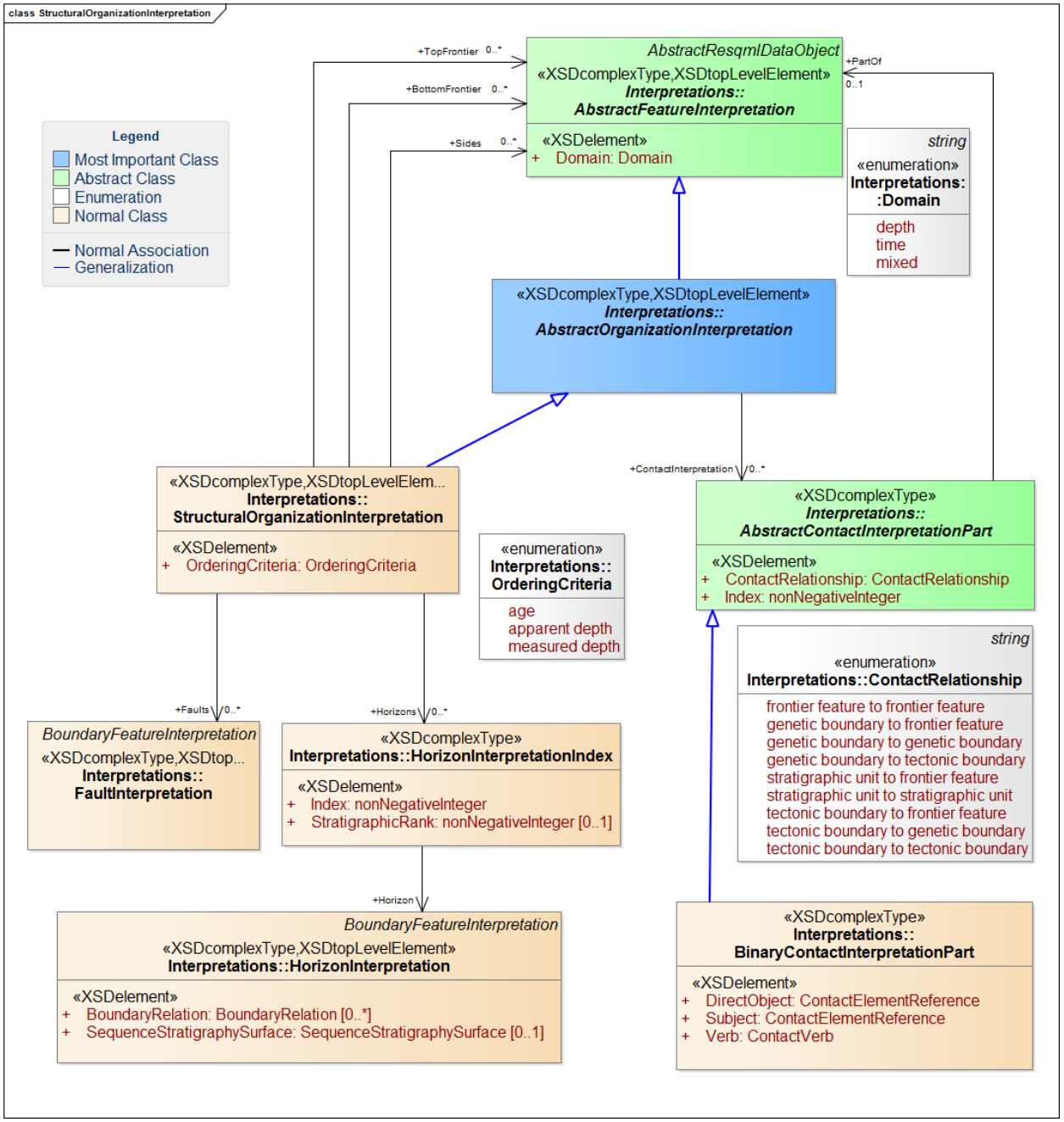


Figure 9-6—Structural organization interpretations.

- **Stratigraphic organization** interpretation defines the relationships between stratigraphic units. **Figure 9-7** shows this class along with the child classes it comprises, which are:
  - **Stratigraphic column** interpretation corresponds to the type of assemblage commonly designated by geologists as a stratigraphic succession or simply as "stratigraphy". It is a global hierarchical level that can be made up of several ranks of stratigraphic units, ordered by age.
  - **Stratigraphic occurrence** interpretation designates a local succession of geological units arranged according to an ordering criterion, which are present along a well, on a 2D map or on a 2D section, or on a part of the global earth volume. Ordering criterion may be age, or apparent or

measured depth along a well trajectory. It is equivalent to stratigraphy occurrence defined by Perrin and Rainaud (2013) (which states: "A stratigraphy occurrence is defined as an assemblage of units and boundaries, whose arrangement agrees with a stratigraphy.")

- **Rock Fluid Organization (Figure 9-7)** is composed of rock fluid units. This part has not been completely evaluated and will be considered with more details in a future version of RESQML.

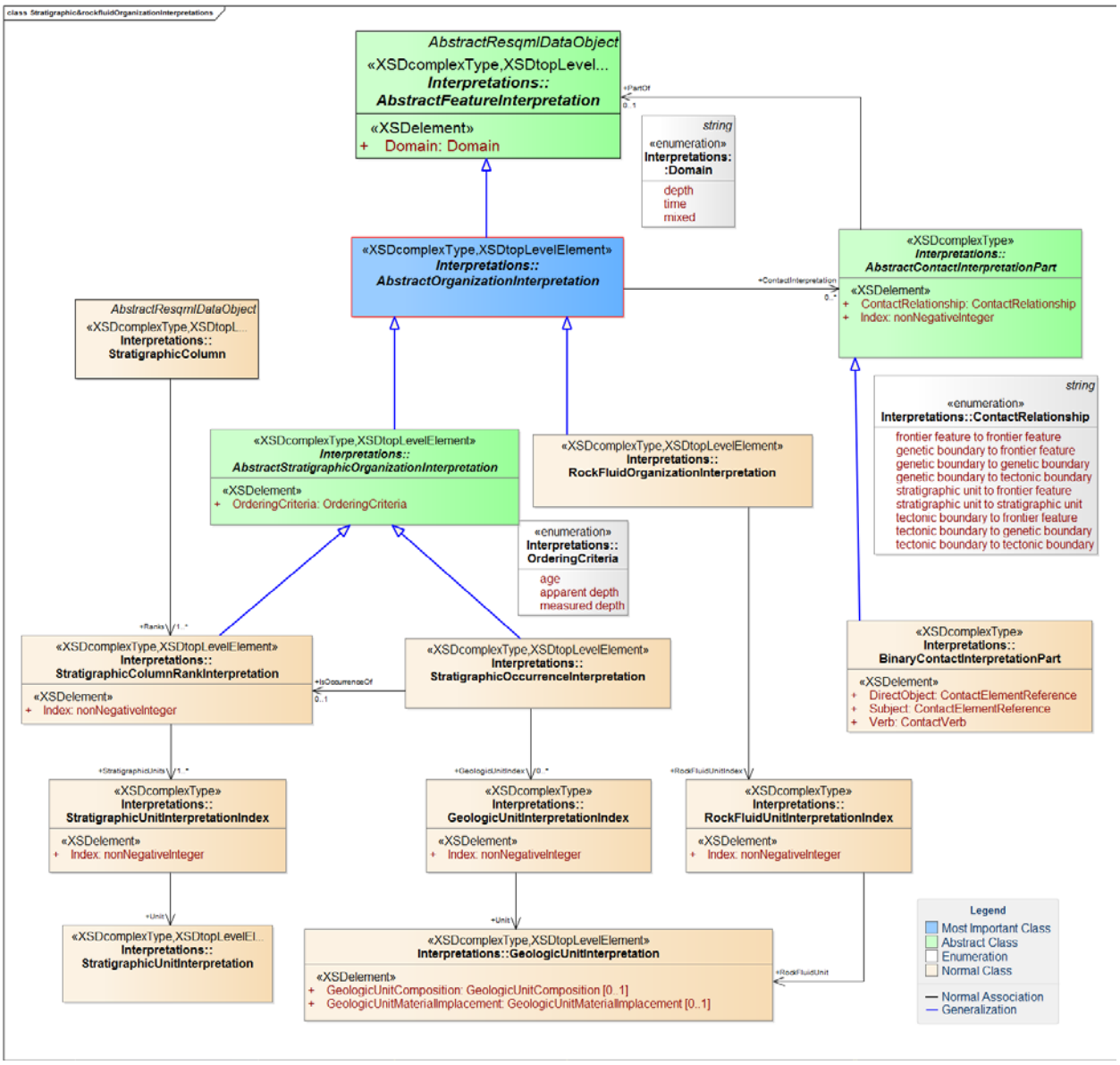


Figure 9-7—Stratigraphic and rock fluid organization interpretations.

- **Earth model organization interpretation (Figure 9-1** (page 84)) refers to a “trusted” interpretation of a geological site at a definite stage of the modeling process; “trusted” means that this interpretation should be geologically and topologically consistent. Additionally, for an earth model organization to be considered trusted, the rock fluid organization interpretation must be based on the stratigraphic organization interpretation and the stratigraphic organization interpretation must be built on a structural organization interpretation. Thus an earth model rests on various kinds of organizations describing the stratigraphic, structural, and rock fluid characteristics of the model.

9.3 Examples: How to Use RESQML in the Life Cycle of an Earth Model

This section walks through several examples that show how RESQML can be used to facilitate the earth modeling process.

- **Example 1: Creating an Earth Model** (Section 9.3.1 (page 93)) is a step-by-step example that shows how to create an earth model in RESQML. It begins with two slightly different seismic interpretations by team leads Paul and Peter. The asset team select's Peter's interpretation and develops it to a non-sealed surface framework, performing tasks and exchanging data between various RESQML-enabled software.
- **Example 2: Possible Next Steps: How to Reuse/Update a Complete Earth Model for Static Property Modeling and Flow Simulation** (Section 9.3.2 (page 103)) extends the first example; the asset team decides to look at Paul's interpretation. The section explains some possible next steps to update the earth model created in the first example.
- **Example 3**: **Strategy to Re-Engineer an "Ancient" 3D Grid** (Section 9.3.3 (page 105)) shows how RESQML can help in reading and updating "ancient" grid from an old project.

NOTE: There are different ways to implement RESQML into software. Typically, a developer may only be concerned with the RESQML format when the user explicitly choses an option to save to this format or export to RESQML. However, in this example, to help map RESQML constructs to an earth modeling business process, the RESQML concepts are discussed in parallel throughout the example.

9.3.1 Example 1: Creating an Earth Model

To best show how RESQML works, this example uses different RESQML-enabled software for different steps in the process (in reality, some software packages could do all or most of these steps). The software used in this scenario includes those listed in the table below. The table also shows the names of the EPC files (which contain all the data objects in a transfer) that each software reads and writes. (Note: EPC files are transient; they exist only for a single transfer. For more information about EPC files, see Section 3.2.6 (page 30).)

Software "Name"	Type / Role of Software	EPC File Read	EPC File Written
Software A	Seismic interpretation		EPC_0
Software B	Surface modeling	EPC_0	EPC_1
Software C	Surface structural framework assemblage	EPC_1	EPC_2
Software D	Sealed surface structural framework modeling	EPC_2	EPC_3
Software E	Stratigraphic volume framework modeling	EPC_3	EPC_4
Software F	3D grid modeling software	EPC_2 or EPC_3	EPC_5
Software G	Fluid flow simulation software	EPC_5	EPC_6
Software H	Gridding software with editing functions	EPC_5	EPC_6

Ideally, it is best to begin thinking about the data exchange at the beginning of the earth modeling process.

The first exchange begins after the realization of step 1, seismic interpretation (see the next section). At the end of this step 1, the users record the results of the seismic interpretation.

9.3.1.1 Step 1: Prospect Creation after Seismic Interpretation

Two teams of geophysicists and geologists, one led by Paul the other by Peter, are each working with the same data on the same task: to obtain the best fit between the seismic image (seismic reflector) and two

2D grids for Horizon1 and Horizon2, and the best fit between the seismic image (noise area) and (a set of lines) for Fault1 (**Figure 9-8**, left). The teams are each using seismic interpretation Software A. (In reality, the geologists might be using log analysis software, but for simplicity of the example we have both groups using the same Software A.)

Software A uses an EPSG code for geographic localization and a user has interpreted a seismic cube and several seismic 2D lines. Horizon1 and Horizon2 are two reflectors corresponding to well-known genetic boundaries in this survey. These well-known genetic boundaries are the Horizon1 and Horizon2 features, which the team creates in the software. By definition, each RESQML top-level feature has a UUID (for this example: HORIZON_1_UUID, HORIZON_2_UUID, FAULT_1_UUID) In Software A, Paul and Peter picked these reflectors, and for each reflector, a 2D grid (Grid2D) was defined.

To manage their results in Software A they name them: Horizon1_Paul, Horizon2_Paul, Horizon1_Peter, Horizon2_Peter, Fault1_Paul, Fault 1_Peter**, Figure 9-8**, right).

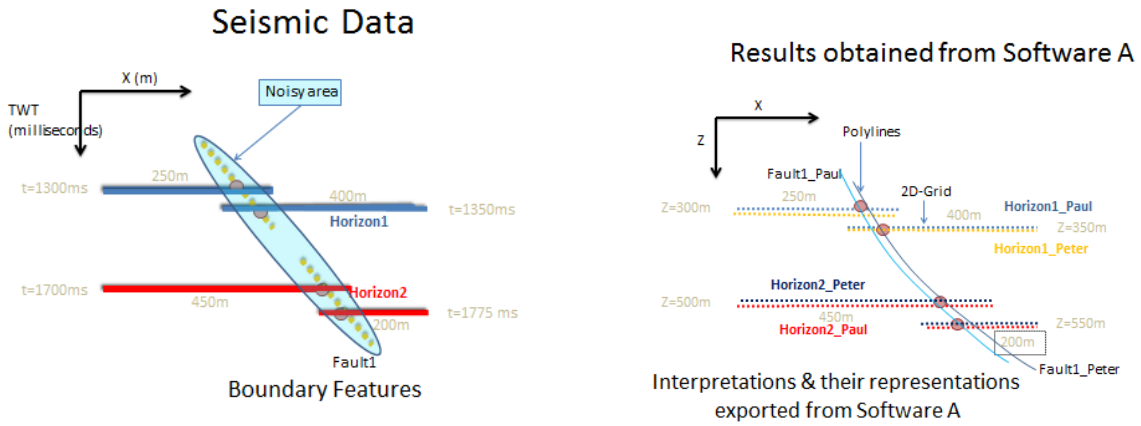


Figure 9-8—Data to be transferred from Software A.

Each of their interpretations is fine, but the results are not identical, with two different interpretations of seismic reflectors and faults lines. They have calculated the potential volume between Horizon1 and Horizon2 and they have different estimations, so they want to export the data from their respective interpretations to Software B, surface modeling software, where they can create triangulated surfaces for more precise results and comparison.

9.3.1.1.1 Preparing for Data Exchange

When working in the context of an asset team and the full life cycle of an earth model, and before beginning to exchange data in the workflow, we must give some thought to how to organize data for iterative exchanges throughout the life cycle. This organization is important so that in the future, we can retrieve the hypothesis used during the successive modeling steps.

The first recommended action is to create an earth model feature in Software A: an organization feature of kind earth model with the title: MY_EARTHMODEL_Feature (UUID_EMF, Citation_EMF) (**Figure 9-1**, page 84). This example does not yet use the earth model feature (because we have not yet created any earth model interpretations). However, in support of long-term organization for full life cycle and iterative workflows, the earth model was created first.

Then, because the team has created features, each with a UUID (for this example: HORIZON_1_UUID, HORIZON_2_UUID, FAULT_1_UUID), the team can attach one or more corresponding interpretations to each feature, using a data object reference to indicate the UUID of the feature that is being interpreted. (For more information, about features and interpretations see Chapter 0 (page 46).)

This reference mechanism allows enrichment of the model, step by step. For example, because of this referencing ability, at a given time stamp, we can export Peter's interpretations. In a few weeks, after more work has been done, Paul's interpretation can also be exported and are associated with the same features by UUID.

So we have a prospect with three individual features: (Horizon_1, Horizon_2 and Fault_1). Each of these features has two interpretations (one by Peter and one by Paul), and for each interpretation, we can attach one or more representations. The representations that can be exported from Software A are:

- For each horizon interpretation, one 2D grid based on a point lattice of 2 dimensions (4 2D grids, all together with only one point lattice 2D).
- For each fault Interpretation, one polyline sets.

9.3.1.1.2 Organization Interpretations Set Up

With the existing information, we can create one RESQML structural organization feature and two structural organization interpretations (one for Paul and one for Peter). In this example, we will create two earth model interpretation instances (which reference the earth model feature we created above), with each one containing a structural model interpretation:

- Paul's earth model interpretation instance contains one (Paul's) structural organization instance, which contains: Horizon_1_Paul, Horizon_2_Paul, Fault_1_Paul.
- Peter's earth model interpretation instance contain one (Peter's) structural organization instance, which contains: Horizon_1_Peter, Horizon_2_Peter, Fault_1_Peter

A set of contact interpretations based on Paul's individual boundary interpretation contacts can also be attached to Paul's structural organization interpretation, with corresponding representations.

This is the setup point of the interpretation management.

After this step, these data objects can be stored in an EPC file named EPC_0 and transferred to Software B or can be delivered on request from a Web service mechanism, which can retrieve these different elements using their respective UUIDs.

9.3.1.2 Step 2: Structural Modeling

9.3.1.2.1 Creation of New Surface Representations

Software B is used to do structural modeling (surface modeling). The information in EPC_0 is used to consistently transfer to Software B (and potentially to additional software packages) all the acquired representations and populate Software B's internal data model **(Figure 9-9)**.

A user can manage all of this information in Software B with only one constraint: Software B MUST keep the RESQML UUIDs (i.e., as an attribute) of the data objects it instantiates.

If Software B can apply surface modeling on 2D grids and polyline sets, it will have access to the detailed information about the topology and the geometry of these representations and can create triangulated surfaces and define contacts as polylines (**Figure 9-10**).

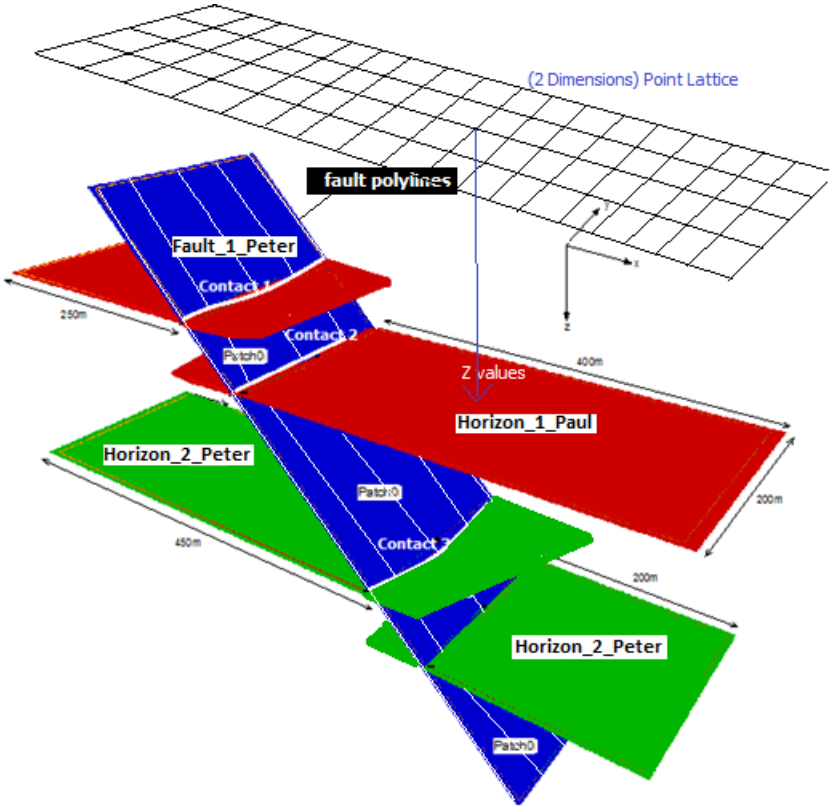


Figure 9-9—Data objects transferred from Software A.

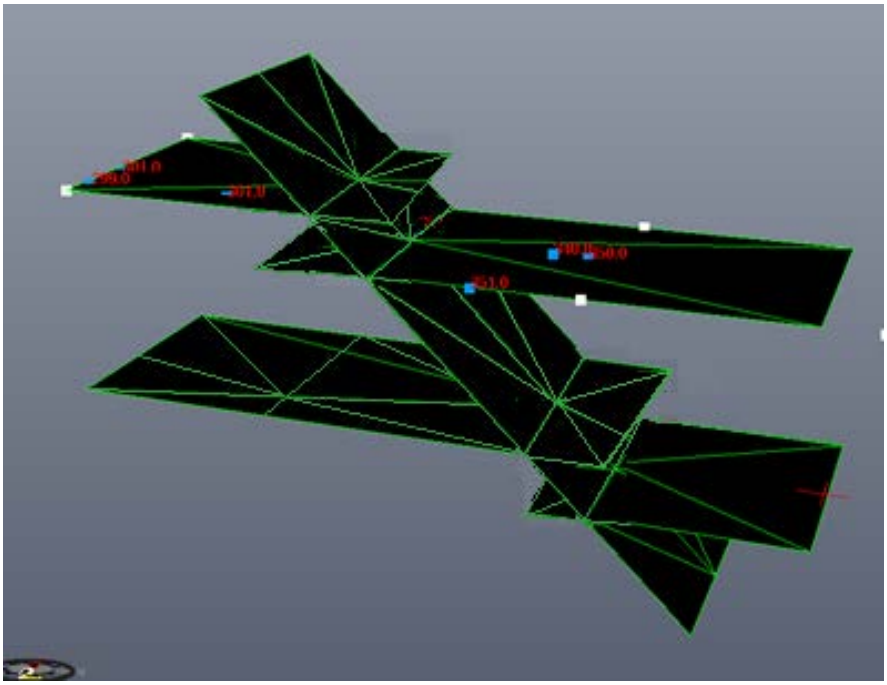


Figure 9-10—Triangulated set surface representations created in Software B.

In this case, after having created these new triangulated representations for both Paul's and Peter's interpretations, Software B adds to the previous RESQML data by linking these new representations to the existing interpretations using the UUID and data object reference mechanism discussed above.

Software B can export only the triangulated surface sets stored in an EPC file named EPC_1, which references the elements in EPC_0.

9.3.1.2.2 Creating a Structural Organization Interpretation and a Non-Sealed Surface Framework Representation

At this step, the asset team must compare both interpretations and decide whether to follow Paul's hypothesis or Peter's. For this example, we'll follow Peter's less optimistic hypothesis.

Software C imports Peter's structural organization interpretation and all of his individual interpretations/representations with the objective to build a first non-sealed surface framework representation with this set of interpretation and representation data objects.

The first task is to complete Peter's structural organization interpretation. To do this, we need to order the horizon interpretations (by age or apparent depth) and we need the contact relationships between the horizons and faults.

For this example, we define a Rank1 containing only the Horizon 1_Peter interpretation and a Rank2 containing Horizon_1_Peter and Horizon 2_Peter interpretations.

Each of these horizon interpretation is represented by two patches; the fault Interpretation is represented by one patch, and the contact patches are represented by a succession of (x,y,z) nodes (**Figure 9-11**). (For more information on patches, see Section 6.3 (page 62).)

In fact, very often, no specific representation will be created during this sub-step; Software C will export an EPC_2 containing a consistent working set on which only one representation is chosen for one interpretation and only one interpretation of a feature contributes to building its structural organization interpretation.

This EPC_2 can be used as a starting point by 3D grid builder software to produce a reservoir grid or by a more sophisticated structural modeler to build a sealed surface framework (Software D, in this example).

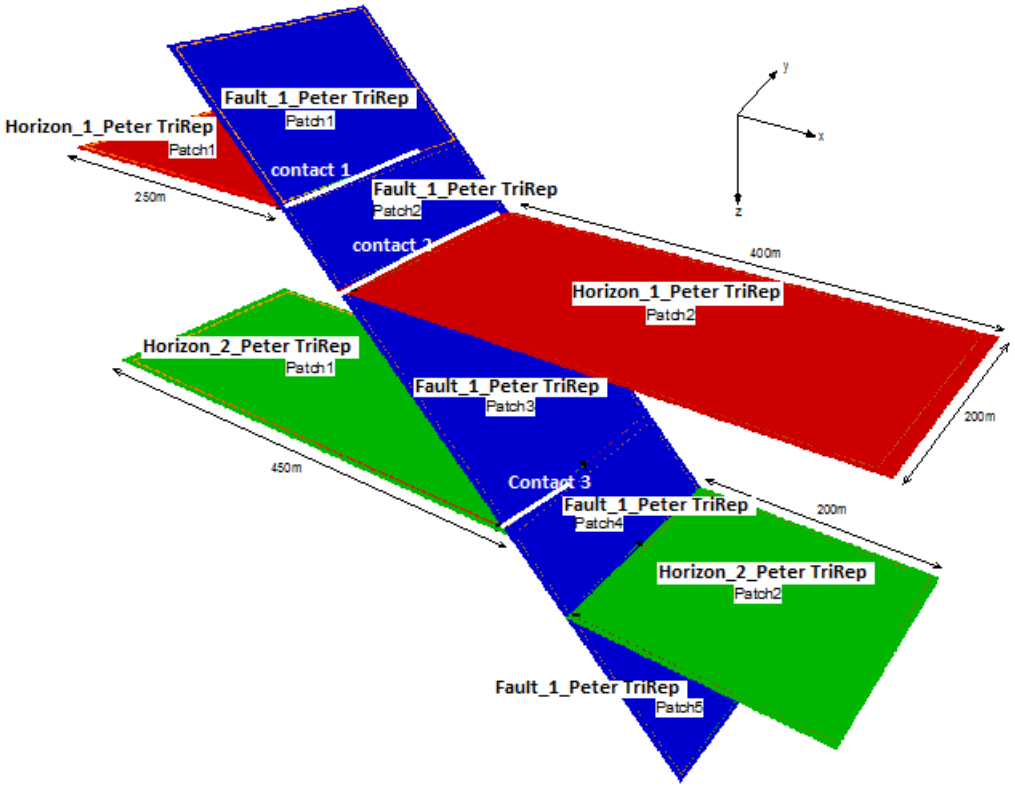


Figure 9-11—Structural organization interpretation represented by a non-sealed surface framework.

9.3.1.2.3 Creating a Sealed Surface Framework Representation in a Structural Organization Interpretation

The previous EPC_2 contains the horizons, faults, and contact interpretations defined during the seismic interpretation tasks, gathered in a consistent manner into a structural organization interpretation (which we defined in the first step (Section 9.3.1.1.2 (page 95)). This EPC_2 also contains their representations, which can exist on different supports (2D grid, triangulated surfaces, polyline sets, 3D points).

The objective of the next sub-step is to obtain a true boundary representation (BREP) of this structural organization interpretation.

Software D imports EPC_2 and uses it to define in detail the topological association of individual nodes of the different supports to build a topologically consistent sealed surface framework (**Figure 9-12**). For each node belonging to one support, the geometry is defined only once.

To build such a sealed surface framework this Software D must realize “clean” intersections between faults and faults, horizons and faults, and horizons and horizons, at least. As an added benefit, this Software D associates the nodes of the intersection lines together. In this case, this framework is sealed because the patches are limited by the intersection lines, and the nodes of the intersection lines could be the same on both sides of the intersection (**Figure 9-13** and **Figure 9-14)**.

Because all the connected patches share their nodes while intersecting, the intersection line is defined as a subrepresentation of the patches, and the geometry of the nodes of the intersection are defined only once in the patch representation. (For more information on subrepresentations, see Section 6.3 (page 62).)

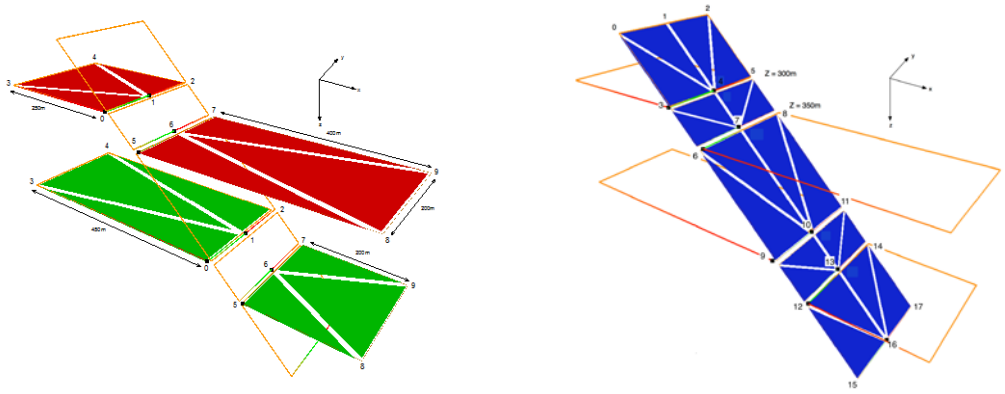


Figure 9-12—Detailed topology needed to obtain a sealed surface framework.

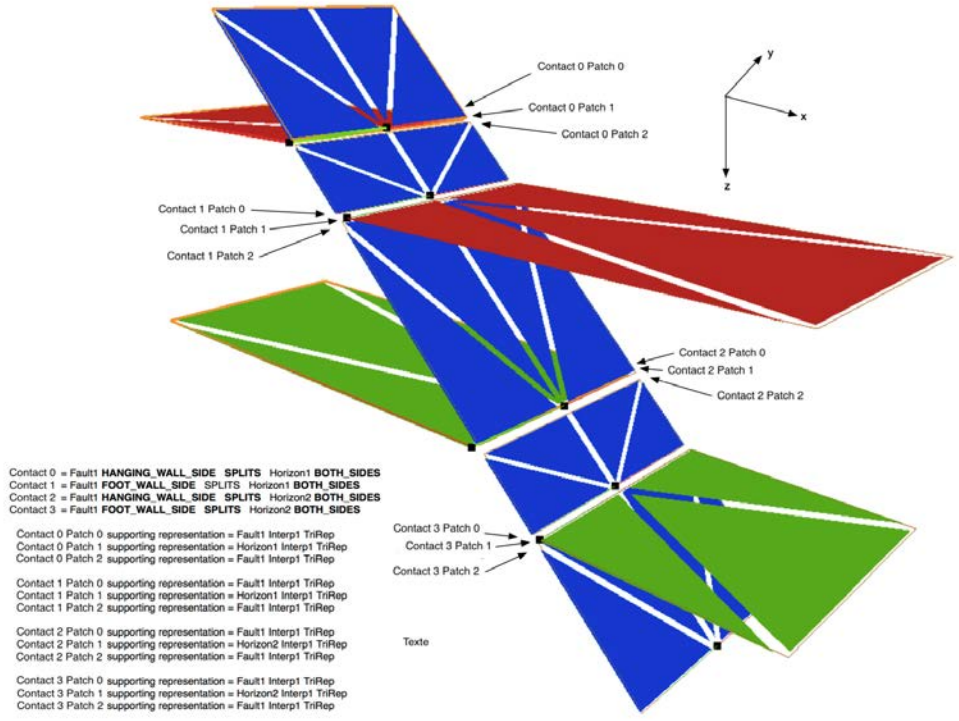


Figure 9-13—Sealed surface framework. For the previous colocated points, see Figure 9-14.

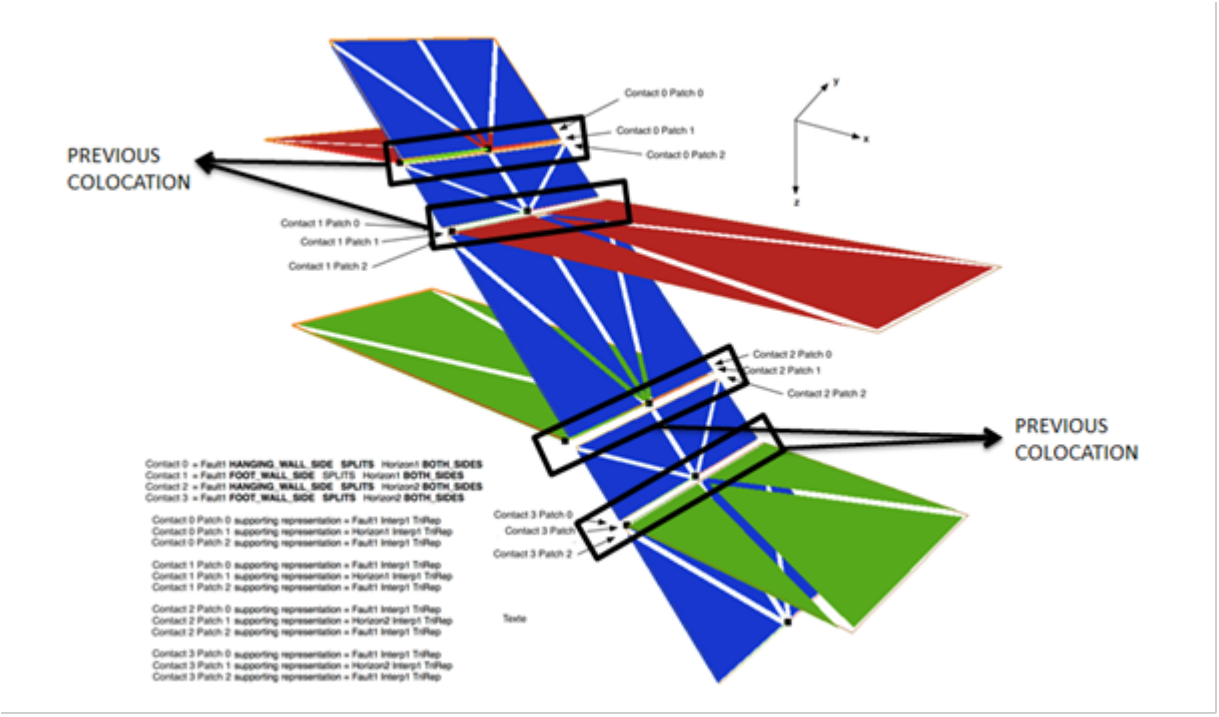


Figure 9-14—Sealed surface framework with previous colocation identified.

The objective of this sealed framework is to avoid geometric differences between two equivalent nodes, difference which could be generated by different 3D gridding software packages that have different geometrical functionality. (For more information on equivalent nodes and colcation in RESQML, see Section 6.5 (page 63).)

This sealed surface framework is an important part of the sealed volume framework, which is discussed in Section 9.3.1.3 below.

Software D exports an EPC_3 package with a lot of new consistent representations, which can be used as a base directly by a 3D grid builder or to set up a stratigraphic organization, which is discussed in the next section.

9.3.1.3 Step 3: Stratigraphic Modeling

Now it's time to build volumic representation, which can be done with a BREP or a 3D grid representation.

9.3.1.3.1 Creating a Stratigraphic Organization Interpretation and a Sealed Volume Framework Representation

Software E imports EPC_3 and is used to define an interpretation of a volume for our model (**Figure 9-15**).

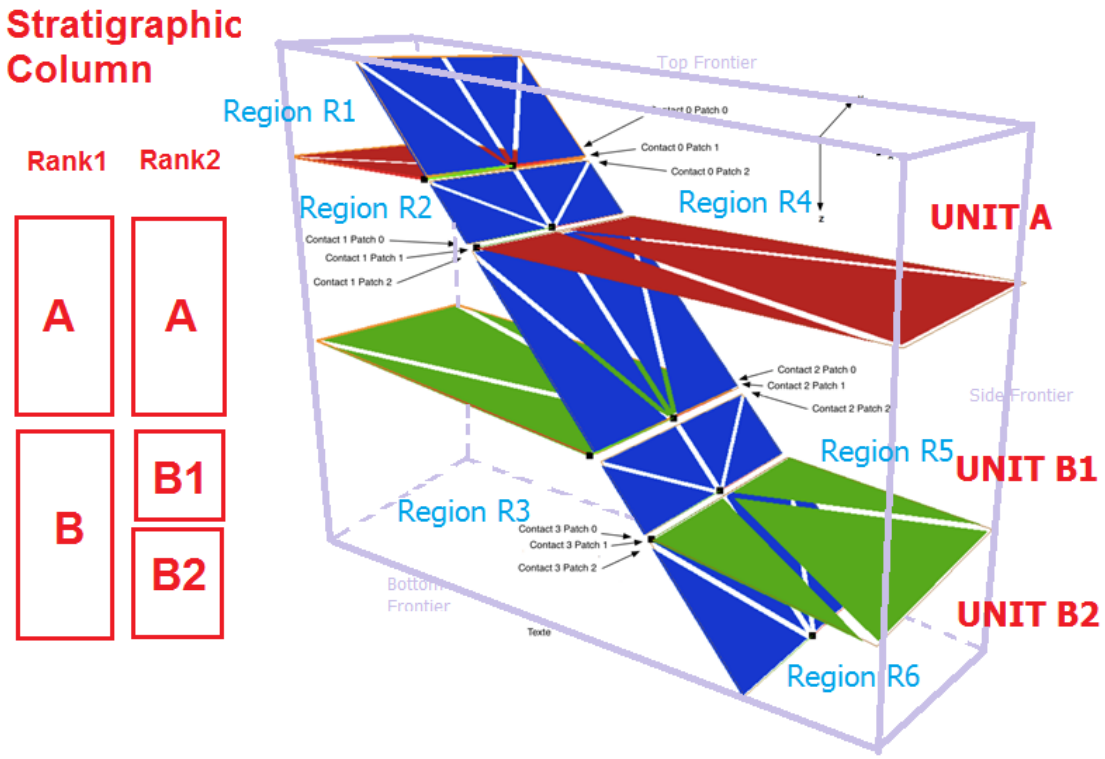


Figure 9-15—Example of a sealed volume framework attached to a stratigraphic organization interpretation.

In Software E, one stratigraphic organization interpretation can be created for each rank of the stratigraphic column. The asset team chooses the rank. In this example, they choose Rank2.

First, we must create the geologic (stratigraphic) units features that are used in Rank2: Unit A, UnitB1, and Unit B2. In the RESQML model, these units are associated with an upper and a lower genetic boundary.

We can also add some interpretation characteristics to these units. For example, Peter was qualifying the Unit A interpretation with a sedimentary siliciclastic composition and Unit B1 and Unit B2 as carbonate composition.

Software E declare as geologic unit features all the stratigraphic unit interpretations that must be identified, which includes Unit_A interp & Unit B interp for Rank1 and Unit_A interp + Unit B1 interp & Unit B2 interp for Rank2. This interpretation constitutes the stratigraphic column, which is attached to Peter's earth model interpretation.

The contact interpretations are defined between these units and follow the rules implied by the deposition mode defined for each stratigraphic unit.

By specifying all these relationships between surface and volume objects, an application can generate a sealed volume framework export, EPC_4, with an earth model interpretation containing a structural and a stratigraphic interpretation with a sealed surface framework and a sealed volume framework (**Figure 9-16**).

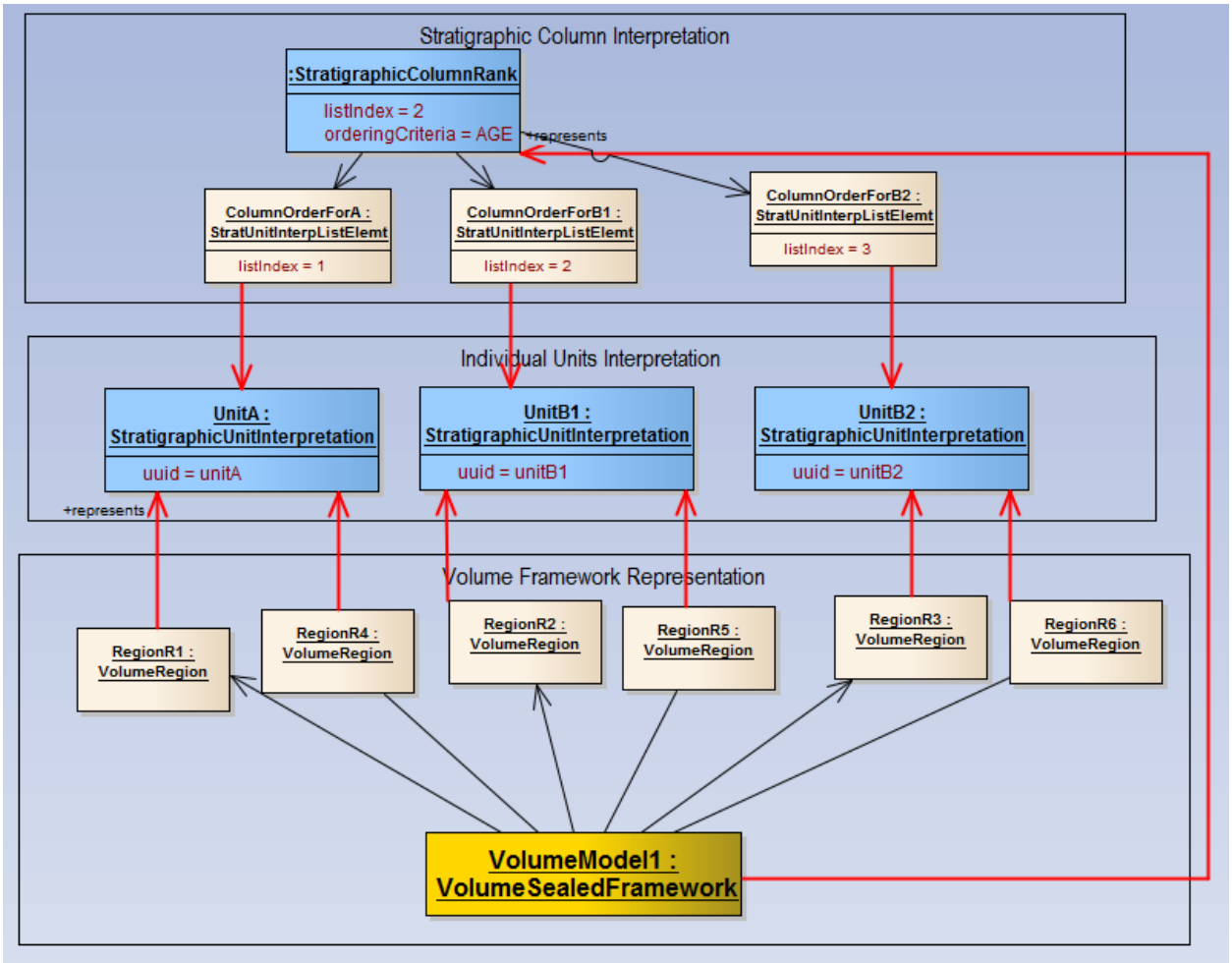


Figure 9-16—This instance diagram shows how a volume framework and a stratigraphic column are associated as shown in Figure 9-15.

9.3.1.3.2 Creating a Stratigraphic Organization Interpretation and a Grid Representation

Software F is "classic" package used to build 3D grid representation. To begin, Software F can import either of these:

- EPC_2, the structural interpretation with a non-sealed surface framework
- EPC_3, the structural interpretation with a sealed surface framework

In either case, the first step with Software F is to follow the same methodology as Software E: Define a stratigraphic organization interpretation by choosing a specific rank (Rank2 in this example) on which to build the 3D grid, and declare as geologic unit features, all the stratigraphic unit interpretations that must be identified (Unit_A interp & Unit B interp for Rank1 and Unit_A interp + Unit B1 interp & Unit B2 interp for Rank2). This definition specifies the stratigraphic column, which will be attached to Peter's earth model interpretation.

Software F can also directly import this information from EPC_4.

Then, Software F can import from EPC_2 or EPC_3 Peter's boundary interpretations (Horizon_1_Peter and Horizon_2_Peter) and use them to build up its 3D grid (**Figure 9-17**).

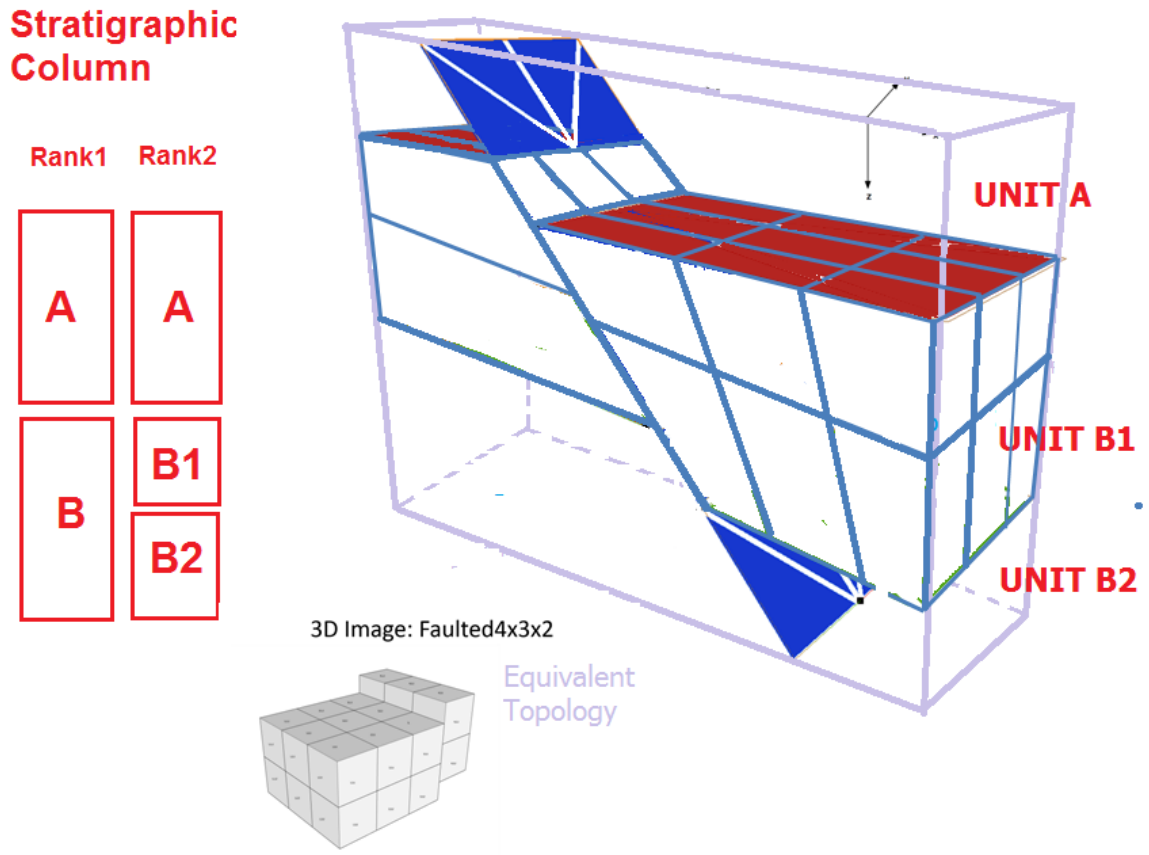


Figure 9-17—Example of a 3D grid representation, which represents a stratigraphic organization interpretation part.

The faulted 4X3X2 grid detailed in Section 11.17.2 (page 172) can be used here to represent the Unit B1_Interpretation.

Commonly, the 3D grid defined in the Chapter 11 (page 126) represents a complete rank of stratigraphic organization interpretation.

EPC_5 package can be created that contains a description of the stratigraphic organization interpretation in terms of stratigraphic column rank interpretation and the grid representation that is linked to it.

9.3.2 Example 2: Possible Next Steps: How to Reuse/Update a Complete Earth Model for Static Property Modeling and Flow Simulation

The asset team has done the modeling (static and dynamic); the results were not what they wanted. The team decides to start working on Paul's interpretation instead of Peter's.

9.3.2.1 Elements Contained in EPC_5

After all the previous tasks described above, EPC_5 should contain the following data objects:

Three organization features:

- Earth Model: MY_EARTHMODEL_Feature (UUID_EMF, Citation_EMF)
- Structural: MY_STRUCTURALMODEL_Feature (UUID_STRUCTF, Citation_STRUCTEMF)
- Stratigraphic: MY_STRATIMODEL_Feature (UUID_STRUCTF, Citation_STRUCREMF)

Seven geologic features:

- HORIZON_1, HORIZON_2, FAULT_1, UNIT_A, UNIT_B, UNIT B1, UNIT B2
- On which the horizon and fault each have two interpretations

Five organization interpretations:

- Peter's earth model organization interpretation belonging to MY_EARTHMODEL_Feature
- Paul's earth model organization interpretation belonging to MY_EARTHMODEL_Feature
- Peter's structural organization interpretation belonging to MY_STRUCTURALMODEL_Feature
- Paul's structural organization interpretation belonging to MY_STRUCTURALMODEL_Feature
- Peter's stratigraphic organization interpretation belonging to MY_STRATIMODEL_Feature

Peter's earth model organization interpretation contains both his structural organization interpretation and his stratigraphic organization interpretation.

Paul's earth model organization interpretation contains only Paul's structural organization interpretation. (In this example, we did not create a stratigraphic organization interpretation for Paul.)

We were working on Peter's interpretation and as a result, we were focusing on horizon and fault interpretation contacts between these interpretations, which are incorporated into Peter's structural and stratigraphic interpretation.

We have these representations linked to interpretations by RESQML data object references:

For all the individual interpretations:

For horizon interpretation, we have:

- Grid 2D representation with their 2D point lattice (4)
- Triangulated surface representation (4)
- Subrepresentation (by interval edge) of the 3D grid (Horizon_1 : interval edge =0, Horizon_2: interval edge=1)

For fault Interpretation, we have:

- Polyline set representation (1)
- Triangulated surface representation (1)
- Subrepresentation (by list of faces) of the 3D grid (Fault_1: face)

For unit interpretation, we have:

- Subrepresentation (by interval) of the grid 3D representation (Unit B1: Interval 0 & 1).

For organizations, we have these representations:

- A non-sealed surface framework
- A sealed surface framework
- A sealed volume framework
- A (4X3X2) 3D grid

9.3.2.2 Strategy that can be Used to Update the Earth Model

Software G (fluid flow simulation software) imports EPC_5 and uses the data to calculate reserve estimations and fluid flow simulations. For this job, Software G mainly uses the 3D grid representation, which represents Peter's stratigraphic organization interpretation, and produces static and dynamic properties attached to this 3D grid representation, which it saves in EPC_6.

However, the results are not convincing and the asset team would like to look at the model using Paul's structural interpretation instead of the current one.

Two strategies can be used to update the earth model, depending on the magnitude of the changes of Paul's interpretation:

- (A) If the changes are significant and we need to rebuild the grid from the structural model, we use the data contained in EPC_2 and re-execute steps 2 and 3 to generate a 3D grid based on Paul's hypothesis. We have all the necessary information to do this work.
- (B) If the topology does not need to be modified, we can use the data in EPC_5.

The basic workflow is: Create a new earth model for Paul's data containing a structural and stratigraphic organization interpretation. Compare Paul's representations to Peter's. If there is not an important difference between Paul's and Peter's representations (the deformation does not modify the topology of the 3D grid), then create and associate a "clone" of this 3D grid representation with Paul's stratigraphic organization interpretation.

In this case, using Software H (gridding software with editing functions) we replace the XYZ values of the nodes of the previous 3D grid-based representations of horizons to fit with the other representations of the horizons (Paul's representation) and then, update the 3D grid by constraining it on this new position of the nodes while minimizing the deformation for all other nodes.

9.3.3 Example 3: Strategy to Re-Engineer an "Ancient" 3D Grid

A geologist would like to use new RESQML-enabled software to re-evaluate an old study. She is using the software listed in the following table.

Software "Name"	Type / Role of Software
Software I	Retro Engineering RESQML Explorer
Software J	3D grid updater

Software I must export the rebuilt representation into a structural EPC package, and then the 3d Grid updater can take this package and do the work,

While examining the old data, she finds only a report describing the geology, a 3D grid representation (an old GRDECL file) and a collection of wellbores.

With the Software I, the geologist must create an earth model feature, an earth model interpretation, and associate it with this last stratigraphic organization. The geologist can import the GRDECL grid and declare that this 3D grid is a representation of this stratigraphic interpretation.

If she wants to produce more information—for example, she wants to update the structural and stratigraphic model—she can create the Horizon_1, Horizon_2, Fault_1 and Unit_B1 feature, and the corresponding interpretations: Horizon_1_Interp, Horizon_2_Interp and Fault1_Interp and UnitB1_Interp.

The representations are:

Horizon_1_Interp = subrepresention of GRDECL grid: interval edge =0

Horizon_2_Interp = subrepresention of GRDECL grid: interval edge =2

Fault1_Interp = subrepresention of GRDECL grid: face =2,4,5,6, N

Fault1_Interp = subrepresention of GRDECL grid: pillars =2,4,5,6, N

Unit_B1_Interp = subrepresention of GRDECL grid: interval = 0,1

A structural organization interpretation also could be created with: Horizon_1_Interp, Horizon_2_Interp and Fault1_Interp.

These representations can be reprocessed and transformed into triangulated surfaces (if needed).

Then, after having acquired new well marker tops, these representations can be fitted to these markers, and the process of rebuilding the structural frameworks, stratigraphic framework, and reservoir grids (as described above) can be done by Software J.

9.4 References

Perrin, M., Rainaud, J-F, et al. 2013. Shared Earth Modeling: Knowledge driven solutions for building and managing subsurface 3D geological models. p123. Paris: Editions Technip ISBN 98-207108-1002-5

10 Structural & Stratigraphic Representations

The representation level of the RESQML knowledge hierarchy corresponds to a 3D modeling expression of a feature that was initialized at the beginning of a business process. For example, the same horizon feature-interpretation can have a 2D grid representation or a triangulated set representation.

This chapter explains information specific to structural and stratigraphic representations.

Representations share several key concepts, which are explained in Chapter 6 (page 59).

For information specific to other types of RESQML representations, see the table of contents in this document.

10.1 Introduction

An abstract representation is the parent class of all specialized digital descriptions of a feature interpretation or a technical feature (**Figure 10-1**).

Every representation may be based on a topology and may contain the geometry of its own digital description or may be based on the topology or the geometry of another representation. RESQML has two main categories of representations:

- **Individual representations**. Each Individual representation is specialized by dimension (point, polyline, surface, volume) and represents only one individual geological interpretation (such as, horizons, faults, geological bodies, geological units, and fluid phase units*).*
- **Organization representations,** which are “sets” of individual representations and frameworks. The individual representations can be collected into a bag or can be associated topologically in frameworks, which are consistent assemblages of different representations to represent interpretations of organizations (such as earth models, structural organizations, stratigraphic organizations, stratigraphic columns, and fluid organizations).

Any of the derived classes of abstract representation, including the grids representations, can be used to describe structural and stratigraphic feature interpretations. Grid representations are discussed in Chapter 11 (page 126).

Because this class inherits from the abstract RESQML data object, all the derived top-level element classes must have an UUID and a citation object attached.

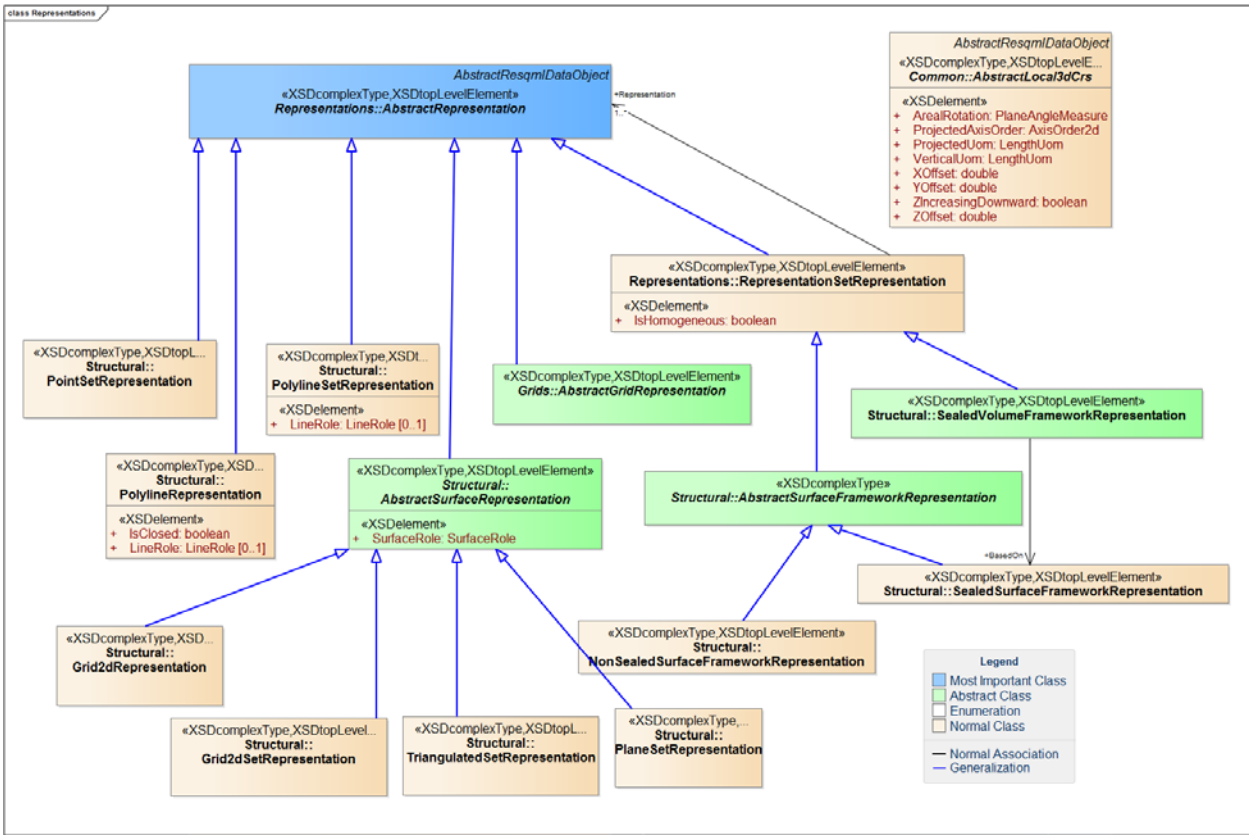


Figure 10-1—Overview of individual and organization representations in the RESQML UML model.

10.2 Individual Representations

Individual representations (which all inherit from abstract representation) are defined by their topology and their geometry. Individual representations may be based on either:

- A discrete definition of the geometry
- A parametric description of the geometry using parametric line descriptions

For discrete representations, the node is the elementary topological atomic element used for each individual representation based on a discrete geometry. Mainly each individual representation contains its topology, which defines how to associate these nodes to represent the individual representation as points, lines, surfaces or volumes.

The topological relationships within a representation may either:

- **Explicit**: For example, a triangle patch, where we must define the node number of the points that are linked together to make up a triangle.
- **Implicit:** For example the index of each node is given only by its order in the array of 3D points of the point geometry (most of the cases).

Non-discrete representations, such as an infinite plane, are also available.

The UML model in EA is organized as shown in **Figure 10-2** and explained in the sections below the figure.

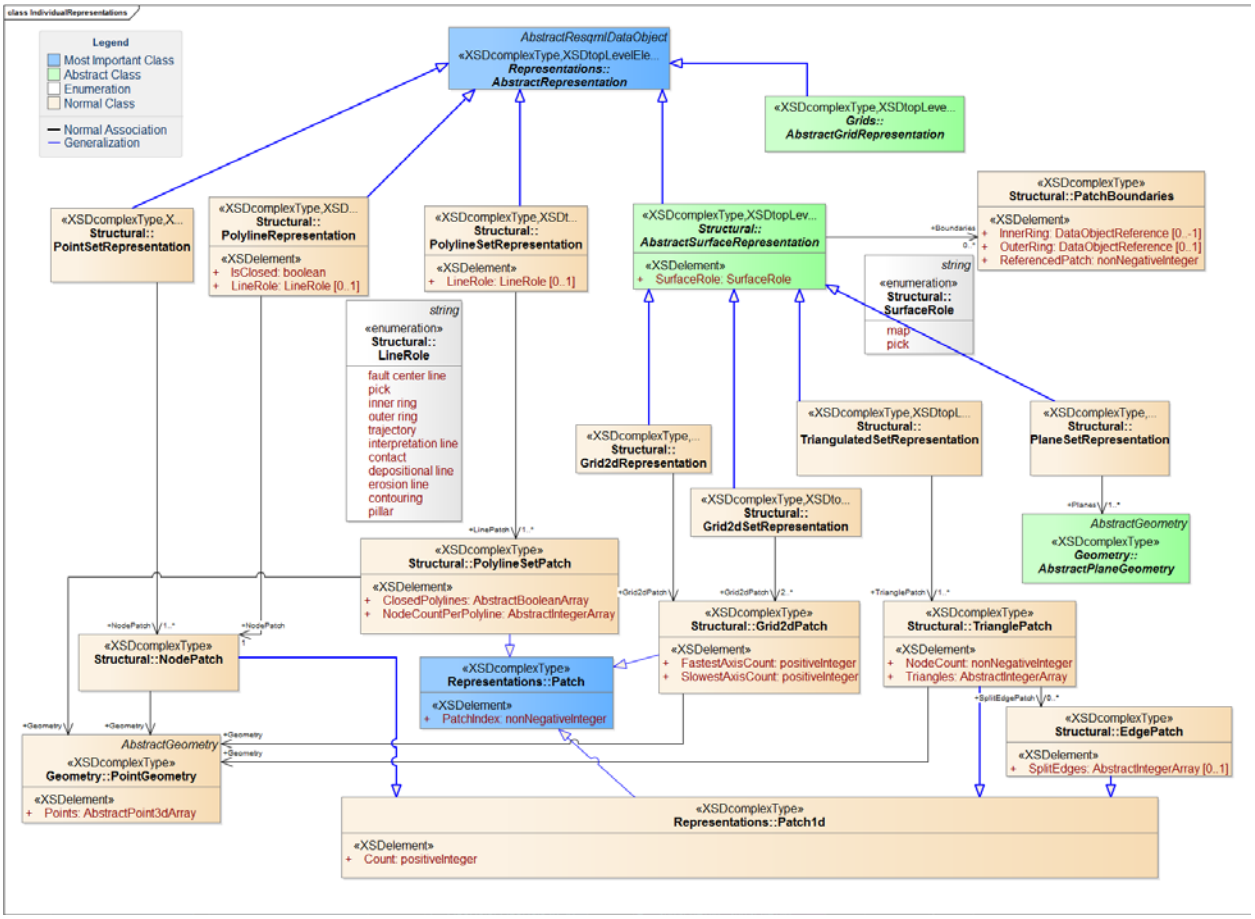


Figure 10-2—Individual representations.

10.2.1 Patch Management

The patch is the atomic element used to transfer individual structural representations. (For more information about patches, see Section 6.3 (page 62).)

All classes with "patch" in their name (e.g. NodePatch, PolylineSetPatch, Grid2DPatch, etc.) inherit from the parent abstract class of patches. Each patch must have a patch index, which is used to uniquely identify a given patch.

This patch index corresponds to the order in which the patches are stored in the XML instance.

RESQML uses this explicit method to avoid any ambiguity in data ordering among the elements. For example, the triangle indexing of a triangulated set representation consists of multiple triangles, each having its patch index, which specifies the relative ordering of the triangle patches.

10.2.2 Points

A point set representation is a set of nodes, with no topological information. It can contain one-to-many point set patches of nodes (node patch). Each set of nodes corresponds to one node patch, which has a count value equal to the number of nodes. Each node patch is a 1D patch, which must know the number of nodes contained in the abstract point 3D array, which is instantiated in a point 3D HDF5 array.

10.2.3 Polylines

10.2.3.1 Polyline Representations

A polyline representation is made of a single polyline or "polygonal chain," which may or may not be closed; it can be specified as closed by setting the Boolean value to true. Each polyline representation

has an implicit topology. This topology consists of attaching the nodes in sequence by following the order of the nodes contained in the abstract point 3D array, which is an instance of a point 3D HDF5 array. The number of nodes of each polyline representation is given by a “count” value.

For a closed polyline (Boolean = true) the first and the last point are identical (the X,Y,Z value are repeated).

10.2.3.2 Polyline Set Representations

For better data transfer performance (more compact datasets), polylines and polygonal chains can be assembled into polyline set representations. In sets, each single polyline embedded into the set representation has an implicit topology. This topology consists of attaching the nodes in sequence by following the order of the nodes contained in a point 3D HDF5 array, which inherits from the abstract point 3D array.

A polyline set representation has two pieces of explicit topological information:

- The number of nodes for each polyline
- A Boolean to indicate if a polyline embedded into the set is closed or not
- When the “closed polyline” Boolean is true, the first and the last point of the given polyline are identical (the X,Y,Z value are repeated).

Note that the topological relationships between the polylines within in a set are NOT explicit. Reader software can read them in the order in which they are stored, but that order may not be important.

Polyline or Polyline Set Roles. The software writer can specify a role for these polylines from this list: fault center line, pick, inner ring, outer ring, trajectory, interpretation line, contact, depositional line, erosion line, contour line, or pillar.

10.2.4 Surfaces

The abstract surface representation is the parent class of all structural surface representations. For surfaces, the concept of patch is used to help the reader software to associate information that may be delivered in several parts. Each patch is a part of a representation, and all the patches together represent one interpretation of a geological object. These surfaces may consist of one or more patches; these patches may be bounded by an outer ring and several inner rings.

A surface may have two roles:

- Map, a representation support for properties.
- Pick, representation support for 3D points picked in 2D or 3D.

A surface may have patch boundaries for some referenced patches as inner and/or outer rings. The inner and outer rings can consist of any polyline representation, polyline set representation, or (linear) subrepresentation of an abstract surface representation.

The writer must give in the referenced patch the patch index corresponding to the order in which the surfaces are stored in the XML instance.

RESQML has these main ways to represent surfaces:

- Triangulated set representations (see Section 10.2.4.1 below).
- Grid 2D and grid 2D set representations, including lattice (see Section 10.2.4.2 (page 114)).
- Plane set representations (see Section 10.2.5 (page 115)).

10.2.4.1 Triangulated Set Representations

The triangulated set representation contains one-to-many triangle patches (**Figure 10-3**). (For an example of a triangulated representation that includes geometry and topology, see **Figure 10-4**.) The patch 1D count specifies the number of triangles in each triangle patch.

The indices of all the nodes on which the geometry is defined are implicit. For each node, this index corresponds to the order of the nodes in an array of 3D points starting with the first; the array is typically stored in an HDF5 dataset. The topological arrangement of these nodes in triangles is described in triangle patches for each patch in the set.

Triangulated set representations also follow these guidelines:

- Split edges can be indicated in an edge patch instance (to complete the topological arrangement).
- The geometry of the nodes is given by a point 3D array, typically stored in an HDF5 dataset.
- The topology association of the triangles is also typically stored as an HDF5 dataset.

Business Rules. The patch construction is a powerful and important concept in RESQML. For use of patches with triangulated set representations, software writers MUST observer the following business rules.

BUSINESS RULE: Within a patch, all the triangles must be connected.

The patch contains:

- Number of nodes within the triangulation and their locations.
- 2D array describing the topology of the triangles.

BUSINESS RULE: Each triangulated patch must have its proper number of nodes, which are used to set up all the triangles of the patch. If a particular node is shared between two patches, the location of this node must be repeated twice (or more, as used). This case results in two (or more) nodes with two (or more) different indices, but with the same X,Y,Z value.

To express the association of nodes that belongs to several patches, the writer must use the subrepresentation and subrepresentation identity mechanism. (For more information, see Section 6.3 (page 62).)

BUSINESS RULE: The writer must ensure that each patch is non-manifold, that is, where two or more triangles contact at one point (see http://en.wikipedia.org/wiki/Manifold).

BUSINESS RULE: The writer must ensure that a patch is correctly oriented. This means that all the triangles have the same local orientation.

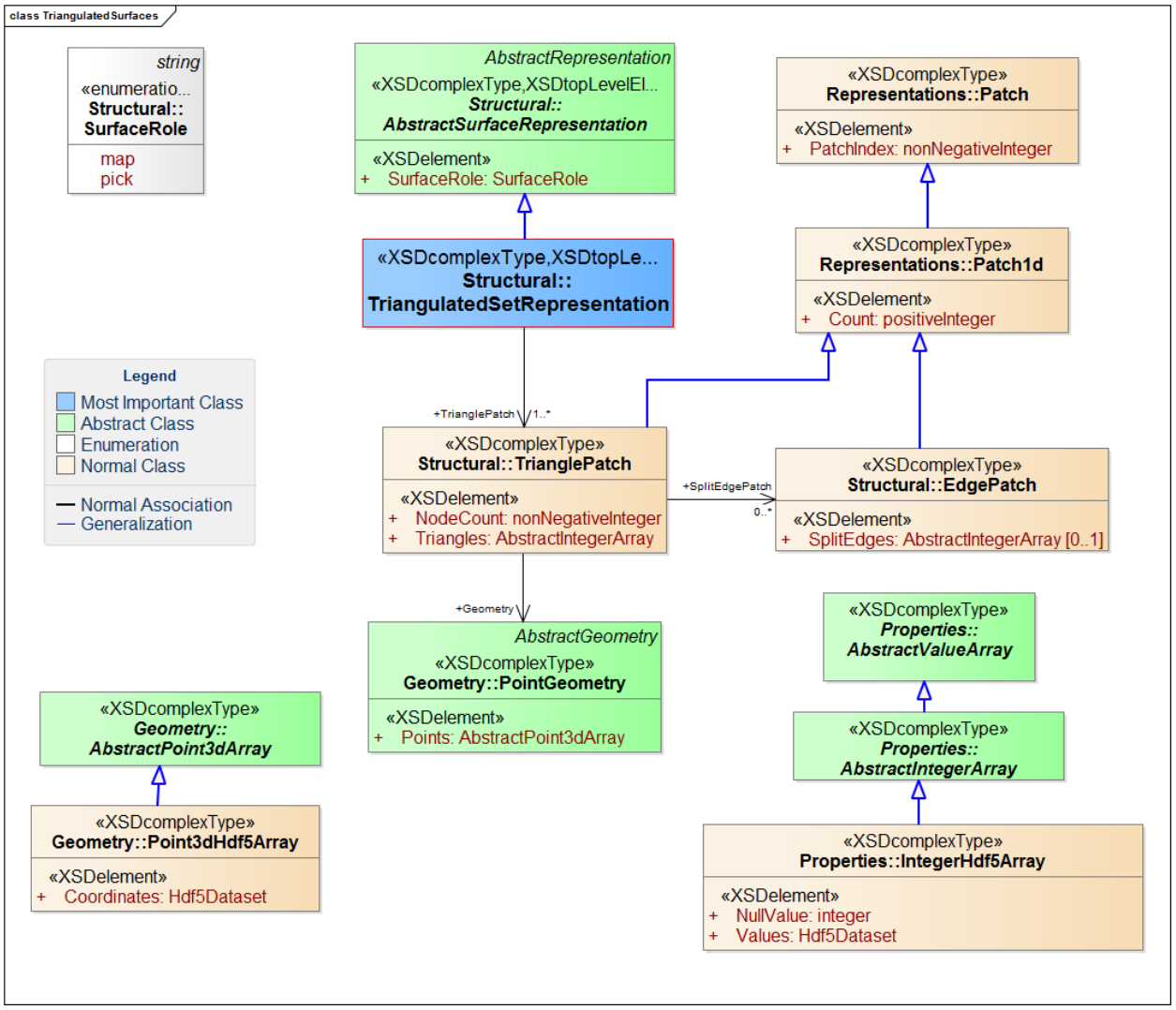


Figure 10-3—Triangulated surface representations.

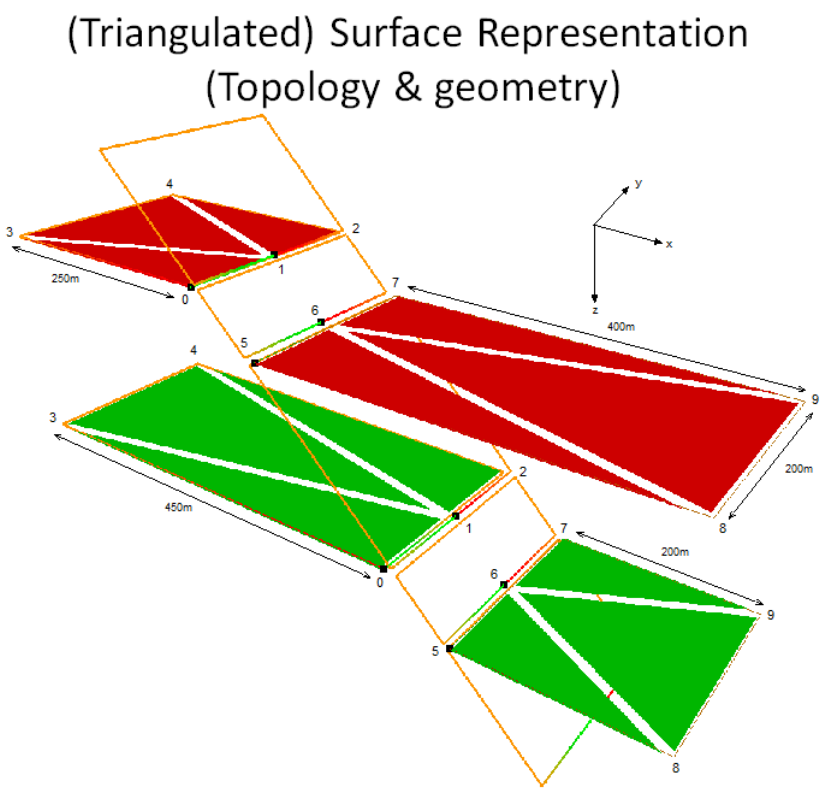


Figure 10-4—Example triangulated surface representation: topology and geometry.

10.2.4.2 Grid 2D Representation and Grid 2D Set Representation

Figure 10-5 shows the UML model for both of these representations, which are explained below.

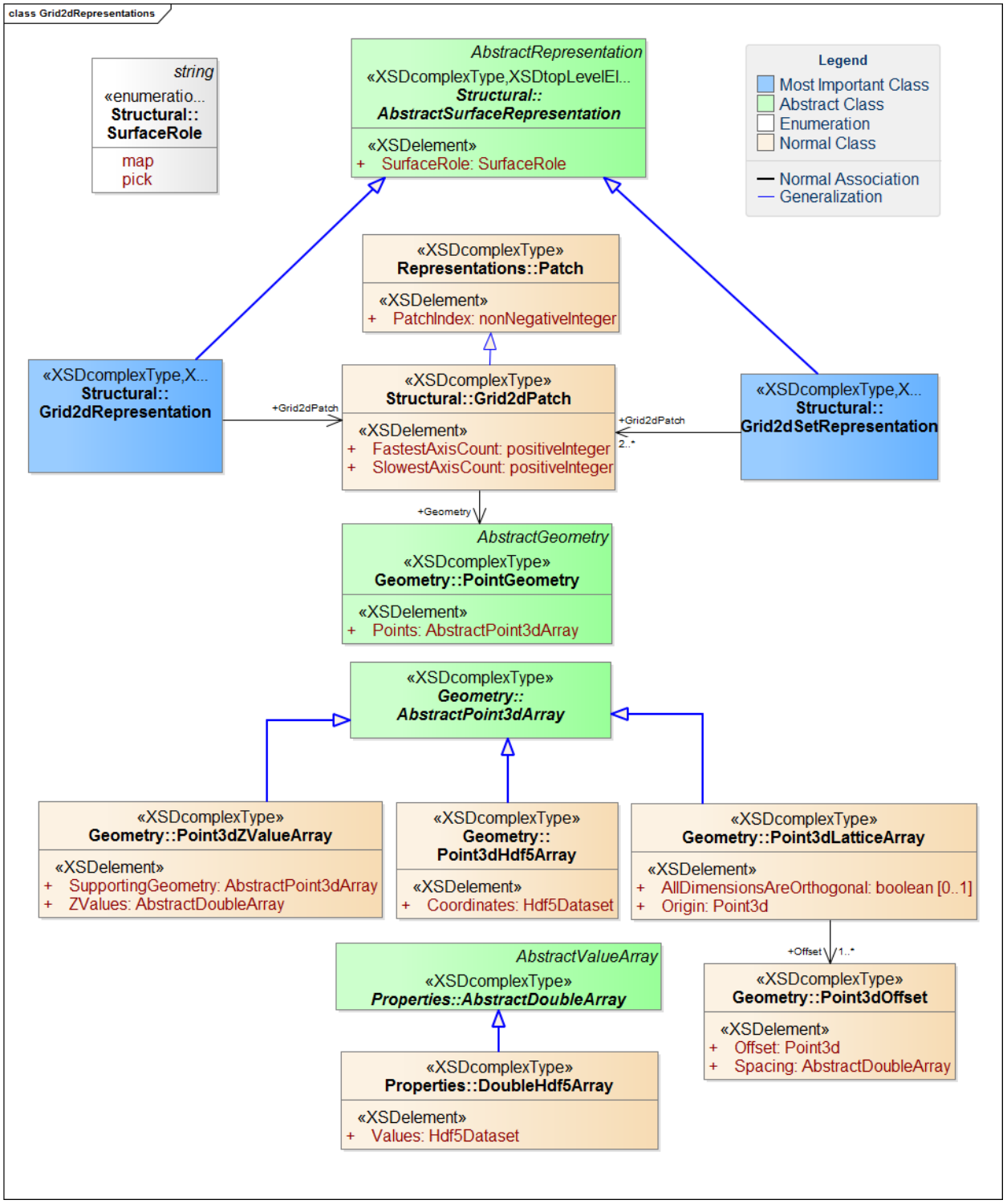


Figure 10-5—Grid 2D and grid 2D set surface representations.

A grid 2D representation is composed of only one patch located on one lattice (defined for 2 dimensions; for more information on lattices, see Section 10.2.4.3 below). The grid 2D set representation is composed

of several patches, which correspond to one unique representation for which the different patches can be located by diverse lattices.

The geometry can be accessible three ways:

1. If no point lattice is provided, geometry is directly accessible on a completely defined array of explicit X,Y,Z 3D points (point 3D HDF5 array).

   For an array of X,Y,Z 3D points without a lattice, an explicit HDF5 dataset is used. The number of points is implicit, given by the dimension of the HDF5 dataset.

2. Indirectly accessible because the geometry can be obtained by the association between an array of Z values of 3D points (Point3DValues) plus a (2D) point lattice defined as the "supporting geometry" on these Z values.

   For an array of Z values of 3D points (Point3DValues) and a lattice, the nodes are aligned in only one 2D array of 3D points:

   - To explore the array of Z values corresponding to these patches (one for grid 2D representation, several for grid 2D set representation), the fastest axis corresponds to the number of nodes in the second direction (N2), with index I2, and the slowest axis corresponds to the number of nodes in the first direction (N1), with index I1. The data order follows the index order: I1 + I2*N1.
   - In this case, the topology association of the nodes is implicit (each I,J point is connected to I-1,J-1; I+1,J+1; I-1,J+1; I+1,J-1) and uses a 1D index, with values from 0 to N1*N2-1 for a structured 2D grid.

3. If a 3D point lattice (with explicit X,Y,Z location of each point) is given, the geometry is directly accessible.

10.2.4.3 How to Use a Point3D Lattice to Complement the Geometry of a 2D Grid Representation

The lattice itself defines the X,Y location of each point. Using this method is very efficient and allows the selection of an offset and a spacing in each direction.

To implement such a lattice:

- The writer may declare that all directions are orthogonal (which allows the reader to avoid some unnecessary checking).
- The writer must define an origin for this lattice.
- The dimensionality of the lattice is given by the number of "offsets" defined. If you write an instance with one offset only, your lattice will be one dimensional.
- For a multi-dimensional lattice, the ordering of the offsets follows their dimension, i.e., the first offset in the XML instance is the first dimension of the lattice array.

For a grid 2D representation, you must declare two instances of point 3D offsets. The dimension of each is the number of offset points declared for each point 3D offset.

To implement, you must know that a lattice of N offset points is described by a spacing array of size N-1. The offset between points is given by the spacing value multiplied by the offset vector. For example, the first offset is 0. The second offset is the first spacing offset. The third offset is (first spacing + second spacing) offset, etc.

The spacing may be regular, in which case, a count and only one spacing value is given. In other cases, the number of spaces between points is inferred from the dimension of the offset.

10.2.5 Plane Set Representation

Figure 10-6 shows the UML model for the plane set representation, which is used to represent things such as fluid boundary interpretations (such as water-oil contacts) or frontiers (boundaries) that limit a volume of interest. Just as any other RESQML surface representation, these planes can have one outer ring and several inner rings to limit their extension.

Each plane can have either:

- a horizontal plane geometry (one Z coordinate).
- a tilted plane geometry defined by three 3D points.

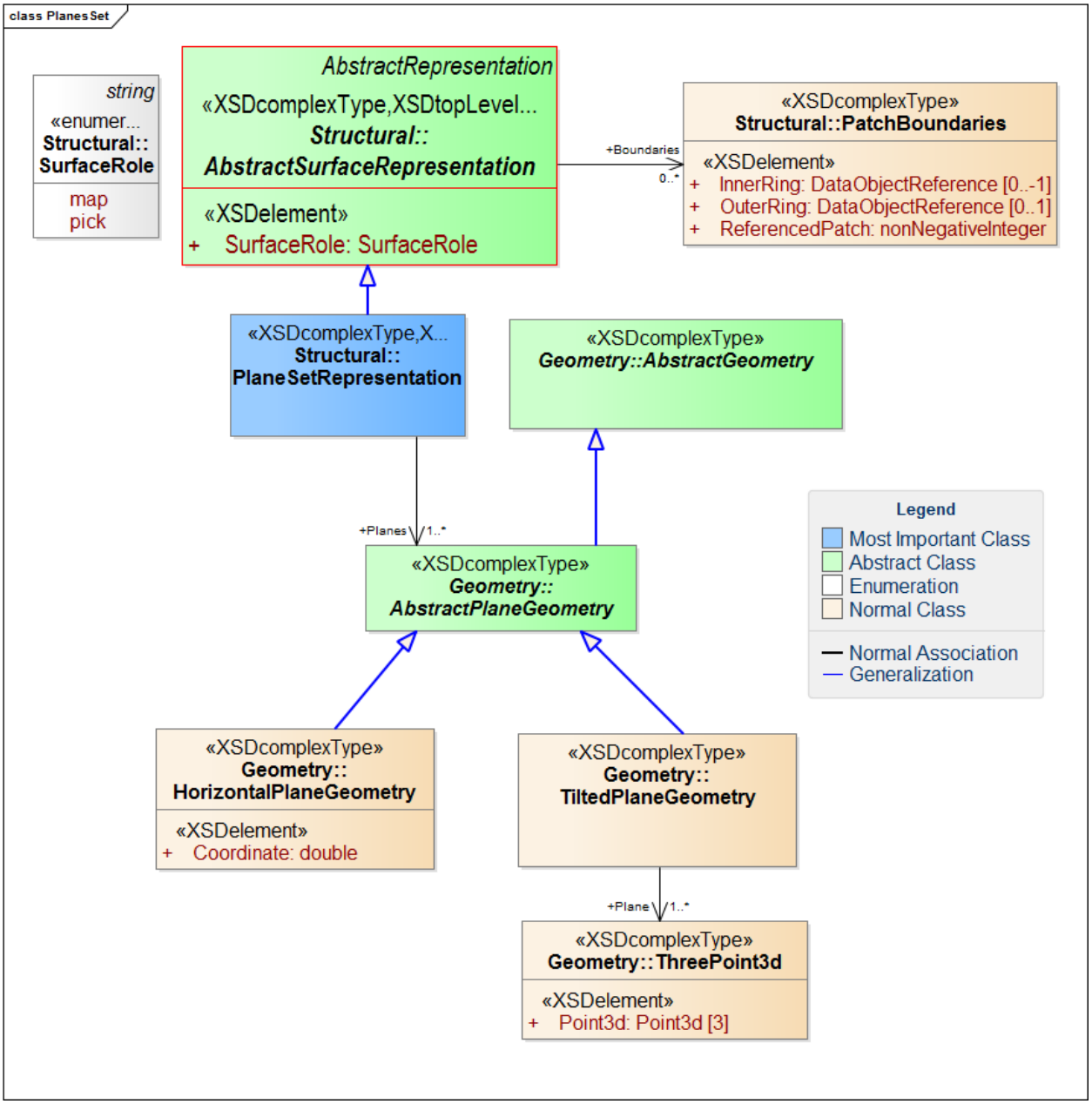


Figure 10-6—Plane set representation.

10.3 Organization Representations (Representation Sets and Frameworks)

Organization representations (**Figure 10-7**):

- Represent interpretations of earth models, structural organizations, stratigraphic organizations, stratigraphic columns, fluid organizations, etc.

- Are created by using representation set representations to collect together a "bag" of interpretations (either individual or other sets) or associate them topologically into a framework. (For more information on representation set representations, see Section 6.7 (page 64).)

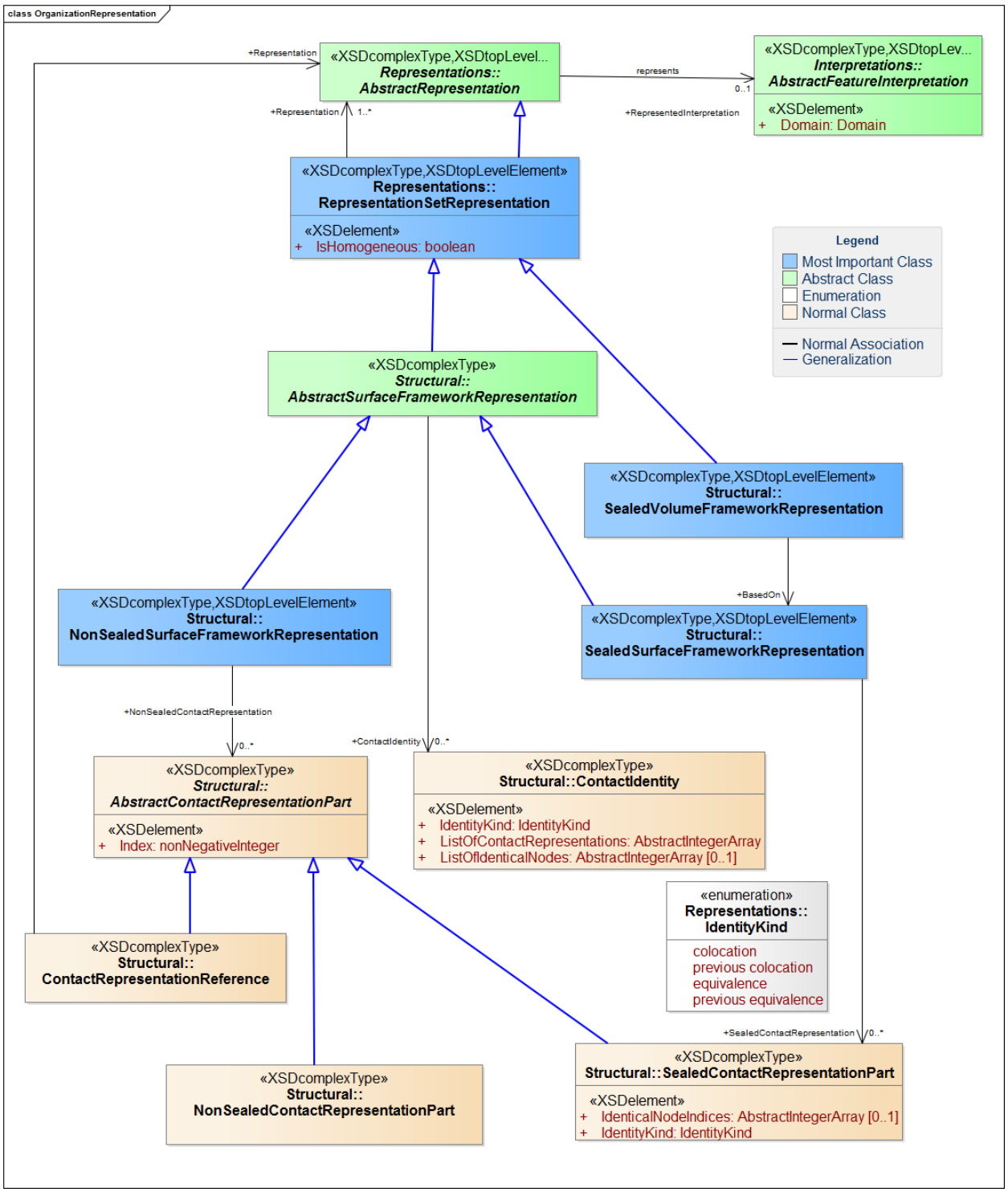


Figure 10-7— Organization representations (simplified diagram).

10.3.1 Representation Set Representation

Representation set representations (**Figure 10-8**) are used to carry an indexed assemblage of individual representations which will be used to set up representations of organizations Interpretations. An implicit representation index is given by the writer as an order in the "sequential" list of Representation UUIDs which will be gathered into the "XML instance" of a representation of an organization interpretation.

This implicit representation index is important because it will be used in the sealed surface framework and sealed volume framework to define the contact patches and the oriented macro faces. In fact the reader must create this index in its own code if he want to reuse it to establish the link between the individual representations and the contacts in the frameworks.

The representation set representation is also the parent class of the framework representations. Because the framework representations inherit from this class, they inherit the capability to gather individual representations into sealed and non-sealed surface framework representations, or sealed volume framework representations. In this context, the representation index is used to define the contact patches.

Other usages of representation set representation are presented in Chapter 6 (page 59).

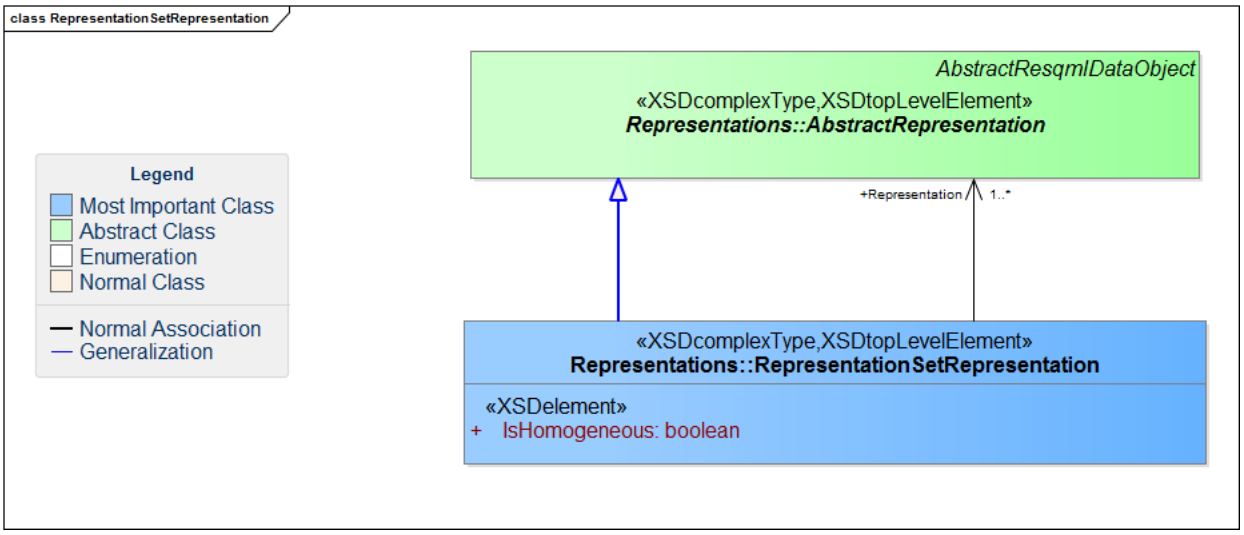


Figure 10-8—Representation set representation

10.3.2 Framework Representations

To create a framework representation, do the following:

- Group individual representations into a set.
- Describe the topological relationships between the individual representations by their contact representations.

These contact representations (in the UML diagram, contact representation parts) can be non-sealed or sealed. If you group only sealed contacts then the surface framework representation is itself sealed. Because a volume framework representation is a boundary representation (BREP), it must be sealed.

Each contact patch is a 1D patch containing count and a patch index, which can be reused to associate other patches together (example use case: "flower faults"). The patch contains a subset of topological elements of an existing supporting representation (identified by its representation index). The topological elements are given by an ordered list of nodes of this supporting representation (integer values).

10.3.2.1 Non-sealed Surface Framework Representation

Figure 10-9 shows the UML model of the non-sealed surface framework representation, which is explained below. **Figure 10-10** (page 120) shows a graphical example of a non-sealed framework.

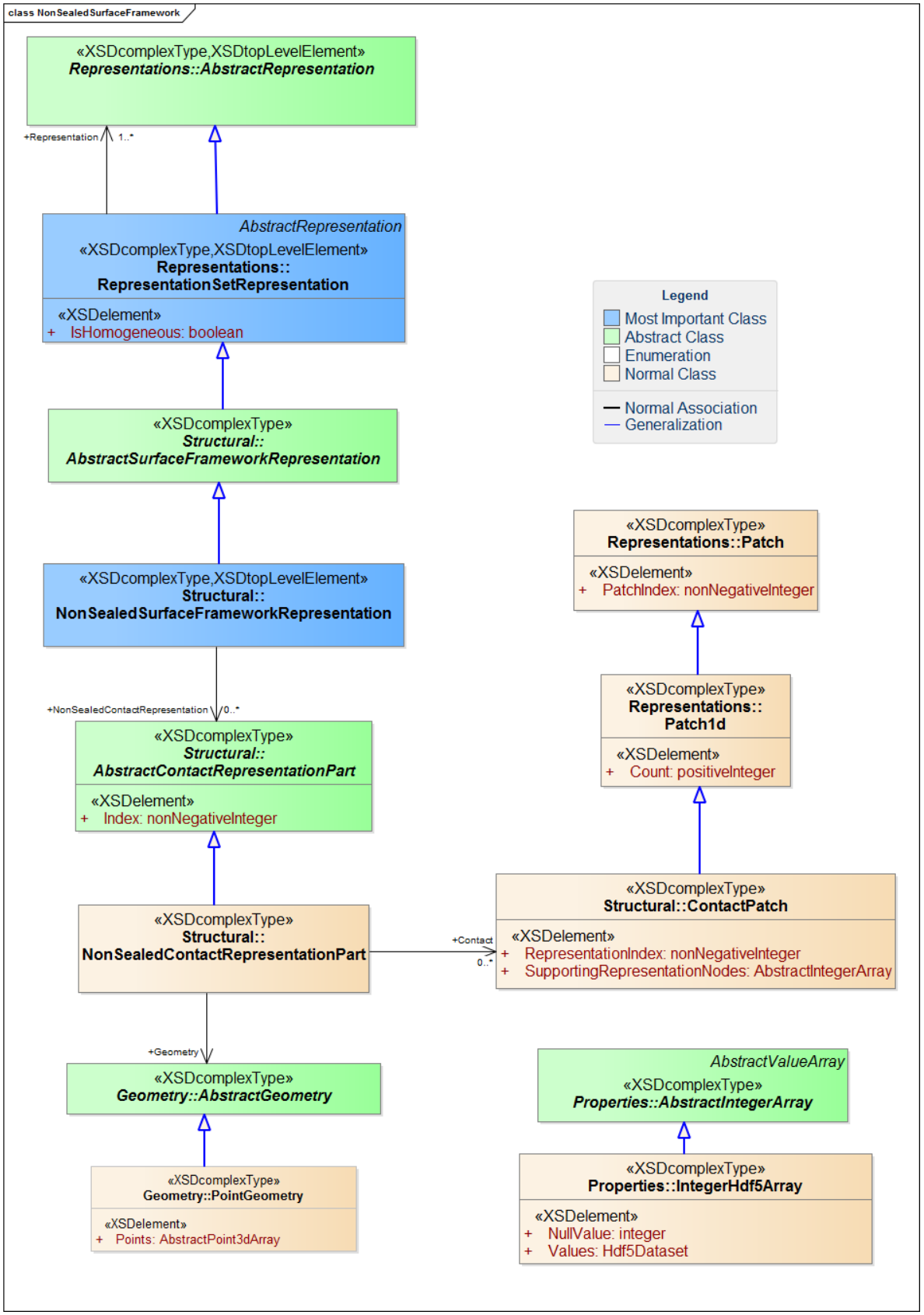


Figure 10-9—Non-sealed surface framework representation.

Figure 10-10 shows an example of a non-sealed framework. The objective of this representation is to gather, step by step, the structural information on boundaries and contacts between boundaries, all along the workflow, even if they are not all totally topologically consistent. A software package can read this information, and based on it, can set up a sealed surface framework representation.

The non-sealed surface framework contains line contact representations (surface/surface contact interpretations between boundaries) and representations of boundary interpretations (horizon, faults, and frontiers). There is no requirement to ensure topological consistency between these representations.

The non-sealed surface framework representation contains a list of representation list elements and a list of non-sealed contact representation parts. Each element of the list has one given “implicit” index given by the writer by the order of writing in the XML instance file.

Each element can have a geometry (one geometry is represented in Figure 10-9 by an abstract point3D array, which can be described by an X,Y,Z point 3D as a polyline. Or each element can be defined by a contact patch.

This construction allows users to include both sealed and non-sealed contacts.

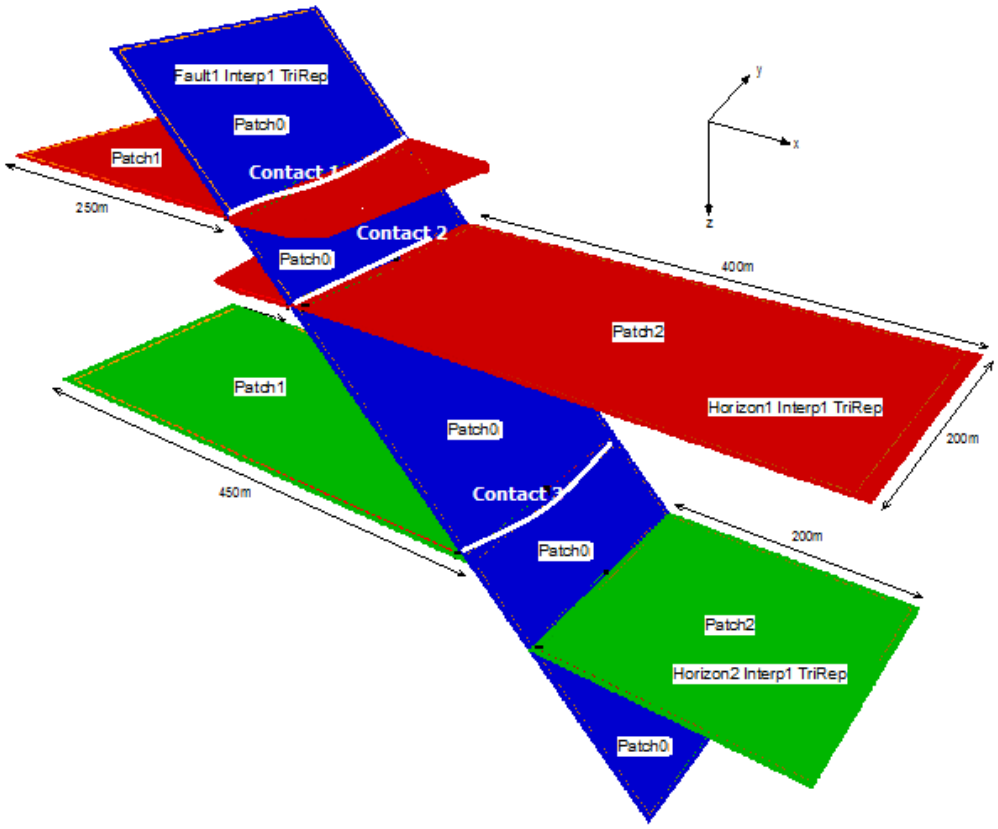


Figure 10-10—Example of a non-sealed surface framework. (The example scenario in Section 9.3 (page 93) is based on this framework.)

10.3.2.2 Sealed Surface Framework Representation

Figure 10-11 shows a UML model of a sealed surface framework representation. **Figure 10-12** (page 123) shows a graphical example of a sealed surface framework.

Use this sealed framework to define a surface representation of a consistent structural organization interpretation. Using this representation as a starting point provides gridding software with a clean topology and geometry framework and avoids inconsistent geometry usage. When several nodes are topologically associated, they have absolutely the same geometry, even if they belong to different representations of “structural objects”. Software can read this information and set up a sealed volume framework representation or a grid representation on this base.

A sealed surface framework representation contains line contact representations (surface/surface contact interpretations between boundaries) and representations of boundary interpretations (horizon, faults, frontiers) and associations between line contact representations (contact identity). These line contact representation are only defined by their topology (node index) into their supporting representation.

Because this sealed surface framework contains only topological information between the involved contacts and individual representations, the geometry of the sealed contact representation part belongs to the supporting representation nodes.

A complete sealed surface framework representation contains a list of representation list elements, a list of sealed contact representation parts (each element of the list having one given index) and a list of contact identities.

To define a sealed contact representation part and contact identity, use the same mechanism as the subrepresentation and (sub)representation identity (see Section 6.5 (page 63)).

A sealed contact representation part associates together two or more contact patches defined by their representation index. These sealed contact representation parts must have an identity kind of “colocated" or "equivalent.” The number of identical node indices associated with a sealed contact representation part indicates which nodes (identified by their common index in all contact patches) of the contact patches are identical. If this list is not present, then it indicates that all nodes in each representation are identical, on an element-by-element level.

A contact identity associates already defined contact patches to add an identity kind ("previously colocated" or "previously equivalent") to this association of contact patches (see Section 6.5 (page 63)).

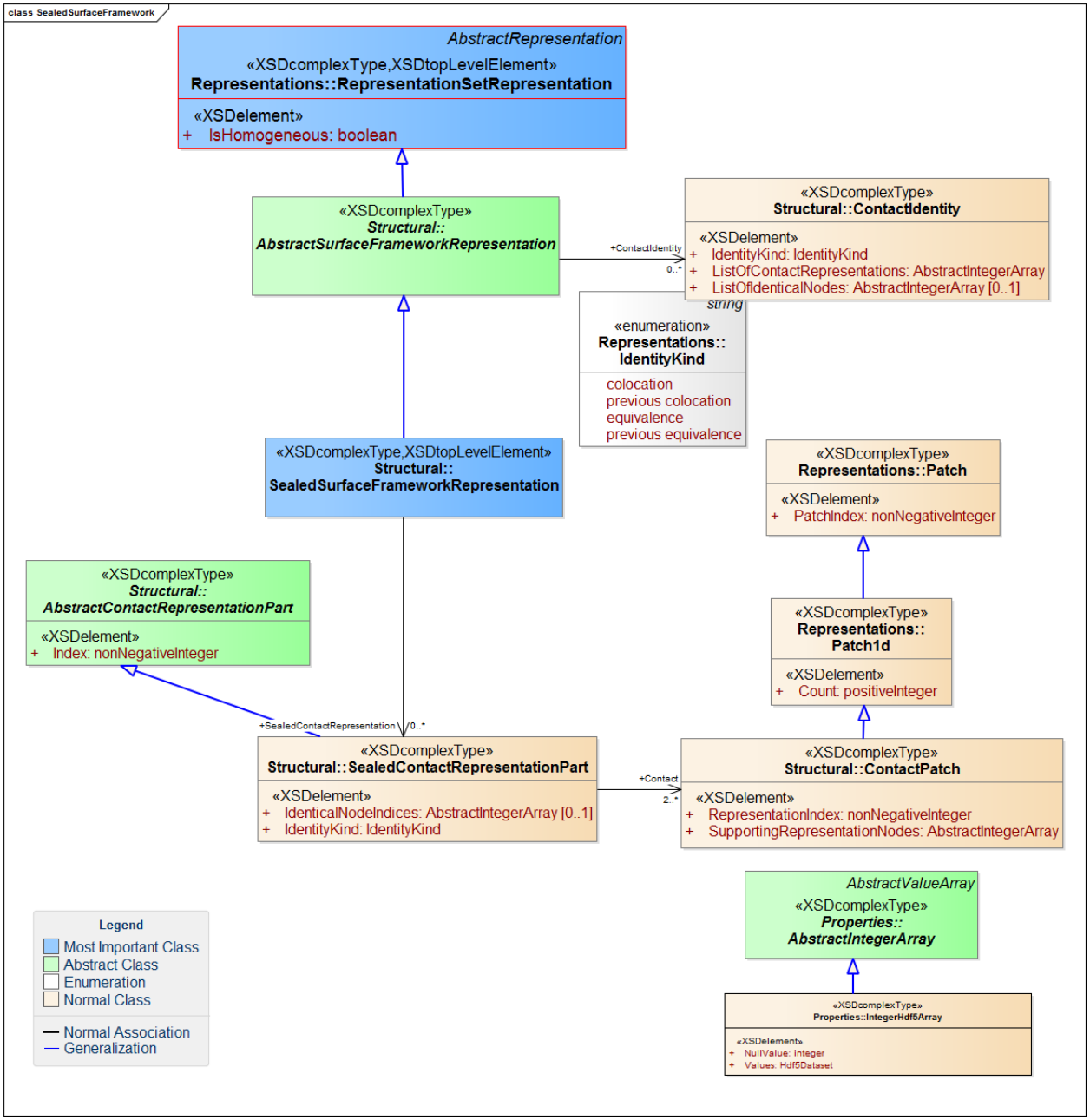


Figure 10-11—Sealed surface framework representation.

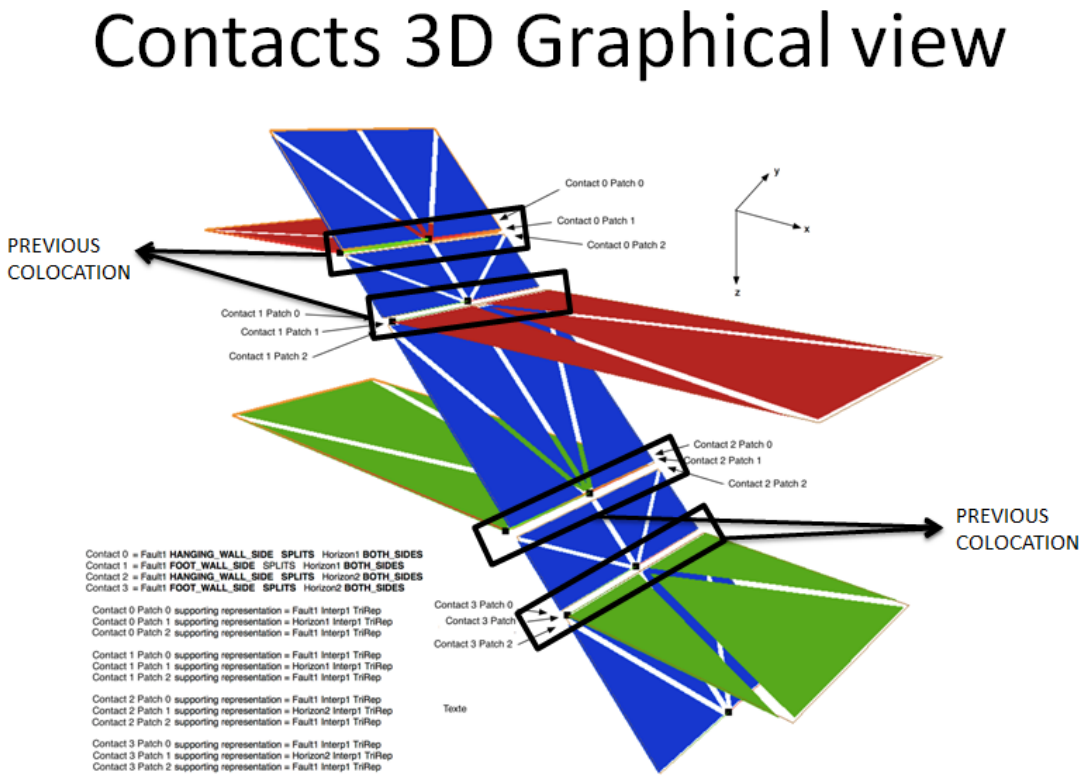


Figure 10-12—Example of a sealed surface framework.

10.3.2.3 Sealed Volume Framework Representation

Use this representation to define a volume representation of a consistent stratigraphic organization interpretation. Using this representation as a starting point gives gridding software a detailed clean topology and geometry framework and avoids inconsistent geometry usage. When several nodes are topologically associated, they have absolutely the same geometry, even if they belong to different representations of “structural objects”.

By delivering a sealed volume framework representation, a software package validates a consistent understanding of the geological stratigraphy interpretation on which property estimations, fluid flow simulation, and basin modeling can be conducted.

Note that the sealed volume framework representation is based on a sealed surface framework representation.

The sealed volume framework representation is described as a boundary representation (BREP): (http://en.wikipedia.org/wiki/B-rep). It contains surface contact representations (volume/volume contact interpretations between rock feature interpretations (stratigraphic units, geological bodies, fluid units) and volumes defined by shells.

Figure 10-13 shows the UML model for the sealed volume framework, which is explained below. **Figure 10-14** (page 125) is a graphical example of a sealed volume framework.

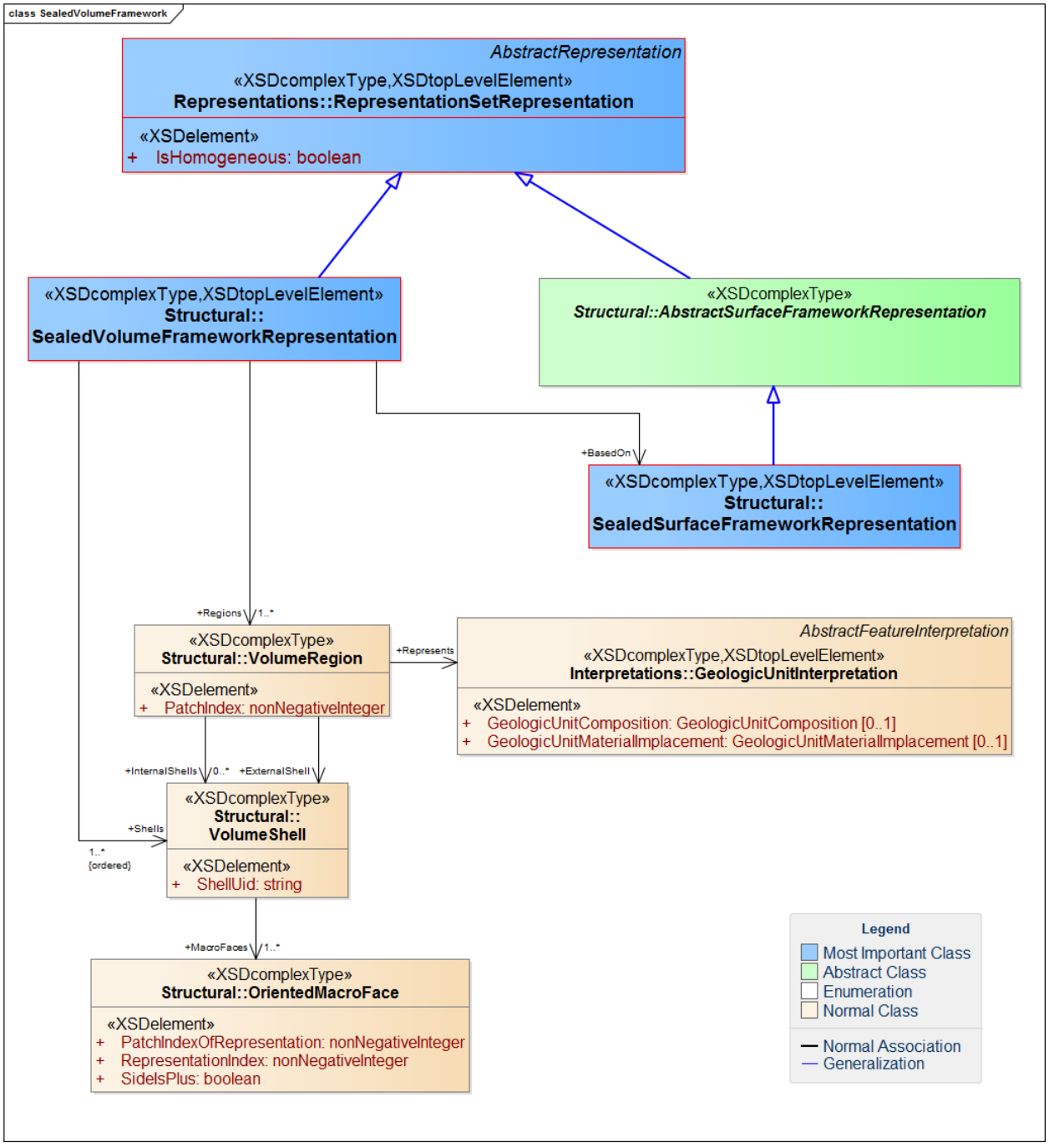


Figure 10-13—Sealed volume framework representation.

A sealed volume framework representation can be composed of several volume regions, each of which represents a rock feature interpretation (a geologic unit interpretation for the geosciML standard (http://www.geosciml.org/).

Each volume region has one external volume shell and can have several internal volume shells.

A shell is composed of the sealed contact representation parts defined in the sealed surface framework representation on which this sealed volume framework representation is based, and by oriented macro faces. An oriented macro face is an element of a volume shell that is defined by a set of oriented faces belonging to boundable patches.

A macroface may describe a contact between:

- two structural, stratigraphic, or fluid units.
- one boundary feature (fault or frontier) and a unit.

This oriented macro face can be described by one patch of an individual representation. To indicate the right surface, the writer software must specify (by a representation index) from which representation patches are “extracted” and must specify which patch is involved by giving its patch index representation.

Usually, a macroface is a bounded open subset of a plane or a curved surface in 3D, delimited by an outer contour and zero and one or more inner contours describing holes.

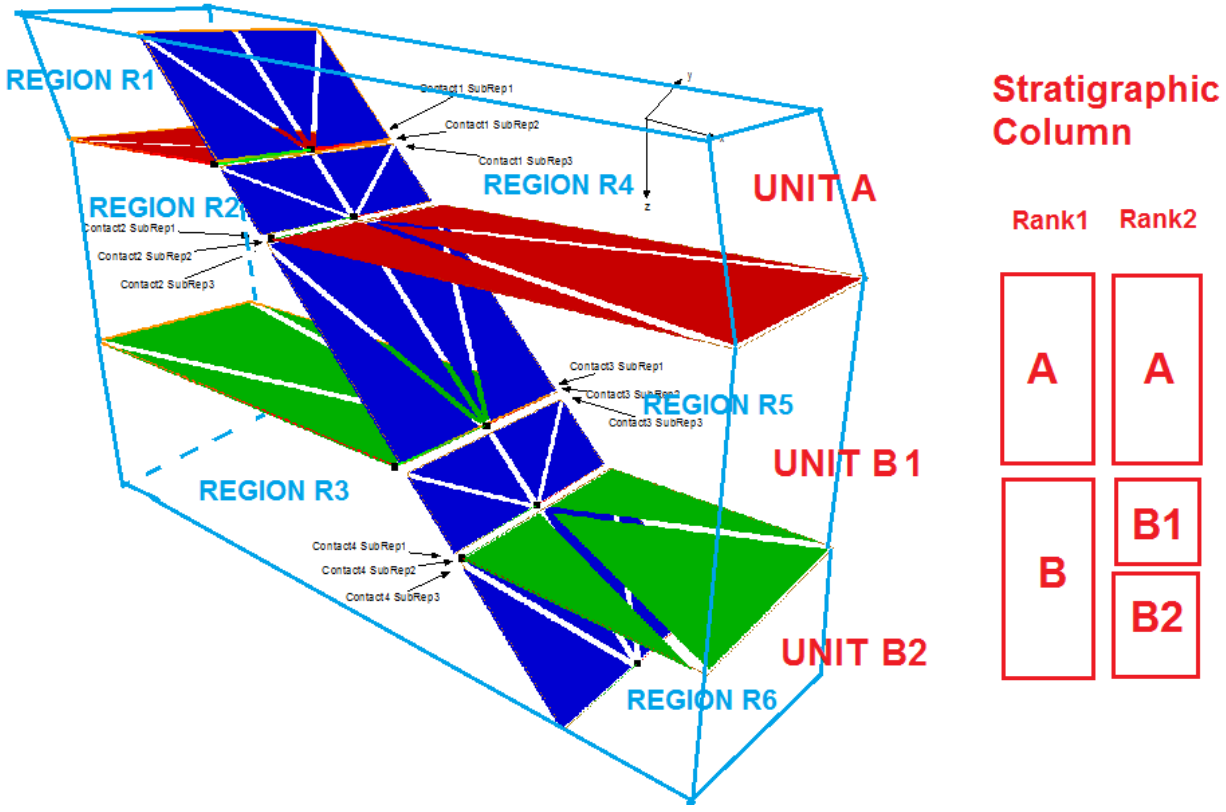


Figure 10-14—Example of a sealed volume framework.

11 Grids

A grid is a RESQML representation that provides a cellular discretization of space. A grid shares three important characteristics with all other RESQML representations:

- A description of the topology (indexing) and geometry of the grid representation.
- A grid, or a subrepresentation of a grid, may provide a representation of an interpretation of a RESQML geologic feature, most often an earth model or a structural organization.
- Properties may be attached to a grid representation, i.e., a grid supplies the topological support for properties.

For information on concepts shared across all RESQML representations, see Chapter 6 (page 59).

RESQML also provides a closely related “grid connection set” representation, which is based on “cell-face-pairs”, for the purpose of describing the connections between grid cells, and a “blocked wellbore” representation to describe wellbore trajectories discretized on a grid.

Although it may seem reasonable to organize grids by the geometry of their cells, industry applications more naturally segregate grids by their topology, i.e., the dimensionality of the indexing of the cells. RESQML follows this approach and supports six distinct grid classes:

- Three grid classes are fundamental and will be recognizable to most practitioners.
- Three grid classes are combinations of these fundamental classes, and provide support for advanced variations in unstructured grids.

All grids support various extensions, such as higher order cell geometry, although some extensions may only exist for particular classes. For example, only IJK grids support radial grid cell interpolation. The corner point grid supported by many applications is a specific example of an IJK grid, although without all of the extensions now supported in RESQML. This chapter provides:

- A "quick start" to grids, which provides advice on the use of those features that are most basic for export/write and import/read of RESQML grids.
- Detailed sections that describe the objects that contribute to each of the grid classes and how they may be used.
- Examples of the various types of grids.

NOTE: In RESQML v2.0.1, capabilities for modeling streamlines have been added. For more information, see Section C.3 (page 230).

11.1 Grids: Quick Start

RESQML provides a rich data model for grids, created for the purpose of data exchange. However, because current and developing industry practice is actually quite diverse, the data model is extremely flexible, to the point where no specific application is expected to be able to import an arbitrary RESQML model. Hence, it is important to provide advice which emphasizes the most basic features of a grid. All of these items will be described in much more detail within the chapter, but basic guidance is provided here.

11.1.1 Topology

The primary organization of grids within RESQML is by the dimensionality and indexing of the grid cells. Fundamental classes are IJK (3 indices), column-layer (2 indices), and unstructured (1 index). This is an intrinsic characteristic which should be preserved on both export and import. Changes of indexing (swaps in IJK axis directions, IJK to column-layer, or column-layer to unstructured) are technically possible, but will sufficiently damage a round-trip workflow that such operations are considered to create a new grid, not to transfer an existing grid.

11.1.2 Geometry

With the exception of block-centered grids, which have no explicit geometry, the geometry of a grid is based upon the geometry of points. Points may be specified explicitly, e.g., by three (X,Y,Z) coordinates,

or implicitly using parametric spline representations. The geometry of any grid is based upon a lowest order description but with additive optional extensions. The latter is a deliberate design to facilitate grid transfers.

11.1.3 Feature Interpretations

Grid representations may support a number of geologic and technical feature interpretations. The geometry of a grid often provides a representation for a structural framework and may be deliberately aligned with the inline and crossline lines of a seismic survey.

With the inclusion of fluids, a grid may also represent a complete earth model. Subrepresentations of a grid based on its indexable elements provide feature interpretations of geologic elements, for example, of horizons and faults. Faults should be represented using the “cell-face-pairs” of a grid connection set representation, because this provides information about the local grid topology, which is otherwise difficult to reconstruct.

11.1.4 Properties

Properties may be associated with any or all of the indexable elements of a grid representation, or of the closely related grid connection set representation. The most basic usage is to associate properties with the cells of a grid or the nodes (connections) of a connection set representation. (For more information on properties, see Chapter 8 (page 77).)

11.1.5 Advice on Grid Export

This section is intended to provide advice on aspects of grid export that experience has shown to be most variable from application to application. It is not an exhaustive list of important and useful grid features.

When exporting a grid, an application should especially preserve information that is difficult or impossible to reconstruct in the absence of the structural framework upon which a grid is often based.

- Include reference to the structural model interpretation from which the grid is derived.
- Export faults as grid connection set representations to support quantitative work, and export faults as a subrepresentation based on the pillars of a grid for qualitative work. (Stair-steps faults cannot be represented simply as pillars and are discussed in more detail, below.)
- Emphasize the use of “cell” and cell-face-pair “node” connection properties in preference to other property attachments.
- Take advantage of the parametric points because these include more information on the geometry of a grid than simply the position of the cell node vertices.
- For a grid with “layer gaps”, consider exporting a version of the grid with extra layers instead of gaps, because many geologic modeling applications do not support grids with such gaps.
- Take advantage of the redefined geometry representation, which allows one representation to be constructed from another. This may be used in a “belts and braces” approach to effectively export the geometry of a representation twice. For example, one representation may use the preferred description based on parametric points on spline curves to describe the coordinate lines of a grid, while another uses explicit (X,Y,Z) points. This ability should allow experimentation between different application vendors as the new standard comes into use.

11.1.6 Advice on Grid Import

- Preserve the topology of the grid by retaining the grid indices and dimensionality.
- Preserve the earth model or structural model interpretation upon which the grid is based.
- Import the lowest order grid geometry even if the higher order geometry or other extensions are not within the scope of the data model of the importing application.
- Be prepared to import parametric point geometry, because the parametric lines upon which they’re based provide more information on the geometry of the grid than the positions of the cell node vertices.

Only one of the six grid classes now supported by RESQML has seen widespread historical use in the industry (corner-point grids). Lack of shared data standards for 2.5D unstructured column-layer grids and for fully unstructured 3D grids have limited their use and accessibility in the industry, and have impeded cooperation between different technical domains, e.g., flow simulation and geomechanical calculations. A period of experimentation and learning should be expected as the new RESQML data standards make their impact.

11.2 Example of Grids that can be Transferred with RESQML

Figure 6-1 shows the variety of grids that may be represented in RESQML, labeled A-F. Of these different grids, only image A, an IJK grid, could be transferred in RESQML v1. Grid B is an example of a 2.5D perpendicular bisector (PEBI) grid, which is represented as a RESQML unstructured column-layer grid. As with an IJK grid, there is a column-layer structure, but unlike an IJK grid, the columns are not structured.

The remaining grids are all examples with very different means of representing the grid geometry.

- In Grid C, each unstructured grid “cell” has been replaced by a pore volume and a point, and each inter-cell transmissibility has been replaced by a link between cells. This is an example of the “grid-free” representation used by the newest reservoir simulation applications.
- Grid D is an example of an IJK grid, but the grid cell geometry is specified by cell dimensions (DX, DY, DZ) instead of by the corner nodes of each cell. This is an example of one of the oldest reservoir simulation grid formats, which can now be transferred in RESQML.
- Grid E is an example of a polyhedral unstructured grid. The geometry of each cell is described as a polyhedra in space.
- Grid F is an example of “XYOT” truncated grid, which has an underlying IJK grid description, but includes split and truncated cells at fault block boundaries. The resulting cells may have more than six faces and more than eight corner nodes.

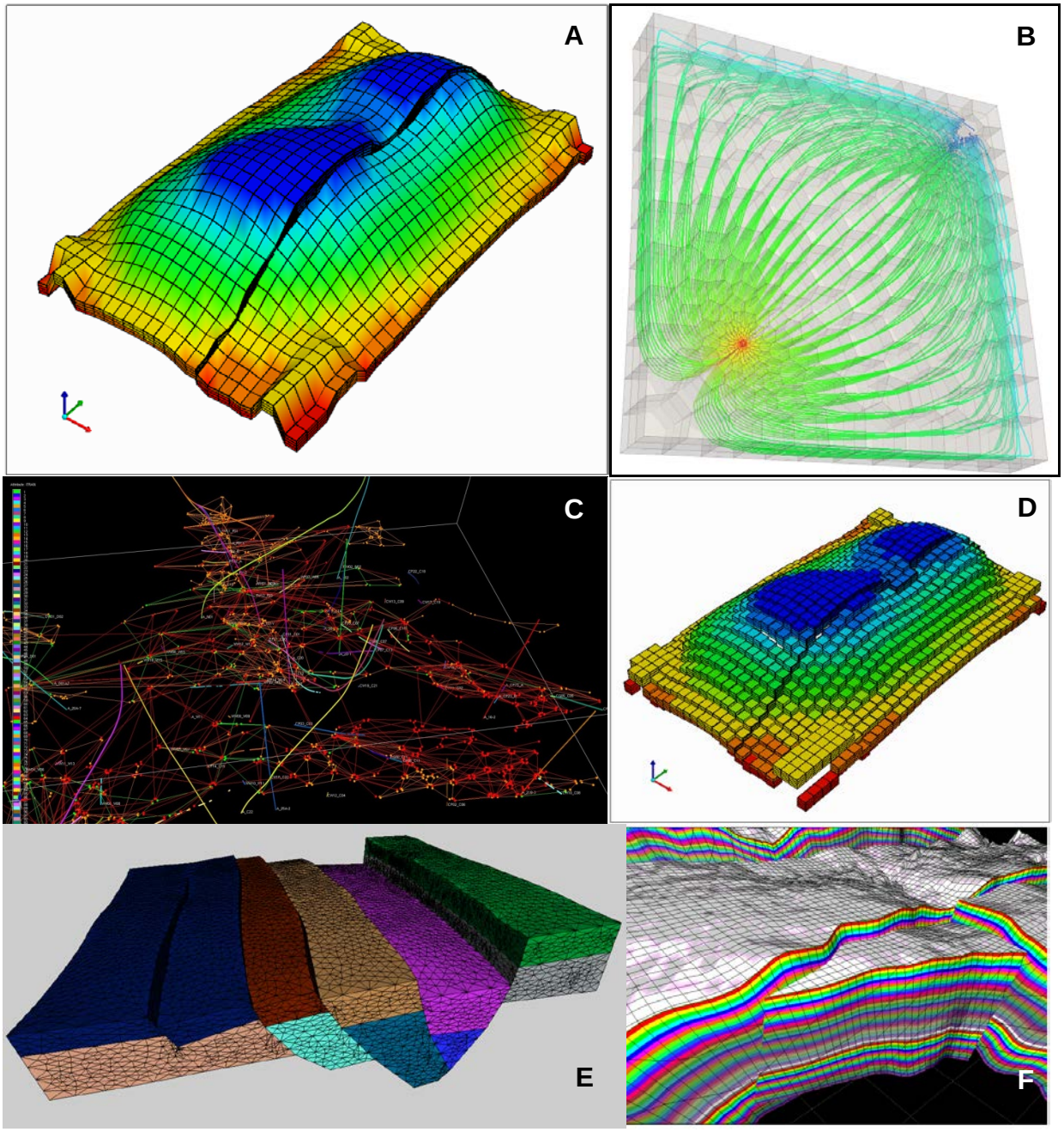


Figure 11-1—Grid examples that can be transferred with RESQML.
Sources: Figures used with permission or re-use policy from the respective sources. Further reproduction prohibited without permission. For full citations and copyrights, see Section 11.18 (page 195). (A), (D) and (E): Contributed by RESQMLSIG members; (B) Zhang et al. (2011); (C) Martin (2010); (F) Lasseter (2004).

11.2.1 Local Grids

Complex grid patterns may also be developed by replacing portions of a grid locally by another grid (**Figure 11-2**). For example, this allows grids to have high resolution near wells, distorted to follow the geometry of the well, embedded in a coarse regular grid. Local grids were supported in RESQML v1 for corner-point grids. In RESQML v2 they may be constructed for any of the grid classes.

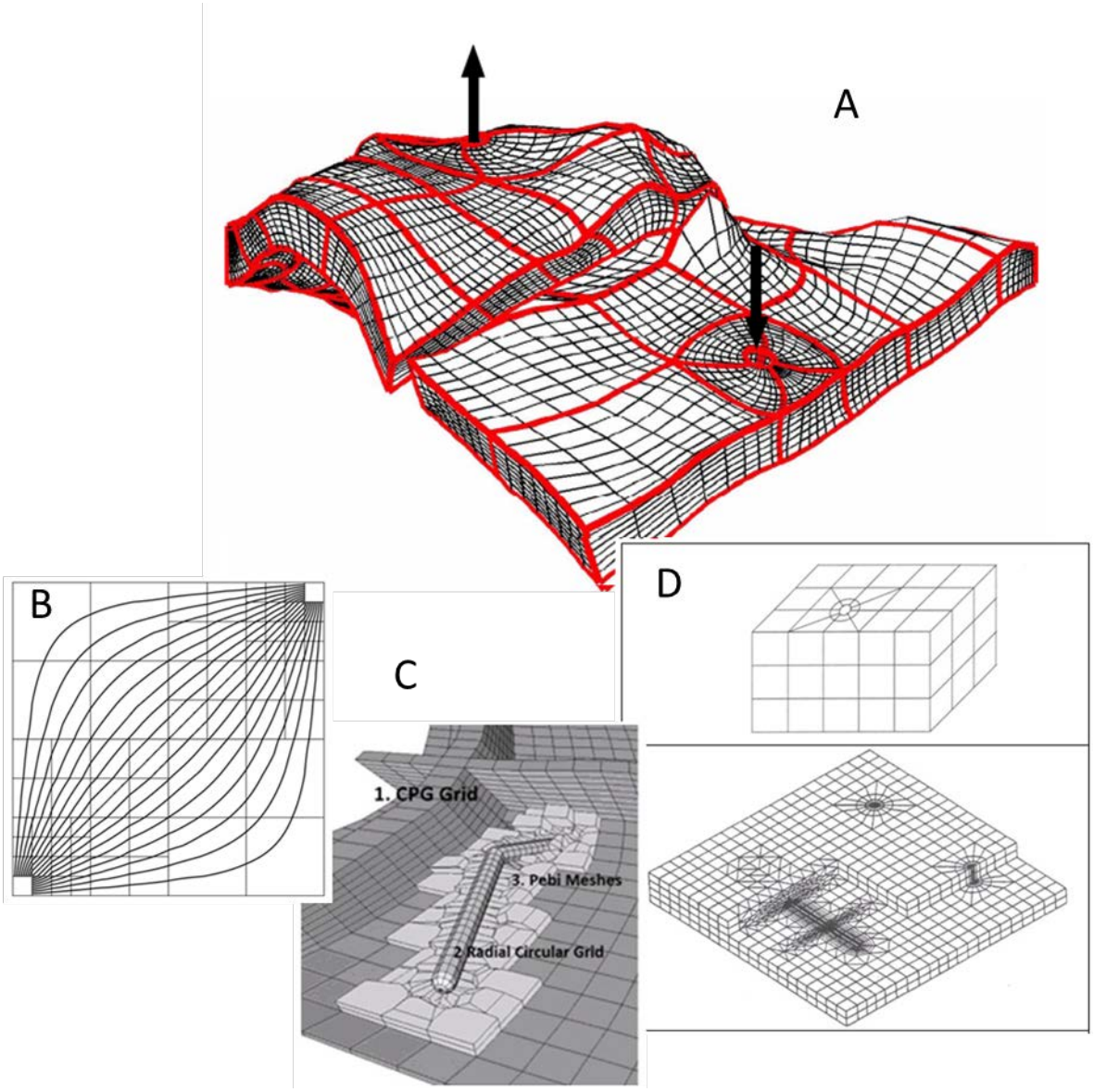


Figure 11-2—Local grid examples.
Sources: Figures used with permission or re-use policy from respective sources. Further reproduction prohibited without permission. For full citations and copyrights, see Section 11.18 (page 195). (A) Jenny (2001) (B) Zhang et al. (2011) (C) & (D) Perrin & Rainaud (2013).

11.3 Grid Topology

The topology of each grid is organized according to the numbering of the cells of the grid.

Figure 11-3 shows the 6 RESQML grid representations and the 3 supporting abstract grid classes, which are explained below. The grid representation contains the topology (indexing) of the grid, the grid geometry, and grid-specific extensions, if any.

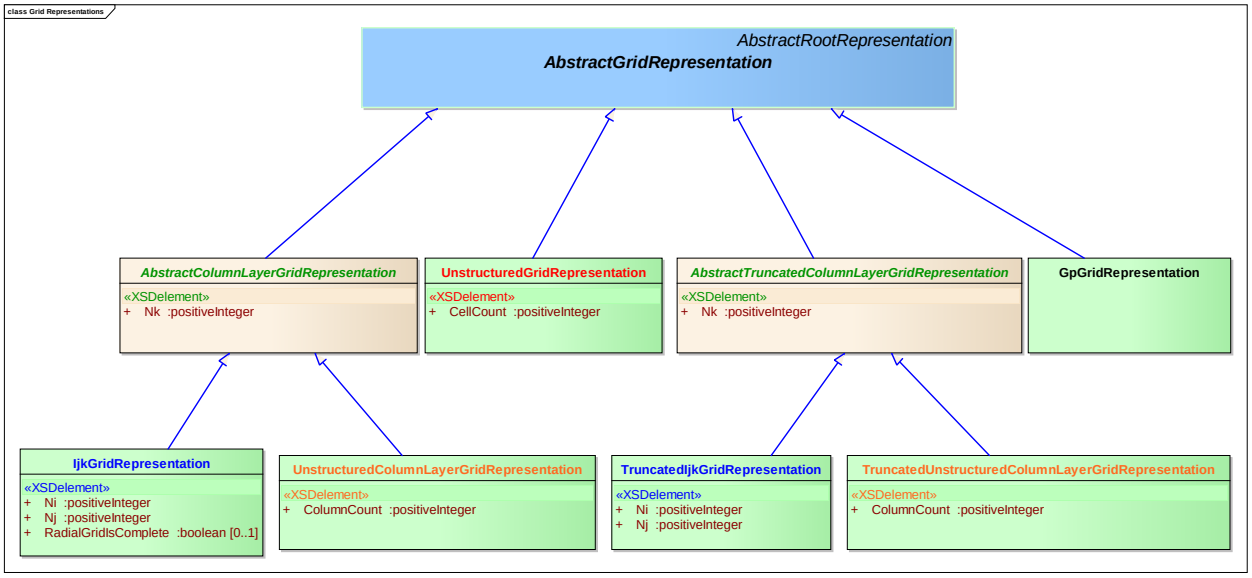


Figure 11-3—The six RESQML grid representations and the three abstract grid classes.

11.3.1 Fundamental Grid Classes

The three fundamental grid classes have 3, 2, or 1 grid cell indices.

- **IJK Grids** have 3 cell indices: NI, NJ, and NK.
  - I0 index = I-1, I=1…NI.
  - J0 index = J-1, J=1…NJ.
  - Layer index = K0 = K-1, K=1…NK.
  - Column index = I0 + NI*J0.
  - Cell index = I0 + NI*J0 + NI*NJ*K0.
  - The corner-point grid of RESQML v1 corresponds to a RESQML v2 IJK grid.
- **Unstructured Column-layer Grids** have 2 cell indices: #Columns and NK.
  - Column index = Column# = 0…#Columns-1.
  - Layer index = K0 = K-1, K=1…NK.
  - Cell index = Column# + #Columns*K0.
  - Unstructured column-layer grids are also known as 2.5D grids and PEBI grids, although there is no RESQML requirement to constrain the grid cell shapes to have perpendicular bisector (PEBI) cells.
- **Unstructured Grids** have a single cell index: #Cells.
  - Cell index = Cell# = 0…#Cells-1.

IJK grids and unstructured column-layer grids are both instances of column-layer grids. As such they each have a layer count, NK.

The (I,J,K) indices for an IJK grid, and the K indices for a column-layer grid have a special status compared to all other indices in the RESQML grid description. These indices may reference information external to a RESQML model, i.e., within a reservoir simulation data deck, which imposes a number of constraints. First, the ordering of the indices of a grid is not arbitrary, but is instead fundamental to the grid. So, if an application flips the order of an index, e.g., to change the parity of a grid, then the resulting grid is a new grid with a new GUID. RESQML may use the Representation Identity to indicate that these two grids are co-located in space, but they should be thought of as two different grids. Second, these indices are constrained by reservoir modeling domain usage to be 1-based. In contrast, all RESQML indices are 0-based. To prevent any confusion, this document and the schema reference the corresponding 0-based indices: I0=I-1, J0=J-1, and K0=K-1.

Notation:

- # prefix and “count” are used inter-changeably in this document, i.e., #Objects = object count.
- # suffix and “index” are used inter-changeably in this document, i.e., Object# = object index.

With the exceptions of NI, NJ, and NK, just noted, elements which provide counts are consistently named “Count” within the RESQML schema. With the exception of the general purpose (GP) grid representation discussed below, the RESQML v2 schema constrains all grid element counts to be positive integers, i.e., degenerate grids are not allowed.

11.3.2 Truncated Cell Grids

Although not as common as the three fundamental grid types, the petroleum industry also uses “truncated” cell grids. These grids are based upon a column-layer fundamental grid, but with the extension that cells can be split and truncated. These splits are used to describe complex juxtaposition and cell shapes at fault block boundaries. The resulting cell indexing is that of the underlying grid, plus additional unstructured cells.

- **Truncated IJK Grids** have 3+1 cell indices: NI, NJ, NK and #UnstructuredCells>0.
- **Truncated Unstructured Column-layer Grids** have 2+1 cell indices: #Columns, NK and #UnstructuredCells>0.

For each of the truncated grids, the cell count is increased by #UnstructuredCells compared to the base column-layer grid. When stored, these additional “truncation cells” are stored in a separate 1d patch array so that the multi-dimensional array structure of the column-layer grid is retained for rapid data access, at least for the majority of cells.

11.3.3 General Purpose Grid

The general purpose (GP) grid is an unconstrained hybrid of any of the other grid types, and provides a grid description toolkit capability. It has been included in RESQML based on the recognition that industry practice in the representation of unstructured grids is still under development. It may have more utility as a research tool than as a data transfer standard. Currently no other industry standard exists to transfer such hybrid grids, so this is a unique capability.

11.3.3.1 Examples of Use

Example 1. A GP grid may be used to represent a discrete fracture model by combining an IJK grid, which describes the geometry of the matrix of a reservoir, with additional discrete fault “cells” for which volumes and transport properties are provided, but with no explicit geometry. The cell indexing of such a model would be 3+1, similar to the truncated IJK grid representation, but without any of the cell truncation description.

Example 2. Because the count of elements is not constrained in a GP grid, it supports degenerate grids. For example, an IJK general purpose grid with NK=0 will be very similar to a grid 2D representation. Similarly, a triangulated mesh could be represented as an unstructured cell GP grid with a cell count of 0, but with nodes and faces.

11.3.3.2 Indexing

Indexing of the GP grid is more complicated than for the other grids because there is no natural sequence or order in how the variety of grid elements within the grid representation may appear. Cell ordering for these hybrid grids is defined using a “patch” construction (For more information on patches, see Section 6.3 (page 62).) The unique index of each patch defines its relative order, i.e., if a GP grid combines multiple IJK grids into a single global grid, the patch indices will specify their order.

11.4 Grid Cell Geometry

RESQML has three grid cell geometries (**Figure 11-4**):

- Block-centered cells
- Column-layer cells
- Unstructured cells

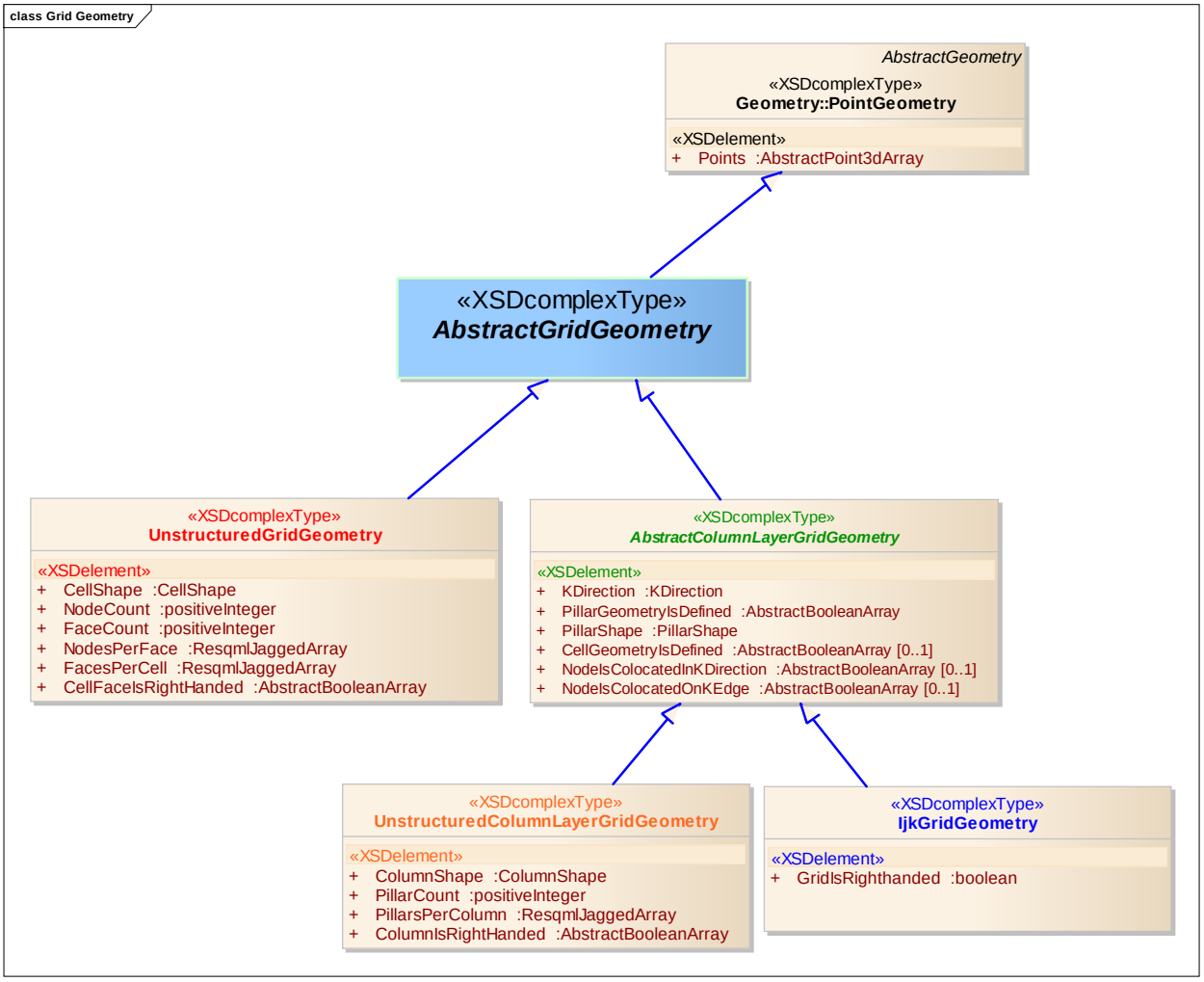


Figure 11-4—The three explicit grid geometries and the two abstract grid geometries, excluding extensions.

If the geometry is explicit, then the RESQML cell geometry is inferred from the cell corner nodes, to which points are attached. The two RESQML examples are the unstructured grid cells, for which cell nodes define the faces of the cells and the column-layer grid cells, for which cell nodes define the coordinate lines of the cells. The column-layer grids may be IJK (structured) or unstructured. The grid descriptions also consist of the topological relationships between cells, nodes, coordinate lines, faces, and/or the other

indexable elements of the grid. Additional points, to support higher order geometries, may also be associated with a grid, as described in Section 11.7.1 (page 139).

11.4.1 Block-Centered Cells

Block-centered cells are cells with no corner nodes and no explicit geometry. In other words, the grid is indexed as described in Section 11.3 above, but no geometry is attached to any of the nodes of the cells of the grid.

This grid type is used to represent the newest reservoir simulation formats, but also the oldest. Instead of an explicit geometry, equivalent properties are specified on the grid, for example, pore volume and transmissibility, or perhaps equivalent cell dimensions: DX, DY, and DZ. Any grid class may be block-centered, with the exception of the two truncated grids, which are constrained to have explicit geometry.

11.4.2 Column-Layer Cells

Column-layer cells have their geometry described by nodes distributed along coordinate lines. All coordinate lines of a grid have the same number of nodes per coordinate line, although their locations may be colocated. IJK grids and unstructured column-layer grids are the two examples of column-layer grids.

Column-layer geometry supports two specific extensions for use in the description of complex reservoir structures:

- Nodes along a coordinate line may be split to provide additional nodes, which modify the geometry of the adjacent cells.
- Additional faces may be introduced to split and truncate any column-layer cell and create additional truncation cells. This extension is only available for truncated column-layer grids or for general purpose grids.

11.4.3 Unstructured Cells

Unstructured cells have their geometry described by nodes distributed on cell faces. The cells of the unstructured grids and the split cells of the truncated grids are all of this kind.

11.5 Grid Element Indexing

RESQML makes extensive use of indexing to attach properties to a representation, and to specify relationships between representations. For a complex object like a grid, with many different indexable elements, the grid indexing may also provide implicit topological relationships between elements, for example, between the columns and pillars of an IJK grid.

In most cases, the indexing of these objects is uniquely specified by their ordering in **Table 8**.

Table 8—Indexable Grid Elements

Indexable Element	IJK Grid	Unstructured Column Layer Grid	Unstructured Cell Grid
cells	NI x NJ x NK (+) TruncationCellCount	ColumnCount x NK (+) TruncationCellCount	Count
columns	NI x NJ	ColumnCount	---
layers	NK	NK	---
intervals	NK + GapCount (layers + gaps interleaved)	NK + GapCount (GapCount usually 0)	---
interval edges	NKL = NK + GapCount + 1	NKL = NK + GapCount + 1	---
hinge node faces	NI x NJ x NKL (K faces)	ColumnCount x NKL (K faces)	Count
I0	NI	---	---
I0 edges	NIL = NI+1	---	---
J0	NJ	---	---
J0 edges	NJL = NJ+1 (usually) or NJ (if periodic)	---	---
faces per cell	6 x NI x NJ x NK (6 faces per cell)	Count (face order per cell: top + bottom + sides)	Count
nodes per cell	4 x 2 x NI x NJ x NK (4 x 2 nodes per cell)	Count (node order per cell: top + bottom)	Count
edges per column	4 x NI x NJ (4 edges per column)	Count (edge order follows faces)	---
pillars	NIL x NJL + SplitPillarCount	PillarCount	---
coordinate lines	NIL x NJL + SplitPillarCount + SplitCoordinateLineCount	PillarCount + SplitCoordinateLineCount	---
nodes	CoordinateLineCount x NKL (+) SplitNodeCount + TruncationNodeCount	CoordinateLineCount x NKL (+) SplitNodeCount + TruncationNodeCount	Count
column edges	NIL x NJ + NI x NJL + SplitColumnEdgeCount	UnstructuredColumnEdgeCount + SplitColumnEdgeCount	---
faces	NI x NJ x NKL + ColumnEdgeCount x NK + SplitFaceCount + TruncationFaceCount	ColumnCount x NKL + ColumnEdgeCount x NK + SplitFaceCount + TruncationFaceCount	Count
nodes per face	4 x FaceCount (4 nodes per face)	Count	Count
edges	CoordinateLineCount x NK + ColumnEdgeCount x NKL + SplitEdgeCount	CoordinateLineCount x NK + ColumnEdgeCount x NKL + SplitEdgeCount	Count
nodes per edge	2 x EdgeCount (2 nodes per edge)	2 x EdgeCount	2 x EdgeCount
	x signifies a multi-dimensional array, indexed in the order shown, with the first index cycling fastest, etc.		
	(+) signifies that this portion of the cell or node data is stored as a separate patch, e.g., 3D+1D or 2D+1D		
	+ signifies a one dimensional index constructed from multiple indices in the order shown		
	+ is in the order shown, and will over-ride patch indices, if any (Order exception: Interval index)		
	GapCount always vanishes for Unstructured Column Layer Grids, but may be non-zero for GPGrid patches		

For example, the coordinate lines for a column-layer grid should always be numbered to first follow the pillars, with any additional split coordinate lines coming last. As with all other RESQML multi-dimensional arrays, the maximum array dimensionality should always be used. For example, the coordinate line nodes may always be stored as a 2D array, but for unfaulted IJK grids, they should instead be stored as a 3D array, since the coordinate lines are in that case two dimensional. When multiple multi-dimensional arrays are combined, for example, for column edges or for faces, then the storage can only be one dimensional.

The one exception to the sequential ordering specification is for intervals, which consists of the grid layers and the gaps between those layers. In this case, the interval ordering is an expanded version of the layer ordering, with the gaps interleaved between the layers. Specifically, if there are NK layers and GapCount gaps between layers, there will be NK + GapCount intervals. The intervals are, by definition, continuous: the bottom of one interval is the top of the next. As a result, the number of interval edges will be NK + GapCount + 1, as shown in **Figure 11-5**. Similar “object edge” constructions appear elsewhere in this table.

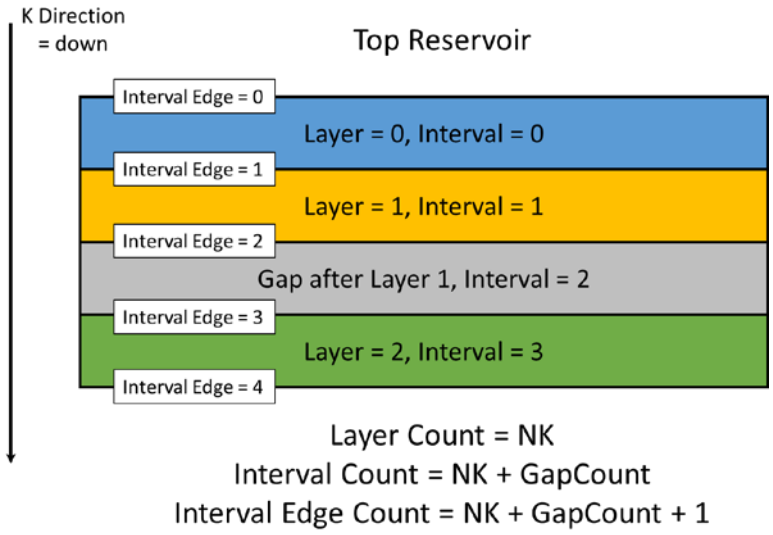


Figure 11-5—Layer, Gap, and Interval indexing for an example three layer grid with a gap between layers.

11.5.1 Indexes that Cannot be Uniquely Determined

Subnodes, split nodes, truncation cells, and general purpose grids are the objects whose index ordering cannot be uniquely determined in a RESQML instance using the relationships in the table. In these cases, a “patch” construction is used in which elements are provided a unique patch index, and then these elements are ordered according to their patch values (for more information on patches, see Section 6.3 (page 62)). For example, cell indexing is uniquely determined for each of the fundamental grid types shown, but when we work with a general purpose grid, multiple grid cell patches will combine to generate a single global cell index. When multiple elements of the same kind need to be combined, they are assigned a unique patch index, whose values determine the relative ordering of the data. This situation may arise even in the fundamental grids, when using subnodes for higher order finite element geometry or properties.

11.5.2 Multi-Dimensional Arrays

Although it may seem reasonable to always merge all objects of the same type into a single long array, this is not always advantageous. For column-layer grids, cells and nodes consist of multi-dimensional arrays, which should be stored in this fashion in HDF5 to facilitate hyper-slabbing and rapid data access. To retain this capability for the bulk of the model data, truncation cells and split and truncation nodes are stored as separate patches, although when indexed, the total count of cells and nodes each includes the multi-dimensional plus the one-dimensional counts. The schema is constrained to have a patch index of 0 for the grid representation itself, so that the relative patch ordering always starts with the multi-dimensional patch, i.e., 2D+1D nodes, not 1D+2D.

As with all RESQML representations, each element of a multi-dimensional array within a grid must have a well-defined 1D index (for more information, see Section 6.2 (page 60)). For example for a two dimensional array (N1 x N2) with indices I1=0,…,N1-1 and I2=0,…,N2-1, then the 1D index is I1+N1*I2. For a three dimensional array (N1 x N2 x N3) with indices I1=0,…,N1-1, I2=0,…,N2-1 and I3=0,…,N3-1, the 1D index is I1+N1*I2+N1*N2*I3. This ordering choice is sometimes called “fastest to slowest”, with the first index varying the fastest, and the last index varying the slowest. RESQML is not restricted to three dimensional arrays, for example, the nodes per cell on an IJK grid follow a 5D (4 x 2 x NI x NJ x NK) array indexing. The equivalent array in RESQML v1 followed a 6D (2 x 2 x 2 x NI x NJ x NK) array indexing, but unlike RESQML v2, it was never necessary to reduce that multi-dimensional array index to a single 1D index.

Examples of multi-dimensional arrays include the coordinate line nodes on a faulted grid, where N1=CoordinateLineCount and N2=NKL. However, the dimensionality of an array may vary with context; for example, the coordinate lines themselves may be either a 1D or a 2D array. In the special case of an

unfaulted IJK grid, the coordinate lines are a 2D array indexed by NIL x NJL and the coordinate line nodes are a 3D array indexed by NIL x NJL x NKL.

11.5.3 Elements per Object

Unlike most of the elements in the table that have shared indexing across objects, the "elements per object" indexable elements are defined on a per object basis. For example, the "faces" indexable element enumerates all of the faces where a face shared between cells will only appear once in the enumeration. In contrast, the "faces per cell" indexable element counts a face each time it appears in a cell. For example, for an IJK grid there are 6 x NI x NJ x NK faces per cell but far fewer faces. **Figure 11-6** is an example of the local cell face numbering for an IJK grid cell: 0…5. In more detail, to index face n of cell m, then the "faces per cell" index will be 6*m+n, where m and n are both zero based indices. This enumeration is much easier to construct than that for the faces themselves, which depends upon the fault structure of the grid, and the split column edge indexing, not just the grid topology.

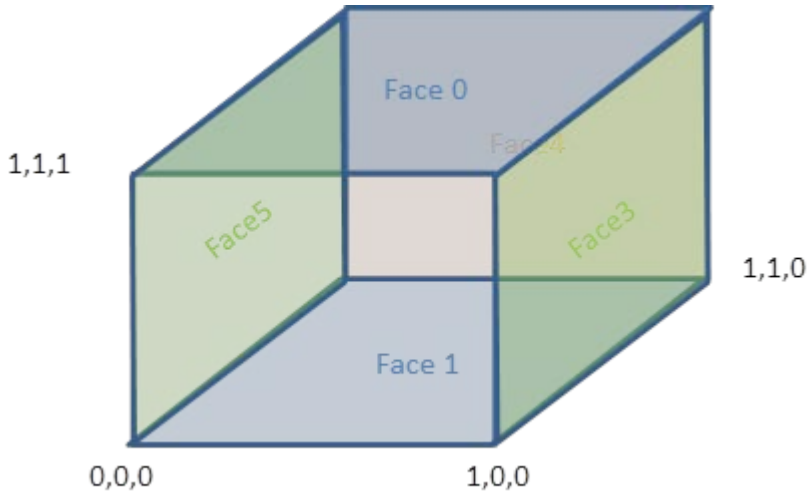


Figure 11-6—Local Faces per Cell indexing for an IJK Grid Cell.

For the unstructured elements, the ordering of these elements is part of the explicit description of the grid geometry. For column-layer elements, the ordering is implicit. By convention, the top (γ=0) and bottom (γ=1) faces always come first, followed by the side faces. Similarly, the top nodes per cell are numbered before the bottom nodes per cell.

11.6 Faulted Grids

Discretized representations of faults, using the following approaches, are a part of the minimum grid export specification. Two fault representations are recommended:

- A grid connection set representation, which is a collection of cell-face-pairs, is the recommended and preferred approach as it provides the detailed local fault topology required for flow simulation or for fault property characterization (transmissibility, throw, fault smear, etc.). Historically this information has often been lost on grid export, and has led to some of the largest discrepancies in reservoir performance prediction between different reservoir simulation applications.
- A subrepresentation of the grid with an ordered list of "pillars" as the indexable element is a more basic approach. We expect the pillars to be ordered from one (lateral) extremity of the fault to the other in order we define a single path for the fault representation. This approach works well to provide a qualitative description of the location of pillar-based faults, and will be natural to many geologic modeling applications. However, it cannot be used for XYZ stair-step faults, and it lacks the information on the local discretized topology of the fault, which is present in the grid connection set representation.
- Use of cell faces is NOT a recommended practice. Just as with the use of a pillar subrepresentation, this approach is lacking the detailed local fault topology. However, if required in order to transfer

historical data sets that lack the information required for a grid connection set representation, this practice can be reproduced using a subrepresentation based on the “faces per cell” for a column-layer grid or the “faces” of an unstructured grid.

11.7 Additional Grid Geometry and Topology

Each of the RESQML grid geometries support a number of grid geometry extensions. Some, such as radial grids, have already been mentioned. Each of these extensions has its geometry specified as shown in **Figure 11-7** and described in **Table 9**. A few of these extensions, such as the radial origin polyline already have a defined indexing (count is NKL). However, most of the additional geometries require extensions to the topological description of a grid. For example, if we want to attach additional “hinge nodes” to some of the faces of an unstructured grid, the enumeration of the hinge node faces needs to be defined first. The grid geometry attachment has the option to take advantage of a patch index to remove any ambiguity in data ordering.

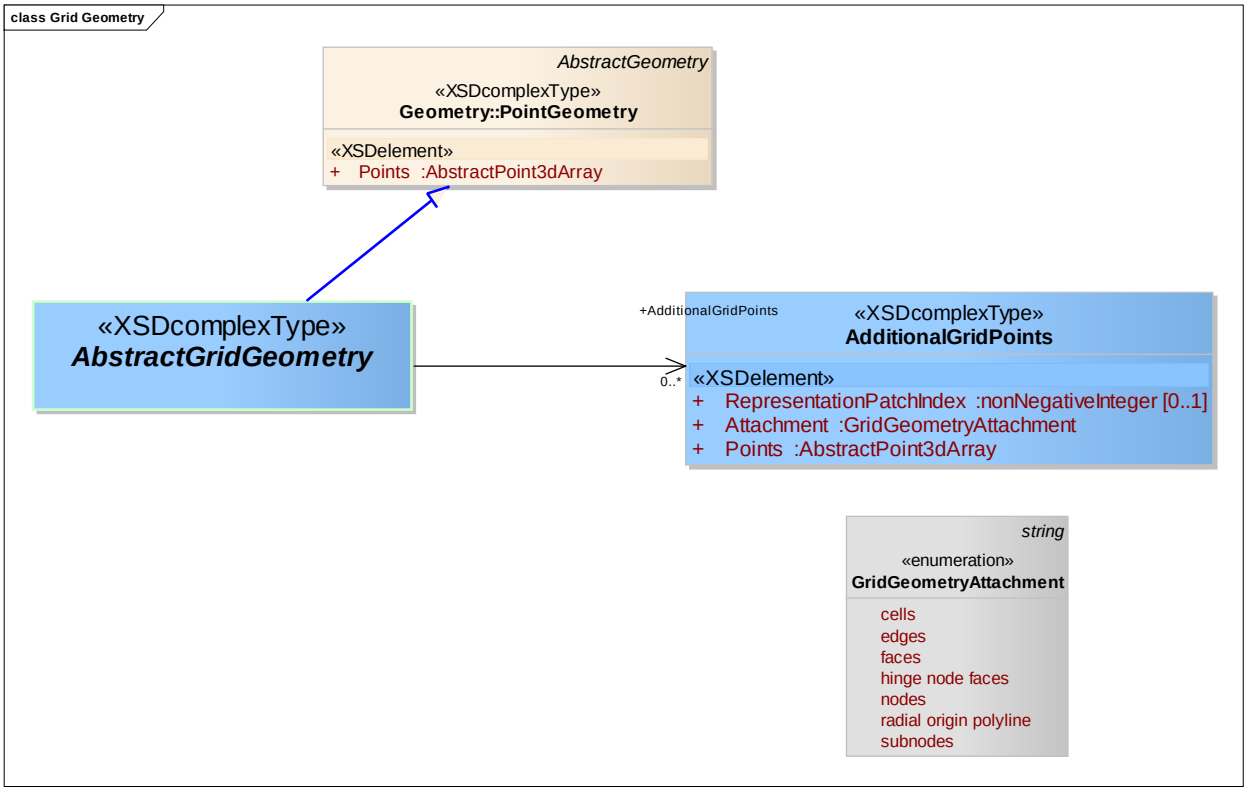


Figure 11-7—Additional grid geometry.

Table 9—Additional Grid Geometry Attachments

Grid Geometry Attachment	Description
radial origin polyline	Count = NKL. Only supported for IJK grids.
hinge node faces	Hinge node faces are the topological support for hinge nodes. A hinge node indicates that the cell face is replaced by a triangulated surface. Hinge node usage originally arose for PEBI grids to supply additional spatial resolution and to uniquely define the surface subtended by the cell face. For column layer grids, the hinge node faces are the K faces. For unstructured grids, the hinge node faces need to be explicitly enumerated.
nodes	Used to specify geometry for the split nodes and truncation nodes.
subnodes	This is a RESQML construction used to support higher order finite element grids by adding additional geometric control to distort the shape of the cells, faces, or edges of a grid.
cells	Identical to a cell subnode defined at the parametric center of a cell.
faces	Identical to a face subnode defined at the parametric center of a face.
edges	Identical to an edge subnode defined at the parametric center of an edge.

11.7.1 Higher Order Grid Geometry and Properties

Recently, the reservoir modeling industry has seen increased integration between reservoir fluid flow and geomechanical calculations, and a corresponding increase in the use of finite element grids. RESQML provides a new vendor-neutral finite element grid description, which supports higher order grid geometry and properties. Higher order grid geometry may be attached to cell faces, cell edges, cells, or additional subnodes. This ability provides the geometric support for higher order finite element grids.

Subnode geometry is not sufficient to uniquely define the shapes or volumes of the resulting cells, as the latter depends on the method of interpolation between the nodes and subnodes, not just the nodal positions. A classification of the possible finite element shape interpolation schemes is not included in RESQML, although in some circumstances, an interpolation scheme may be inferred from the corresponding lower order grid description. This is in contrast to hinge nodes, where an explicit interpolation (triangulation) of the cell face is implied.

RESQML treats these geometries as additional information to an existing column-layer or unstructured geometry. This is an example of a deliberate strategy in which we start with a simple grid and then provide optional extensions. This provides guidance to a RESQML reader on how to ignore extensions that are not included within their internal data model, while still providing the possibility of some degree of data transfer. Instead of using flags to describe grid options, the extensions themselves are localized in specific data objects, and the RESQML reader may check for their existence and respond accordingly.

11.7.2 Finite Element Subnodes

Subnodes are used in RESQML to introduce additional degrees of freedom to represent either higher order finite element geometry or properties (**Figure 11-8)**.

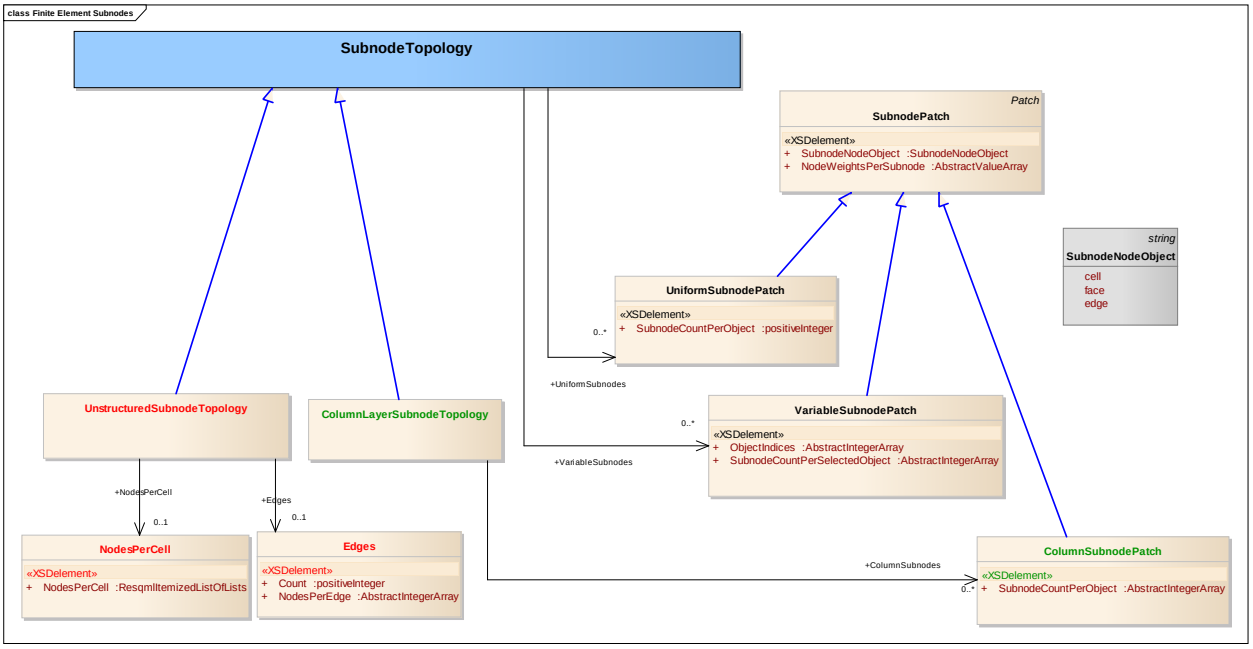


Figure 11-8—Finite element subnode specification.

A subnode is defined with respect to an ordered list of nodes specified by the reference subnode node object. For example, if there are N reference nodes, then a subnode is defined by N parametric weights. For visualization purposes, the inferred location for the subnode is at the weighted average location of all of the nodes $\vec{x} = \sum_{\ell=1}^{N} w_\ell \cdot \vec{x}_\ell \Big/ \sum_{\ell=1}^{N} w_\ell$. When RESQML attaches a point to a subnode, it replaces this implicit position with an explicit position.

The additional geometry attachment also includes cells, edges, and faces. These attachments use implicitly defined subnodes with parametric weights equal to unity on the respective objects. This approach is useful, for example, to describe a face subnode defined at the parametric center of each face, irrespective of the number of nodes per face, which may vary from face to face.

The choice of subnode object controls the node count per object for each subnode. Before subnodes may be defined for an object, an ordered list of nodes must first be defined or otherwise known for the same object. The known ordered lists of nodes may vary from grid class to grid class. For example, an ordered list of nodes per cell can be inferred for any of the column-layer grids, but not for the unstructured grids. By construction, such an ordered list is always known for the face nodes, but need not have been defined for nodes per cell or nodes per edge.

The number of subnodes per object may be as uniform or as variable as the associated objects. For uniform subnodes, the count of subnodes is identical for each object. An example is an edge subnode describing a cubic spline, with two nodes per edge and two subnodes per edge, giving a total of four node weights that need to be specified. Column subnodes allow the number of subnodes to vary by column within a grid, while the variable subnodes object allows the number of subnodes to vary per object.

The continuity of the subnode geometry or property is controlled by the choice of subnode object, which may be cell, edge, or face. For example, if the choice is cell, then the geometry or a property associated with a cell subnode has no continuity to adjacent cells. This is how a discontinuous finite element basis is constructed. For continuous finite elements, either face or edge nodes are used, where the continuity of the basis follows the continuity of the object specified.

Subnodes are patches. Grid topology allows the definition of independent subnodes of multiple kinds. To provide more specificity on the subnode geometry or property attachment, subnodes are defined with patch indices, which should provide a unique specification to the attachment.

11.8 Local, Child and Parent Grids

Any RESQML grid may be a child of another grid. Specifically, a grid may inherit its geometry, topology and/or properties from a parent grid (**Figure 11-9**). A grid with explicit geometry may also be a child grid, for example, to support inheritance of properties while providing more spatial resolution of the reservoir grid geometry than was present in the parent representation. The “regrid” data object, described below, is used to specify the parent-child grid relationship.

11.8.1 Local Grids

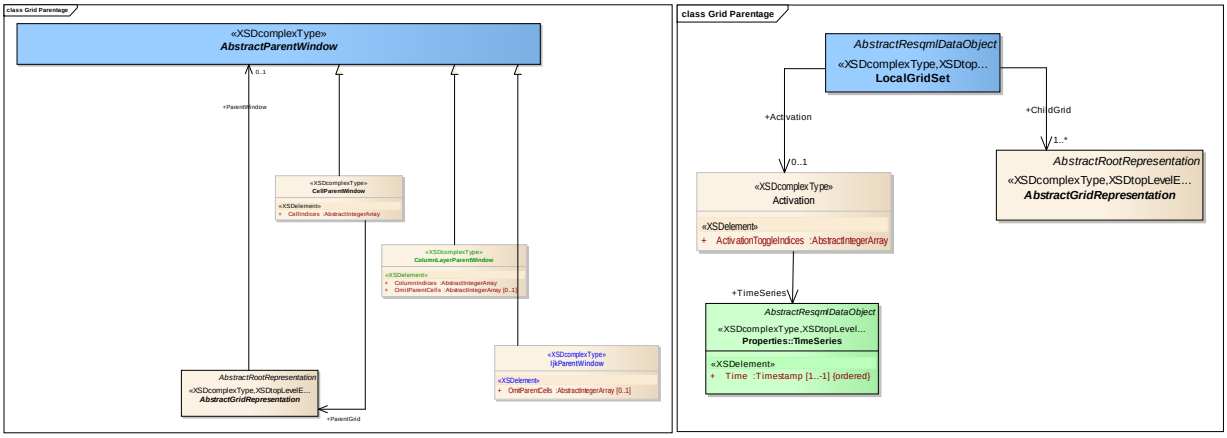


Figure 11-9—Child and local grids.

Key characteristics and differences between local grids and child grids:

- Parent-child grid relationships support multi-scale workflows in which more than one grid covers the same volume in space.
- In contrast, local grids are used to replace a portion of a parent grid by its child. Child grids that are listed as part of a local grid set are defined as a local grid.
- Multiple local grid sets are supported, and each set may include multiple local grids.
- **Time-dependent activation.** RESQML provides optional time-dependent activation and deactivation of local grids. Unless otherwise indicated, a specified local grid replaces a portion of a parent grid. However, if the optional activation object is present, then local grids do not replace a portion of the parent until activated. The state of the local grid may be toggled multiple times between inactive and active.

11.8.2 Parentage and Re-Gridding

A child grid is related to a parent grid by a parentage construction. The parentage construction consists of a parent window, which is a collection of parent grid cells, with potentially a re-gridding description between the parent and child grid. Re-gridding is a one dimensional operation in which the number and size of cells may be changed between the parent and child grids (**Figure 11-10**).

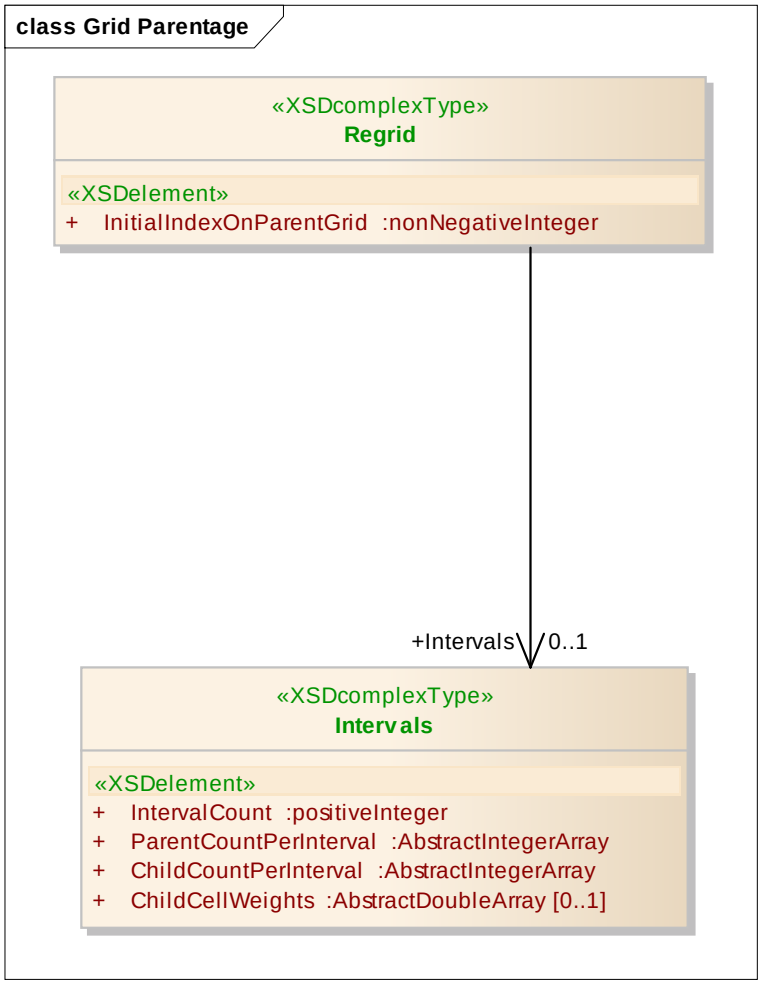


Figure 11-10—Regrid specification.

The regrid description is performed within intervals. The parent and child grids share cell faces at the interval boundaries, which allows the specification of implicit geometric or property relationships between the two grids. Within each interval, the number of parent and child grid cells is each specified. For example:

- For grid refinement, the number of parent cells in each interval is 1, and the number of child cells varies.
- For grid coarsening, it is the opposite, with the number of parent cells varying while there is only one child cell in each interval.

Regrid is not restricted to simple refinement or coarsening but instead supports mapping an arbitrary number of parent cells to an arbitrary number of child grids within each interval. By default, the child cells are of equal size within an interval. If uneven child cell sizes are required, they may be specified using the weights, which are proportional to the child grid cell sizes within each interval.

11.8.2.1 Example Regridding: Radial Grid Near a Well

Consider the refinement of a radial grid near a well. The global grid has dimensions of 10x1x3 and the child grid is a refinement of the innermost three cells on the second layer, with highest resolution near the well. The child grid also increases the angular resolution from a single 360^{o} cell to four 90^{o} cells.

I Regrid	Initial index on parent grid=0, Interval count=3, Parent count=(1,1,1), Child count=(4,2,2), Weights=(1,2,4,8,1,2,1,1)
J Regrid	Initial index on parent grid=0, Interval count=1, Parent count=(1), Child count=(4)
K Regrid	Initial index on parent grid=1, Interval count=1, Parent count=(1), Child count=(1)

For the I regrid, the weights indicate fractions of 1/15, 2/15, 4/15, 8/15 of the first parent cell, the weights indicate fractions of 1/3, 2/3 in the second parent cell, and the weights are equal indicating fractions of 1/2, 1/2 in the third parent cell. The J regrid has equal fractions of 1/4 and the K regrid indicates no refinement. Because the K regrid indicates 1:1 mapping, it need not be specified. For I, J, and K, because this is pure refinement, the parent count only takes on values of 1.

If the parent grid is an IJK grid, then the regrid may be in I, J, and/or K. If the parent grid is an unstructured column-layer grid, then the regrid may only be in K. No other grid cell geometries support a regrid geometry description. For other parent geometries, no intervals should be specified, and the child grid should have its geometry defined explicitly. However, the parentage construction may still consist of a window into the parent grid.

11.9 Grid Feature-Interpretations

Any RESQML representation, including a grid, may provide a representation of an interpretation of a feature (for more information, see Chapter 5 (page 51)). The most common application of this subsurface knowledge hierarchy is to indicate that different grid representations either share or have disparate interpretations of the features of an earth model, especially the reservoir stratigraphy and its fluid contacts. In addition to the generic relationships common to all RESQML representations, grids support several interpretation objects, which rely on the interval or cell indexing of a grid to provide specific representations for a stratigraphic column or for a fluid phase unit, as shown in **Figure 11-11**.

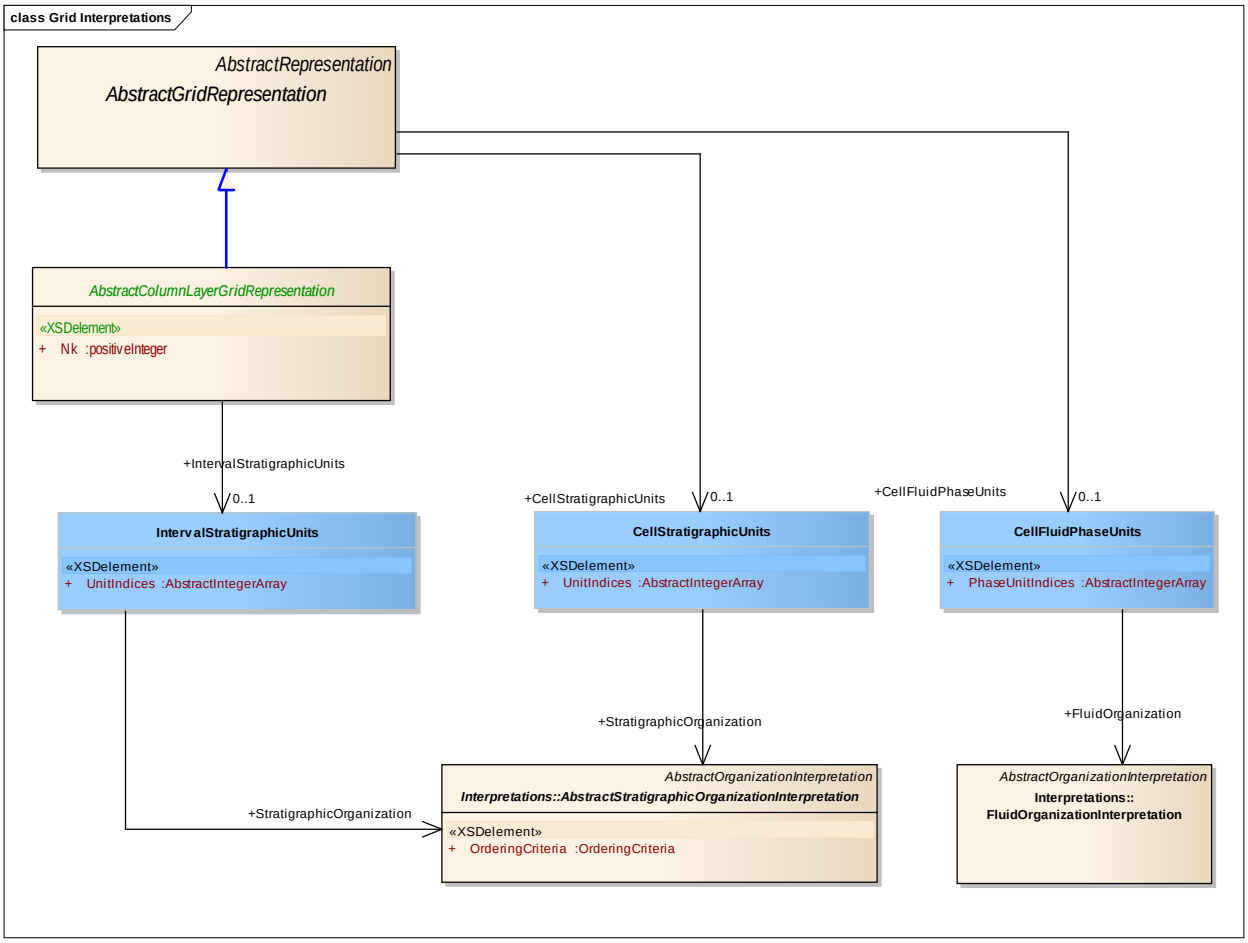


Figure 11-11—Specialized grid interpretation.

The interval stratigraphic column Interpretation takes advantage of a mapping between the intervals of a grid (layers + gaps) and a stratigraphic column. Implicit in the column are a definition of geologic units and their horizons. Many grids have such a mapping, although exceptions may arise when we attempt to represent complex structures, especially with reverse faults. In such a case, a “K-layer” mapping to a stratigraphic organization may not exist. In this case, a mapping from the grid cells to the stratigraphy is available instead to provide a representation of the stratigraphic column interpretation. Similarly, the cell fluid phase interpretation provides a mapping from grid cells to a fluid organization, which specifies the hydrostatic fluids that are used to fill the model. These element level interpretation objects may also be applied to the intervals or cells of a wellbore frame or of a blocked wellbore. (For more information on wells, see Chapter 12 (page 197).)

11.10 Unstructured Grids

11.10.1 Unstructured Geometry

New to RESQML at v2, are unstructured grids and their geometry, which include support for:

- Block-centered grids, one of the newest reservoir simulator data formats, which lack all geometry and which currently lack a standard industry representation.
- Unstructured grids with cell geometry, which provides a new vendor-independent specification of the grid geometry to complement the existing proprietary reservoir simulator formats and to support more general subsurface workflows.

Figure 11-12 shows how the geometry of an unstructured cell is defined by a list of (signed) faces, where each face is itself defined by a list of nodes.

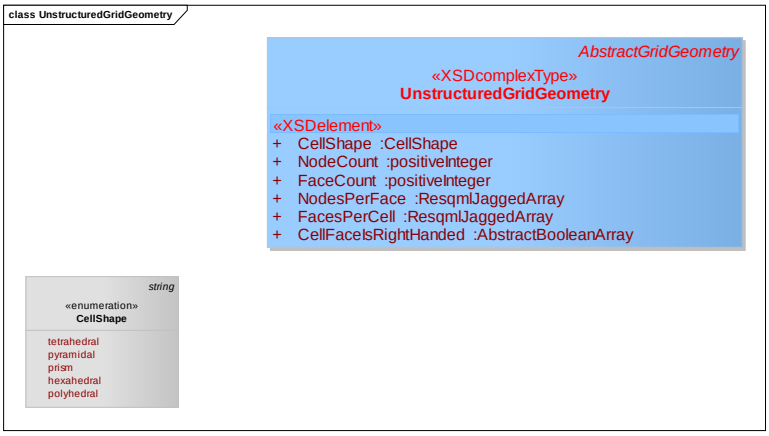


Figure 11-12—Unstructured grid geometry.

Point geometry is attached to these nodes. The sign (or parity) of a cell face is positive if the face normal defined using a right hand rule is outwardly directed.

- For faces with three nodes, the geometry defined is a plane.
- For faces with four nodes, bi-linear interpolation from the unit square is most often used to define a smooth surface. However, some applications have been known to triangulate the surface instead and treat it as two or four planes.
- For faces with five or more nodes, there are a variety of interpolation schemes in the literature. RESQML transfers the node point geometry, but does not specify the method of interpolation other than for hinge nodes, which utilizes triangulation. When an interpolation method is well-known in the industry, e.g., tri-linear interpolation for corner-point cells, the RESQML reader is expected to be consistent with domain usage.

The description of the unstructured grid geometry also includes a cell shape specification. This enumeration is intended to be used by a RESQML reader to determine if a grid instance can be reconciled with an internal application data model. For example, many geomechanical calculations may be restricted to tetrahedral cell shapes.

11.10.1.1 Unstructured Geometry Extensions

Figure 11-13 shows that unstructured grid geometry supports two extensions: hinge nodes and finite elements.

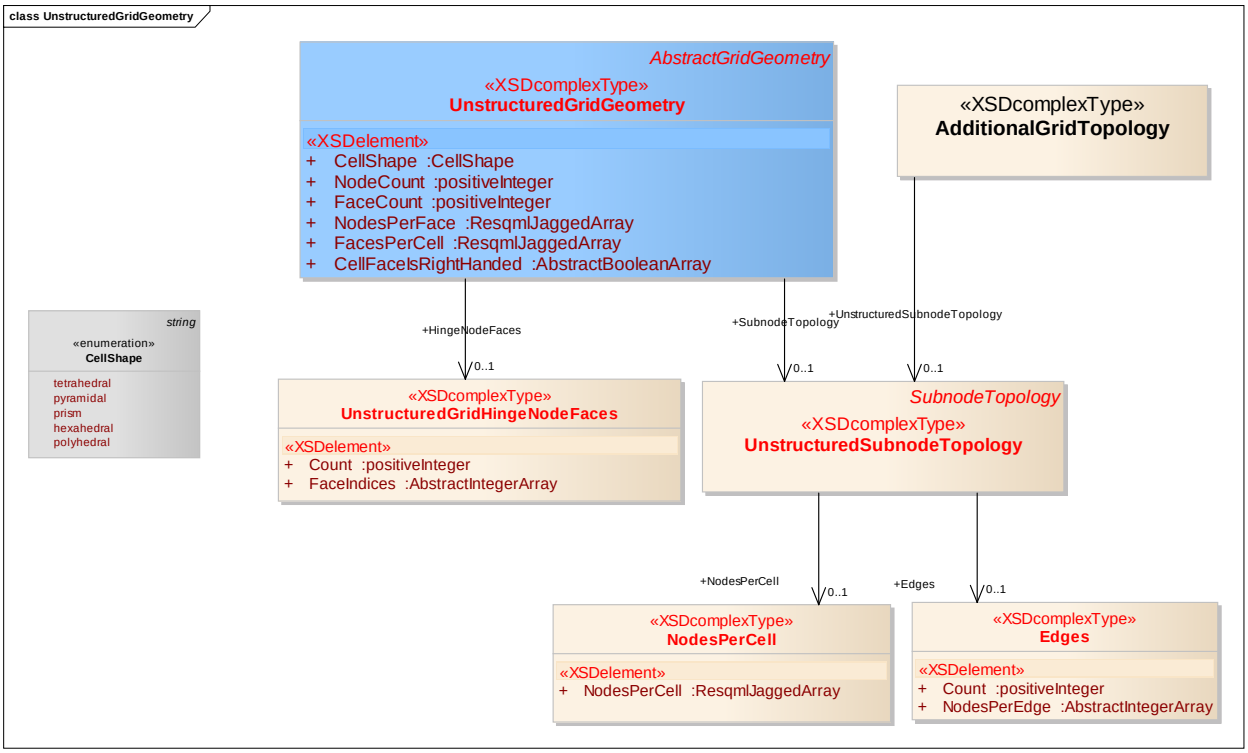


Figure 11-13—Unstructured grid geometry with extensions.

Unlike grids based on columns, the hinge node faces are not defined implicitly. Instead any cell face to which it is desired to associate hinge nodes must be specified as a hinge node face. Hinge nodes are an example of explicit interpolation on a face, in which the surface is replaced by a triangulated surface using the additional point geometry of the hinge node. The unstructured grid geometry also supports finite element extensions, as shown. The unstructured grid geometry supports the unstructured grid representation and also arises in the general purpose grid as a patch. A similar construction is used when defining the truncation cells for the truncated column-layer grids.

11.10.2 Unstructured Grid Representation

Figure 11-14 shows the unstructured grid representation, which supports:

- Block-centered grids, with no geometry. The topology of the grid is very simple; it is the number of cells, with no implicit relationships between objects.
- Grids with unstructured cell geometry, which have additional topological relationships between cells, faces, and nodes.

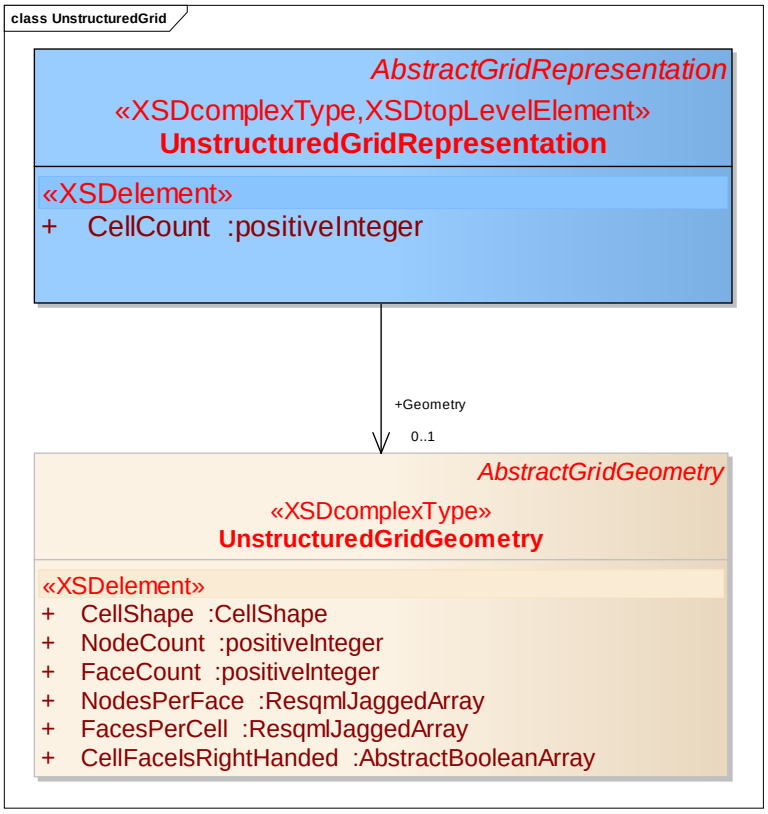


Figure 11-14—Unstructured grid representation.

11.10.3 Unstructured Grid Indexable Elements

The unstructured grids have the simplest indexing of any of the grid types because all of the topological relationships between the grid elements are explicit. **Figure 11-15** shows the indexable elements organized into three categories: topology, geometry, or additional elements.

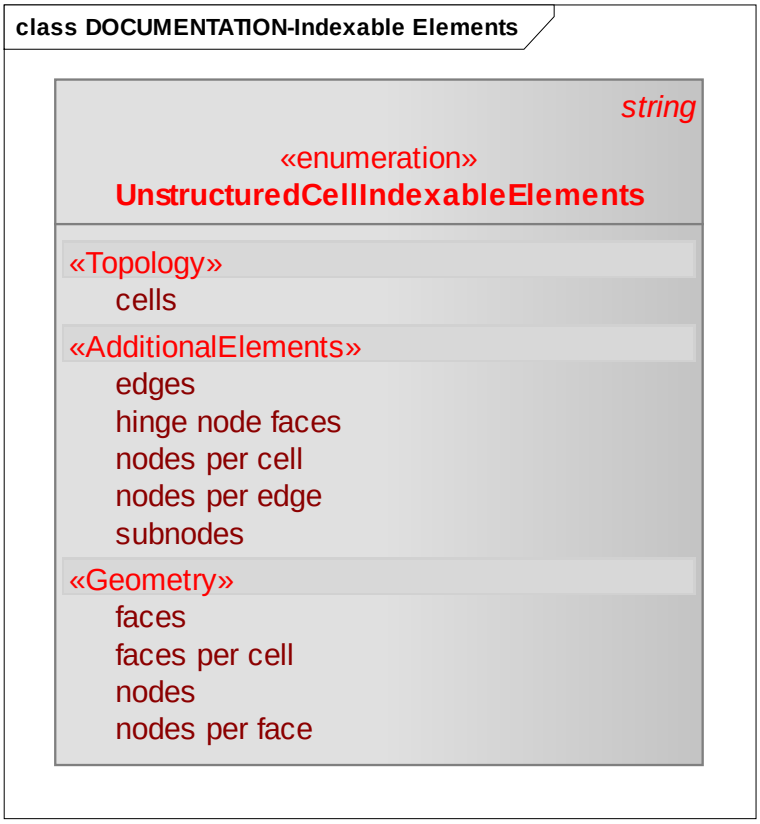


Figure 11-15—Indexable elements for an unstructured grid.

Element	Definition / Description of Use
Topology	Those elements whose indexing depends upon the grid index, which in this case is simply the cell count. For an unstructured grid, this index describes the enumeration of the cells of the grid.
Geometry	Those elements that need to be introduced to support the description of the geometry of the grid, which in this case are the nodes on the cell faces. For an unstructured grid, the faces and nodes are indexed according to the face count and the node count respectively. Two other indexable elements are also implicit in the unstructured cell geometry: • faces per cell are an ordered list of faces per cell, and • nodes per face are an ordered list of nodes per face. Both of these ordered lists are defined implicitly by the RESQML jagged array construction when defining the cell geometry. (For more information about jagged arrays, see Section 4.3.4 (page 50).)
AdditionalElements	Required to describe higher order geometry or properties. If hinge nodes are used as part of the higher order geometry of the cells, then hinge node faces must be defined. The remaining elements are part of the finite element construction. • Edges and nodes per edge need to be specified before edge subnodes can be defined. • Similarly, nodes per cell need to be specified before cell subnodes can be defined. • Face subnodes require the specification of nodes per face, but their enumeration is already implicit in the construction of the unstructured cell geometry.

As with the column-layer grids, unstructured grids have a number of “object1 per object2” indexable element kinds, which may be used in favor of “object1” indices when the latter are more complicated. For example, for an unstructured grid, for a cell of the model with N faces as specified by the “faces per cell” element, the faces are numbered from 0 to N-1 in this order. Unlike the faces indexing, which depends upon whether faces are shared between cells, this simple enumeration is completely local to the cell. Faces per cell indices appear in the grid connections representation and the blocked wellbore representation.

Nodes per cell and faces per cell appear as part of the finite element subnode construction, but these should not be confused with the node, face and cell enumerations, each of which have their own indexing.

11.11 Column-Layer Grid Geometry

The column-layer cell geometry (**Figure 11-16**) is used to provide the topological support for nodes on coordinate lines. This provides the geometric description for the IJK and unstructured column-layer grids.

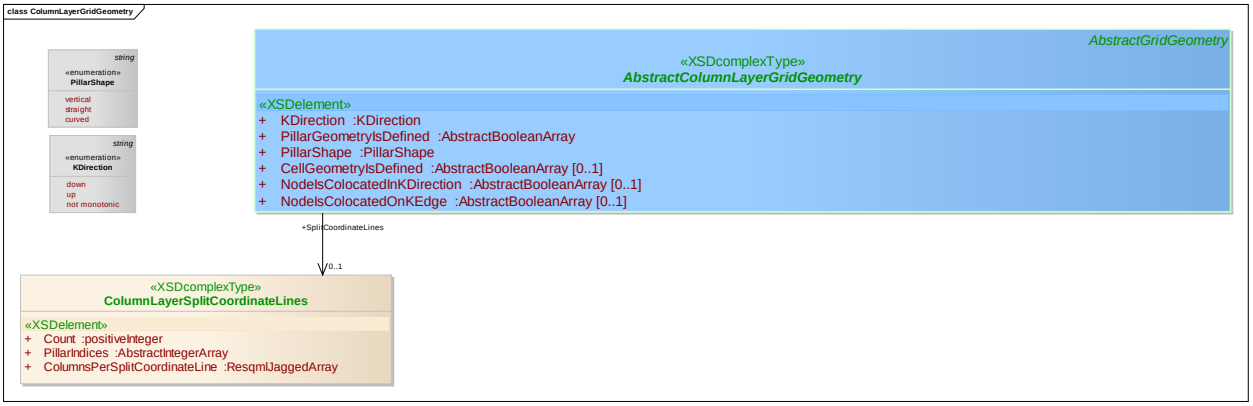


Figure 11-16—Column-layer cell geometry.

This geometry is based on pillars and columns, coordinate lines, and nodes.

11.11.1 Pillars and Columns

Pillars and columns describe the 2D topology of the grid.

- For IJK grids, each column has four pillars,
- For unstructured column-layer grids, each column is defined by a list of three or more pillars for each column.
- For an unfaulted grid, each pillar has one corresponding coordinate line.
- For faulted grids each pillar requires additional “split” coordinate lines.
- For a faulted IJK grid each pillar can have up to four coordinate lines per pillar.
- For faulted unstructured column-layer grids, each pillar may have as many coordinate lines as there are adjacent columns.
- The number of nodes per coordinate line is fixed at NKL = NK + GapCount + 1, and provides the topological support for the node geometry of the grid with an array of CoordinateLineCount x NKL points.

11.11.2 Coordinate Lines

RESQML provides support for parametric points and parametric lines. If the node points are defined parametrically, then each pillar must have a parametric line defined. The parametric point construction uses the mapping from coordinate line index to parametric line index, which is identical to the mapping from coordinate line to pillar.

- For an unfaulted grid, the count and indexing of coordinate lines is identical to that of the pillars.
- For an IJK grid, there are four pillars per column of the model.
- For an unstructured column-layer grid, there is an arbitrary number of pillars per column, which are specified explicitly as part of the grid description.
- For a faulted grid, the count of coordinate lines is increased by the number of split coordinate lines. The indexing of the coordinate line is defined by the “columns per split coordinate line” jagged array construction. The pillar index for each split coordinate line is also specified. With these two pieces of information, the topology and geometry of the faulted grid cells can be inferred from the specification of the unfaulted grid description.

- In order to have a well-defined index for the cell faces in the case of a faulted grid, a column edge index must be defined first. This is part of the faulted column-layer grid construction.

11.11.3 Additional Information Included in this Construction

This construction also includes additional geometric information on:

- the orientation of the coordinate lines (K direction)
- the shape of the pillars
- whether geometry has been defined for each cell and pillar
- colocation information on the coordinate line nodes

For the nodes along each coordinate line, there are #CoordinateLine x (NKL-1) Boolean values, which indicate whether the nodes are colocated. When describing the continuity of the nodes along each K edge, the count depends upon the topology of the grid. For example, for an IJK grid, the count will be 4 x NI x NJ x NKL, where the first index indicates that there are 4 edges for an IJ column. Ordering is shown in **Figure 11-17**, and is chosen to be identical to the natural ordering for an unstructured column-layer grid.

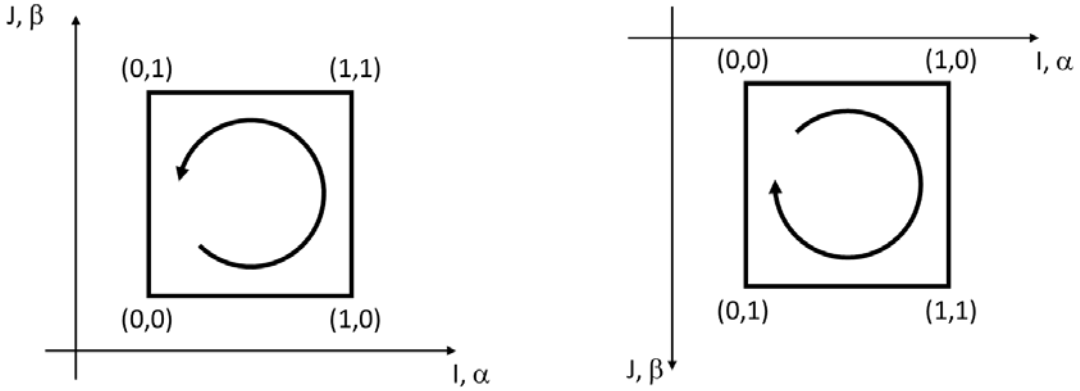


Figure 11-17—RESQML IJ node ordering.

- For an IJK grid, the RESQML IJ node ordering within a column of the grid starts at the (α,β) = (0,0) corner and then increases first α then β: (0,0), (1,0), (1,1), (0,1). For the “nodes are colocated on K edge” element, the colocation direction follows this node ordering.
- For an IJ grid, there are 4 Boolean values indicating colocation between (0,0) and (1,0), between (1,0) and (1,1), and so on. As shown in Figure 11-17, this may appear to be either a clockwise or counter-clockwise direction when viewed in a spatial (XY) context, but at the indexing level the two diagrams are identical. The RESQML grid description includes mandatory parity information and K direction information, from which the spatial orientation may be inferred, but there is no direct specification of a clockwise or counter-clockwise data ordering.

11.11.4 Supported Extensions

The column-layer cell geometry supports two optional geometric extensions: split nodes and finite element subnode topology (**Figure 11-18**).

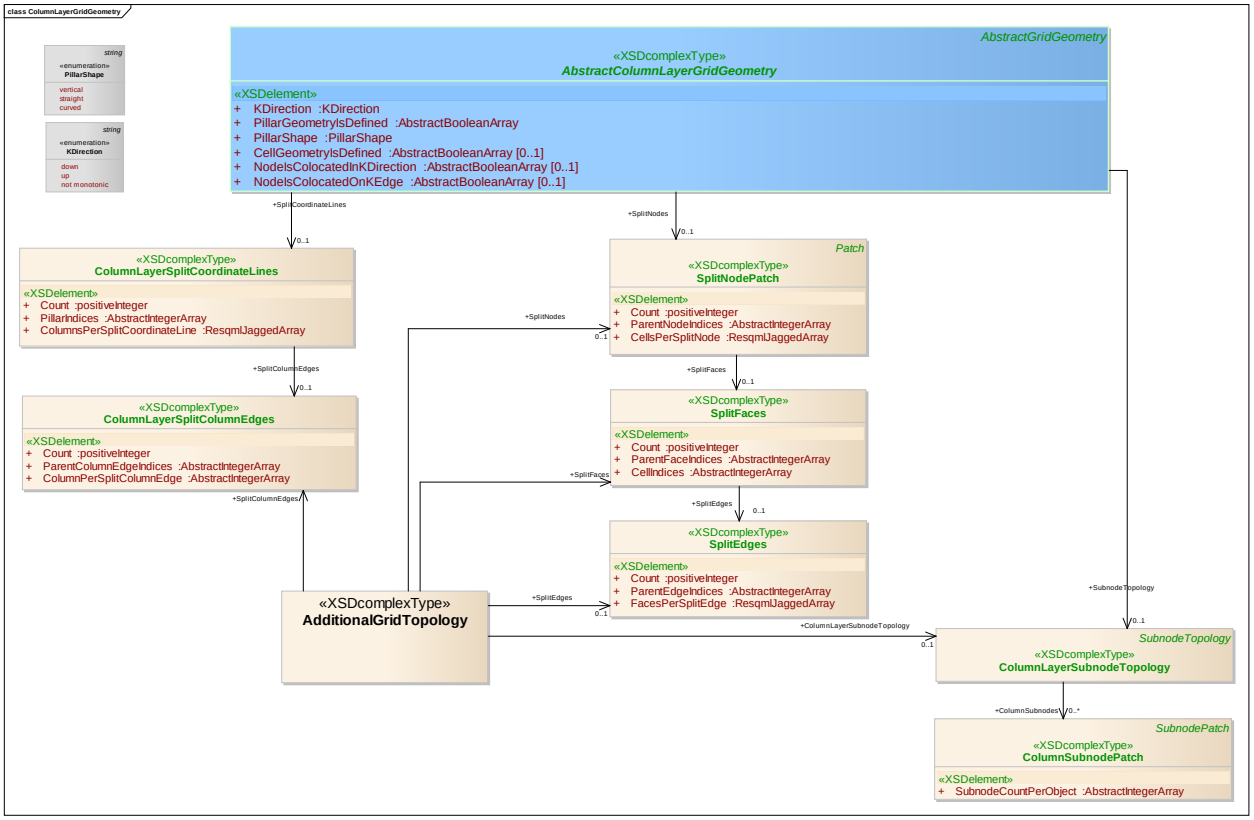


Figure 11-18—Column-layer cell geometry with extensions.

Split nodes introduce additional nodes and hence additional spatial resolution into a column-layer grid. They are used by some modeling applications, most often to improve the representation of stair-step reverse faults. After split nodes are introduced, additional split faces and split edges may also need to be defined. The additional grid topology object collects all of these extensions so that they are available for property attachment, even if they are not used for geometry extensions.

Subnodes are used as part of the finite element grid description. Again, both of these extensions are structured to localize these degrees of freedom, to provide guidance to a RESQML reader which may not support these features.

11.12 IJK Grids

11.12.1 IJK Grid Geometry

The IJK grid geometry is a column-layer grid geometry together with a mandatory specification of the grid parity (left handed or right handed) (**Figure 11-19)**. Parity is described in Section 11.12.211.12.4 (page 154). In addition, IJK grids support areal gaps between columns of the grid through the introduction of additional “split” pillars. These are described using the IJ gaps object.

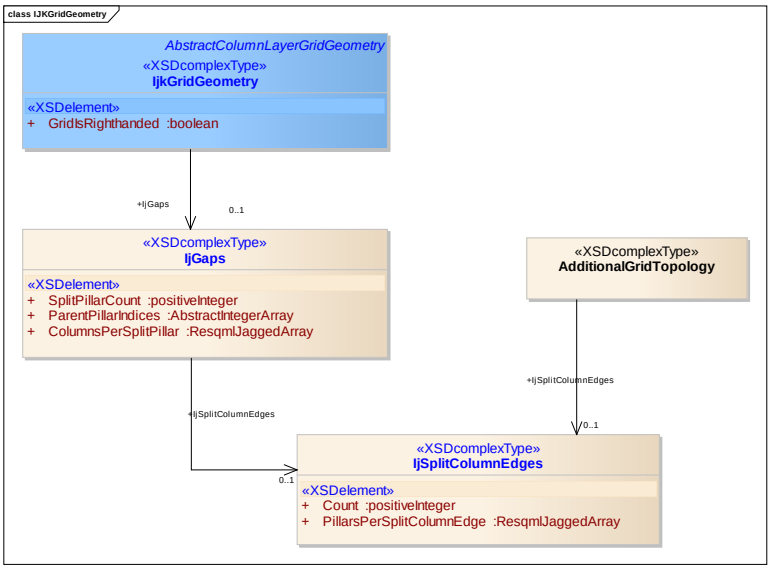


Figure 11-19—IJK grid geometry.

11.12.2 IJK Grid Representation

An IJK grid representation is the most common example of a grid with column-layer cell geometry. To match industry usage, this grid type supports several extensions not present within the unstructured column-layer grid or the unstructured grid, specifically, IJ gaps, K gaps, and radial cell interpolation (**Figure 11-20**).

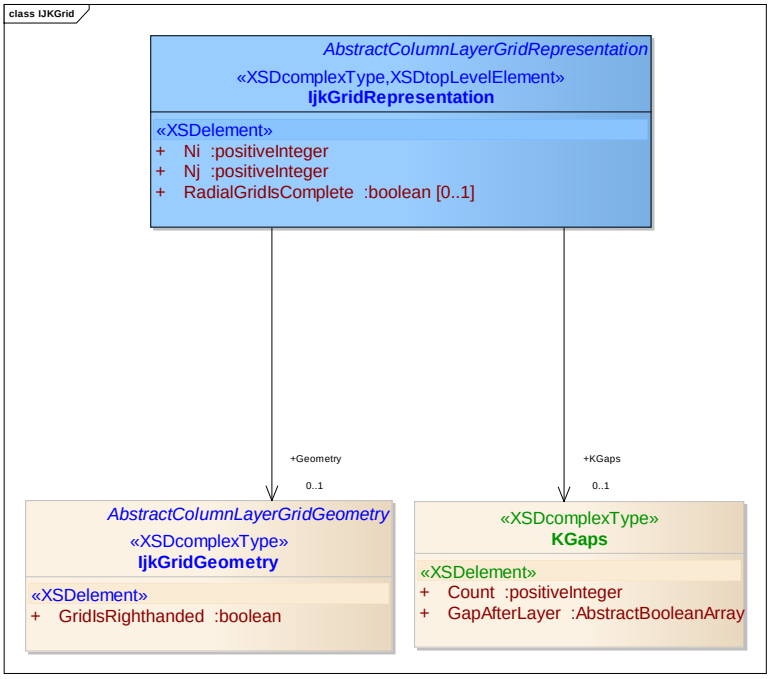


Figure 11-20—IJK grid.

The IJK Grid has seven primary indices, all of which may be obtained from the IJK grid objects shown in **Figure 11-20**:

- NI, NJ, NK, as previously described
- #Intervals = NK + GapCount
  - GapCount is the number of K gaps in the model. In RESQML, unless stated otherwise, the bottom of one layer is contiguous with the top of the layer below it. As a consequence, the number of nodes along a coordinate line needed to describe the cell geometry is NK+1, not 2*NK, which would be required if no assumptions were made about continuity.

    If gaps are introduced between layers, then GapCount>0, #Intervals>NK, and the number of nodes also increase. Eclipse GRDECL/GRID and VIP/Nexus CORP data formats, for example, make no assumptions about the continuity of cell geometry. Each would have GapCount = NK–1, #Intervals = 2*NK. This indexing may be preserved within RESQML, if desired, using the gap count.
- NIL, NJL and NKL are used to define the number of the edges (or “lines”) of the cells.
  - NIL = NI + 1 (always)
  - NJL = NJ + 1, except for “complete” (periodic) radial 360^{o} grids, in which case the first and last cell faces are identical and NJL = NJ
  - NKL = NK + GapCount + 1

The first three of the seven indices appear explicitly within the schema, as shown in **Figure 11-20**. The others are inferred from the optional IJK grid objects, as just described.

IJK grids support a radial interpolation option. For radial grids, the r=0 origin point must be specified independently for each interval edge of the model. This geometry is attached through the additional grid geometry attachment kind of “radial origin polyline”. The number of nodes on this polyline must match the coordinate line nodes and hence has a count of NKL. The use of an explicit center point allows arbitrary inclinations for the radial grid, for example, to represent horizontal radial (or elliptical) grids aligned with horizontal wells.

The IJ gaps object is used to describe gaps between columns of the model. i.e., to describe fractures with finite volumes instead of simply fault surfaces. Grids of this type may be described using Eclipse GRID and VIP/Nexus CORP data formats, but not Eclipse GRDECL. This option does not modify the indexing of the cells or columns, but it does increase the number of pillars and coordinate lines.

IJK grid geometry inherits from column-layer geometry, and provides the topological support for the coordinate line nodes of the grid. In addition, it carries several elements that describe the grid geometry:

- Of these, the grid parity (±) is mandatory. Its value is needed for the calculation of cell volumes and cell face transmissibility. The parity is defined as the sign of the triple cross product obtained from the three cell tangent vectors.

$$\pm = Sign\left(\vec{t}_1 \times \vec{t}_2\right) \bullet \vec{t}_3 = Sign\left(\vec{n}_3 \bullet \vec{t}_3\right)$$

$$\text{Cell Volume} = \pm \iiint_{Cell} \left(\vec{t}_1 \times \vec{t}_2\right) \bullet \vec{t}_3$$

$$\text{Face Transmissibility} = \pm \iint_{Face} \left(\vec{n}_f \bullet \vec{t}_f\right) \Big/ t_f^2$$

  These are the geometric components to cell volume and face transmissibility, and do not include the additional physical properties, e.g., porosity, permeability or viscosity. The parity calculated from this triple product is uniform on a well-formed grid, although local defects may occur. Typically, negative cell volumes or negative transmissibilities are set to zero within reservoir modeling applications.

- The other elements provide information on whether geometry is degenerate (node colocation) and are optional.

11.12.3 IJK Grid Indexable Elements

Figure 11-21 lists the indexable elements for IJK grids.

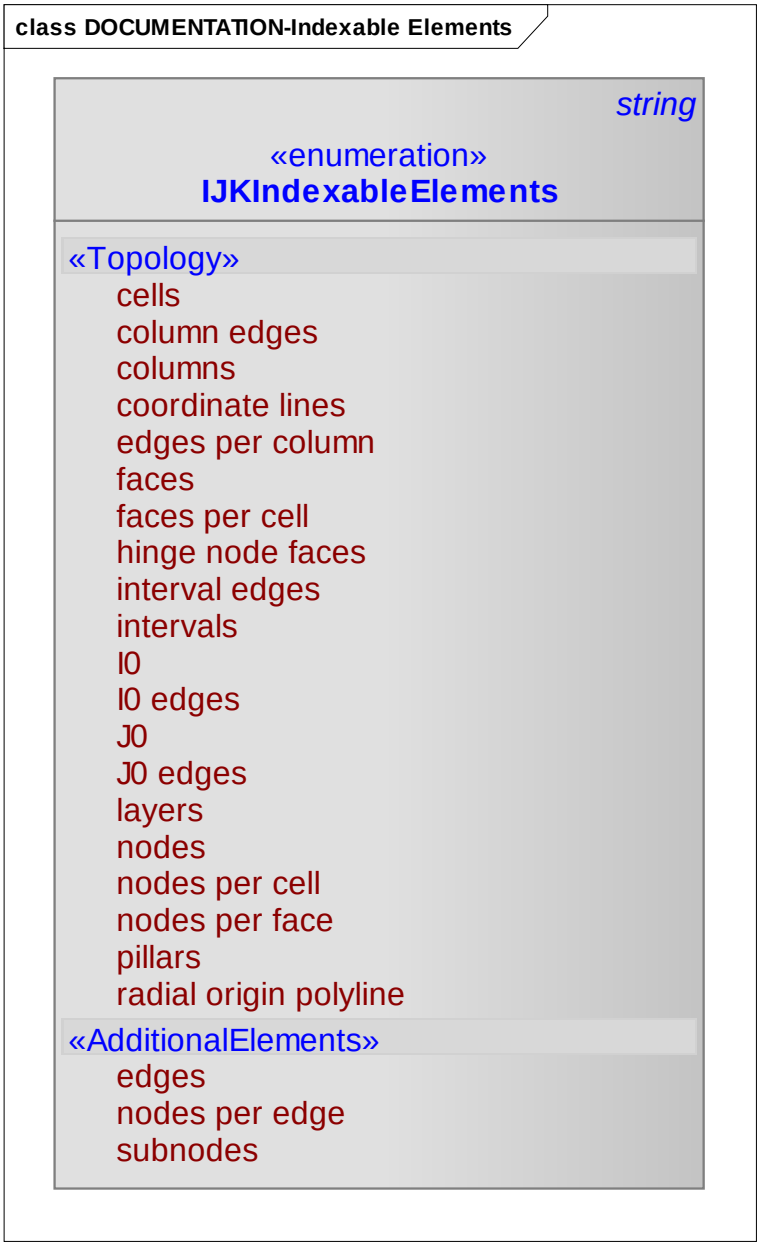


Figure 11-21—Indexable elements for an IJK grid.

RESQML v1 introduced six indices for the corner-point grid: (α,β,γ,I,J,K), which are also part of RESQML v2. The (I,J,K) indices have already been described.

The (α,β,γ) indices each take on the values (0,1). They are aligned with the (I,J,K) directions, respectively, and are used to index the nodes and faces within a cell. In v2, they also contribute to the enumeration of many of the other grid elements. When designing the IJK grid indexing we made two choices, which are intended to simplify implementation:

- Consistent grid indexing between block-centered (no geometry) and nodal grids.

- Consistent grid indexing between IJK and unstructured column grids using a shared column-layer indexing and geometry.

As an example of the enumeration and the use of the indices to implicitly specify the grid topology, consider the relationship between columns and pillars shown in **Figure 11-22**.

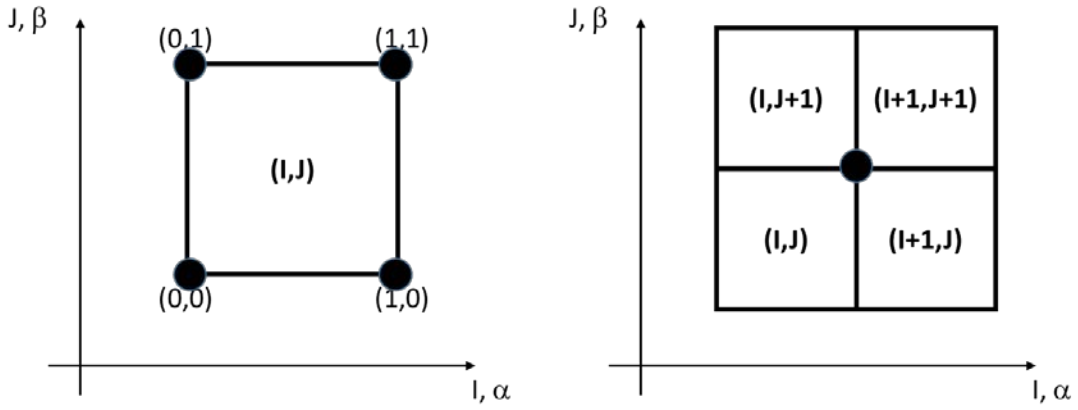


Figure 11-22—Columns and pillars of an IJK grid.

Their indices are:

Column index = I0 + NI*J0

Pillar index = (I0+α) + NIL*(J0+β)

Again, I0=I-1, J0=J-1 and also NIL=NI+1. The form of the indexing in these equations determines the topological relationship between the columns and the pillars. For one column, indexed by (I,J), there are four adjacent pillars indexed by (α,β) = (0,0), (1,0), (1,1), and (0,1). With the form of the pillar indexing, we obtain the same index for I and α=1 as for I+1 and α=0. As a consequence, the four columns (I,J), (I+1,J), (I+1,J+1) and (I,J+1) implicitly share the same pillar. Similar relationships exist in a cross-sectional view of a grid, for example, between the layer intervals and the interval edges.

The indexing for the IJK grid has more implicit relationships between the grid elements than any other grid class. By choice—as much as possible—the IJK grid indexing and the unstructured column-layer grid indexing are identical. Specifically, the following node order is followed for IJK grids: (α,β) = (0,0), (1,0), (1,1), (1,0), (0,0). With this specification, the indexing for the IJK grid is identical to that of a corresponding unstructured column-layer grid. However, unlike the unstructured column-layer grid, the relationship between column and pillar is implicit.

Element indexing is described using the following indices:

- I0=0…NI-1, J0=0…NJ-1 and K0 = 0…NK-1
- α = 0,1, β = 0,1 and γ = 0,1
- L=0…NKL-1 = NK + GapCount

The first three indices correspond to the (I,J,K) indices of a corner-point grid, except that they are now explicitly 0-based. The next three (node) indices have not changed their usage since RESQML v1. The interval index, L, includes both layers and gaps, and is useful for indexing grids with K gaps.

A number of indexable elements that depend upon NI and NJ, and which are not present within the unstructured column-layer grid, arise for IJK grids. Specifically, I0 and J0 and the I0 and J0 edges each have one dimensional indices.

11.12.3.1 Special Consideration: Column Edge

The only indexable element where the commonality in indexing between the IJK grid and the unstructured column-layer grid is not obvious is the column edge.

- For the unstructured column-layer grid, the indexing of the shared column edges is explicit.
- For the IJK grid, the indexing is implicit and first follows the I column edges (NIL x NJ) and then the J column edges (NI x NJL). The I faces and J faces do not appear as explicit indexable elements but are instead part of the range of elements of the faces. The edge and face indices correspond to the enumeration of shared edges and faces. This ordering is a RESQML choice. The column edge indexing needs to be defined to support face indexing.

There are a number of "object1 per object2" indexable element kinds for IJK grids, which may be used in favor of "object1" indices when the latter are more complicated. For example, for an IJK grid, there are 6 "faces per cell": 0=top, 1=bottom, 2-5 are side faces following the IJ circular node ordering, described previously. This is a very simple enumeration, versus the "faces" indexing, which depends on the grid faulting and column edge enumeration. Faces per cell indices appear in the grid connections representation and the blocked wellbore representation.

11.12.4 IJK Grid Origin

A frequently-asked question is: How do I determine the location of the origin of an IJK grid in the field of view? Generally, this is a function of the data, not of the schema, but certain inferences can be made from the grid parity and from the specification of the K direction. A number of observations can be made:

- In practice, almost all grids have their origin on the left of the field of view, which specifies the direction of the I axis. Origins on the right, are possible, but are extremely rare in practice.
- The K direction can be used to determine if the origin is on the upper face of a model (K direction = down) or on the lower face of a model (K direction = up).
- The direction of the J axis is determined uniquely by the grid parity, given the directions of the I and K axes.

Calculation of the Jacobian for volume and the transmissibility for flux, are based on the triple-cross product of the cell or grid tangent vectors. To ensure that they are correctly calculated, they also need to know the parity of the 3D coordinate reference system..

11.12.5 IJK Cartesian and Radial Cell Interpolation

RESQML provides support for radial cell interpolation as part of the IJK grid representation. Unlike reservoir simulation software, which provides special keywords to allow specification of grids directly in (r,θ,z) coordinates, RESQML continues to specify cell nodes as (x,y,z) points. This specification allows reasonable interchange with geologic model vendors, the majority of whom do not provide support for radial grids. However, when the "radial grid is complete" Boolean element is included in a RESQML grid description, together with the radial origin polyline geometry, it then implies that radial interpolation should be used to describe the cell shape.

- Specifically, for a Cartesian corner-point cell, the cell volume is defined by the tri-linear interpolant of (x,y,z) in (α,β,γ) between the 8 corner nodes.
- In contrast, for a radial corner-point cell, the cell volume is defined by the tri-linear interpolant of (r^2,θ,z).

This choice follows from the transformation of unit volumes: $dx\,dy\,dz = r\,dr\,d\theta\,dz = \frac{1}{2}\,dr^2\,d\theta\,dz$. In other words, the interpolation describes a radial (cylindrical) cell shape. The I (or α) coordinate (dimension: NI) is always in the radial direction, and the J (or β) coordinate (dimension: NJ) is always in the angular direction. For a fixed value of γ, we have a 2D radial coordinate system.

- To define r from (x,y,z), we need the coordinates of an origin at that same value of γ. The definition of the radial grid includes the specification of NKL origin points, which may be interpolated linearly in γ.
- To define θ from (x,y,z), we may use the usual trigonometric functions.

Some care must be taken to ensure that the branch cut does not lie within the cell. For the special case of complete 360^o grid cells with NJ=1, care must be taken to have strictly monotonic values for θ. This

construction is sufficiently general to represent simple radial grids with vertical coordinate lines, or more complex radial grids that may conform to a complex horizontal or undulating well trajectory.

Radial IJK grids may have a slightly different topology from Cartesian IJK grids. If a radial grid is complete, then it is periodic and covers 360°. Consequently the last J cell face is identical to the first, and NJL=NJ instead of the usual NJL=NJ+1.

Local radial grids use a modified interpolation method on the outermost ring(s) of cells (I=NI). To ensure geometric consistency with the parent grid, the α range is reduced so that the radial cell shape remains consistent with the cell volume interpolation method of the parent grid cell. Specifically, a circular arc between two node points on the local grid normally extends beyond a linear interpolant on the parent grid. The extent of the radial cell in the α direction is reduced so as not to exceed the linear interpolant.

11.13 Unstructured Column-Layer Grids

11.13.1 Unstructured Column-Layer Grid Geometry

The unstructured column-layer grid geometry is an extension of the column-layer grid geometry used to describe the geometry of unstructured column-layer grids. As with the column-layer cell geometry, it provides the topological support for nodes on coordinate lines.

Unlike the IJK grid geometry, the unstructured column-layer grid geometry must include explicit topological relationships between the columns of a grid, and geometric grid parity information, as shown **Figure 11-23**.

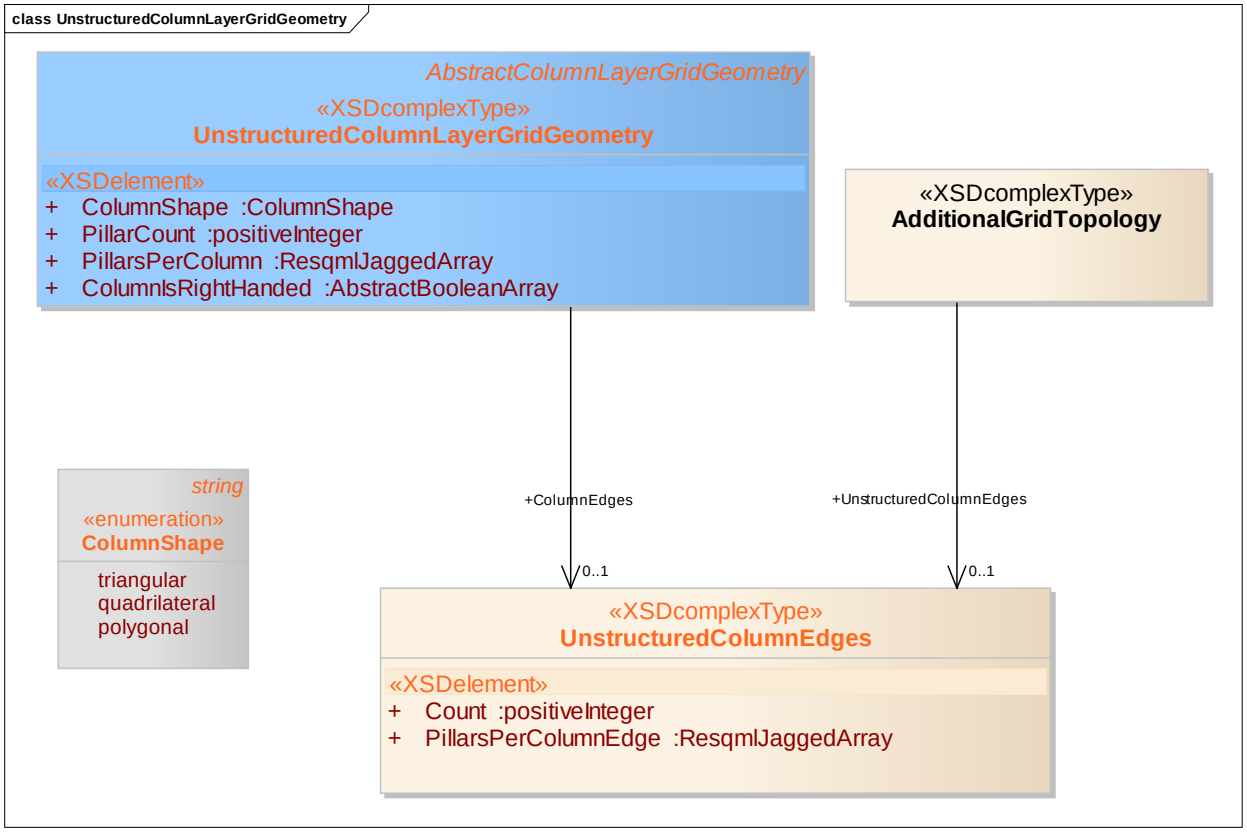


Figure 11-23—Unstructured column-layer cell geometry with extensions.

Specifically, this information is required: the number of pillars, the specification of which pillars are used to delineate which columns, and the parity of each column of the model. In contrast, for IJK grids, much of this information is known implicitly from the IJ indexing, or is uniform on the grid.

As with the column-layer cell geometry, if faces are to be indexed, then column edges must be defined. Neither faces nor column edges are required as part of the description of the grid geometry. However, this optional definition is retained as part of the additional grid topology. In addition, the description includes information on the column shapes for the grid. The shapes are defined topologically, i.e., by the number of pillars used to define each column.

The unstructured column-layer grid geometry supports the unstructured column-layer and the truncated unstructured column-layer grid representations. It also is used in the general purpose grid as a patch.

11.13.2 Unstructured Column-Layer Grid Representation

The unstructured column-layer grid is based on the unstructured column-layer cell geometry, and hence the column-layer cell geometry. In a 2D sense, these grids are not structured, and all column and pillar adjacency information is explicit. However, just as with IJK grids, there is a well-defined global layering within these grids, which holds for all columns.

The grid description for an unstructured column-layer grid (**Figure 11-24**) has many of the same elements as the IJK grid. However, unlike an IJK grid, RESQML provides no optional extensions, because none arise in current industry practice. If such a requirement does arise in the future, then the general purpose grid description is available for use.

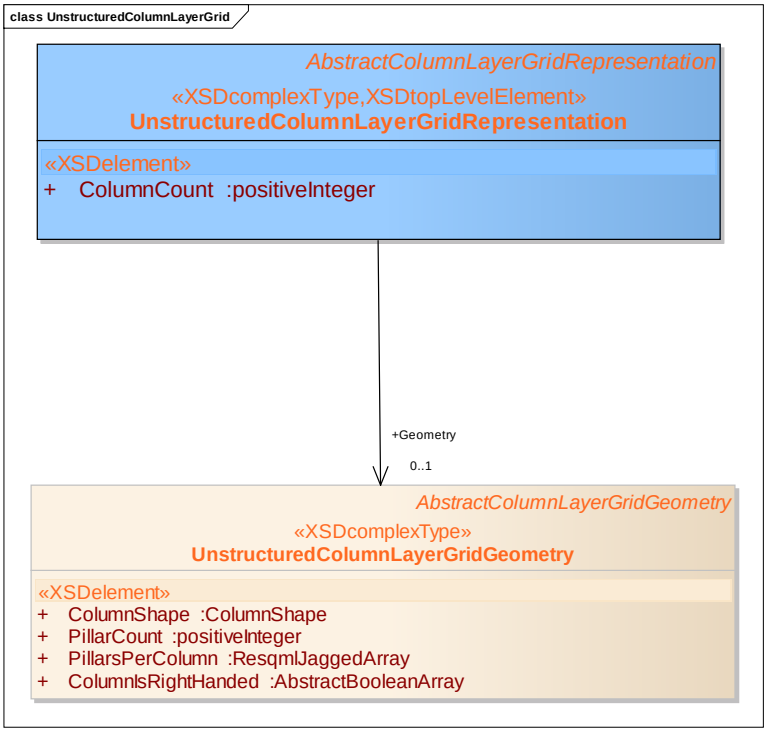


Figure 11-24—Unstructured column-layer grid representation.

11.13.3 Unstructured Column-Layer Grid Indexable Elements

The unstructured column-layer grids have both implicit and explicit topological relationships between the grid elements and a corresponding mixture of implicit and explicit indexing. As shown in **Figure 11-25**, the indexable elements can be organized into three categories: topology, geometry, or additional elements.

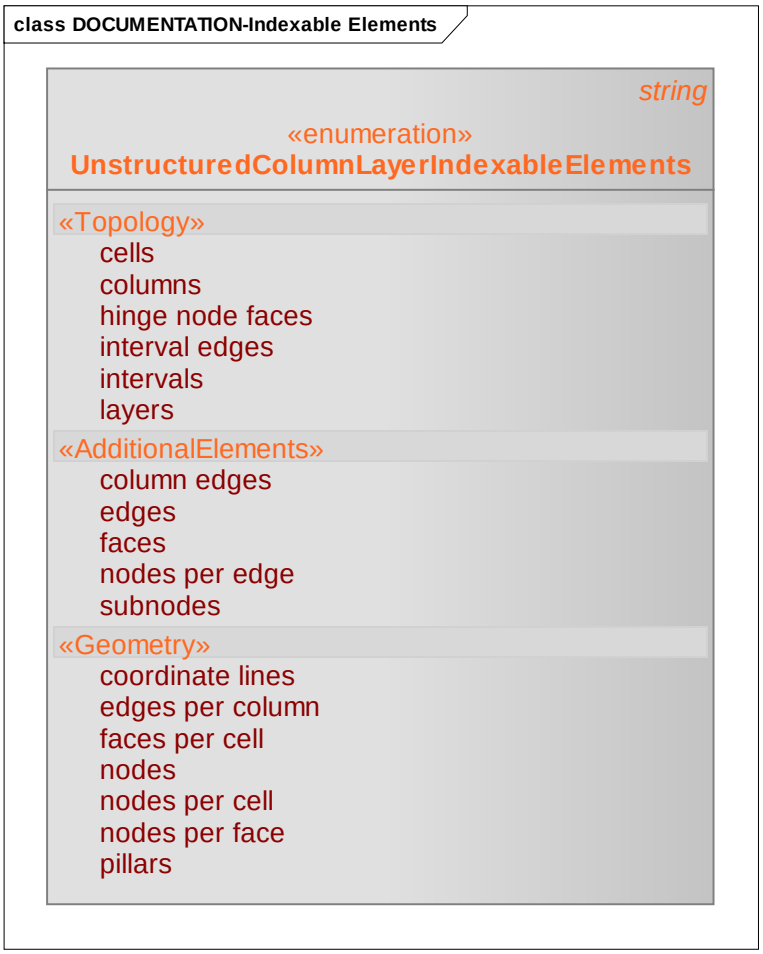


Figure 11-25—Indexable elements for an unstructured column-layer grid.

Element	Definition / Description of Use
Topology	Those elements whose indexing only depends upon the grid indices, which in this case are the ColumnCount and NK. Element indexing is described using the following indices: • Column index = Column# = 0…ColumnCount-1 • Layer index = K0 = 0…NK-1 and γ = 0,1 • Interval index = L = 0…NKL-1 For the unstructured column-layer grid representation, the GapCount=0 and the interval and layer indexing are identical. However, when this topology is re-used as part of a general purpose grid, gaps are supported and these two indices need not be identical.
Geometry	Those elements that need to be introduced to support the description of the geometry of the grid, which in this case are the nodes on the coordinate lines of the grid. The pillar count is explicit, and the CoordinateLineCount = PillarCount + SplitCoordinateLineCount. Both are 1D indices. The nodes always have a 2D index constructed from the number of coordinate lines with NKL nodes per coordinate line. Faces per cell, nodes per cell and nodes per face are indexed in an implicit fashion, which is in contrast to the unstructured grid, where indexing is explicit. By RESQML convention, for all of these elements, the γ=0 face or nodes are indexed first, followed by the γ=1 face or nodes. The areal ordering of the elements follows from the explicit definition of columns

Element	Definition / Description of Use
	in terms of pillars.
Additional Elements	Faces are the most commonly used, and their definition requires the specification of the column edges. Neither are required for the specification of the column-layer grid cell. They may be required for either property indexing or for higher order finite element geometries. The face count is a one dimensional index constructed from an ordered combination of the column edges, the columns, NK and NKL: FaceCount = ColumnCount x NKL + ColumnEdgeCount x NK, in this order. Faces should not be confused with faces per cell. If a face is shared between two cells, then it appears only once as an enumerated face, but twice as an enumerated face per cell.

As with IJK grids, there are a number of “object1 per object2” indexable element kinds for unstructured column-layer grids, which may be used in favor of “object1” indices when the latter are more complicated. For example, for an unstructured column-layer grid, for a column of the model with N sides, there are N+2 “faces per cell”: 0=top, 1=bottom, 2-(N+1) are side faces following the explicit pillars per column ordering. This is a very simple enumeration, versus the “faces” indexing, which depends on the grid faulting and column edge enumeration. Faces per cell indices appear in the grid connections representation and the blocked wellbore representation.

11.14 Truncated Column-Layer Grid Representation

RESQML supports two truncated column-layer grid representations, which may be based upon either 1) IJK or 2) unstructured column-layer grid geometry. These grids are very similar to the underlying fundamental grids but with the extension to allow cells to be truncated and split along the fault surfaces of a structural framework. The truncated cells have more faces than in the underlying grid, and the portions of the cell volumes that are split create additional split cells. The resulting grid cell topology has 3+1 indices for truncated IJK grids and 2+1 indices for truncated unstructured column-layer grids.

Figure 11-26 shows the grid representation. Its elements are similar or identical to those already described. Unlike other grid classes, explicit grid geometry is required and the truncated grids do not support geometry-free, block-centered representations.

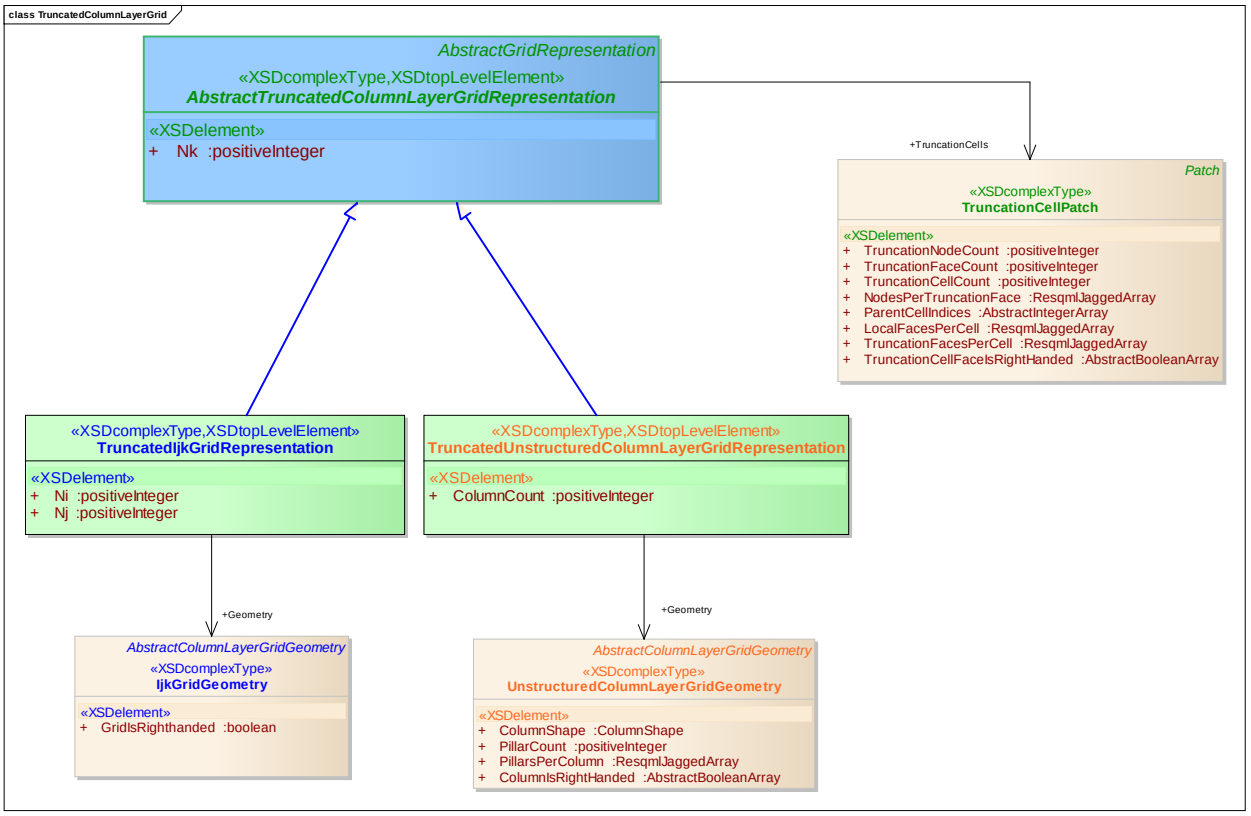


Figure 11-26—Truncated column-layer grid.

11.15 General Purpose (GP) Grid Representation

The general purpose grid representation (**Figure 11-27**) is supplied as a research tool for unstructured grids. It consists of all the grid objects described elsewhere in the schema, combined in a general way. It supports block-centered, explicit geometry, implicit geometry, and higher order grid geometries. Because the general purpose grid allows objects to be mixed in arbitrary combinations, patch topology must be defined for each of the component grid types.

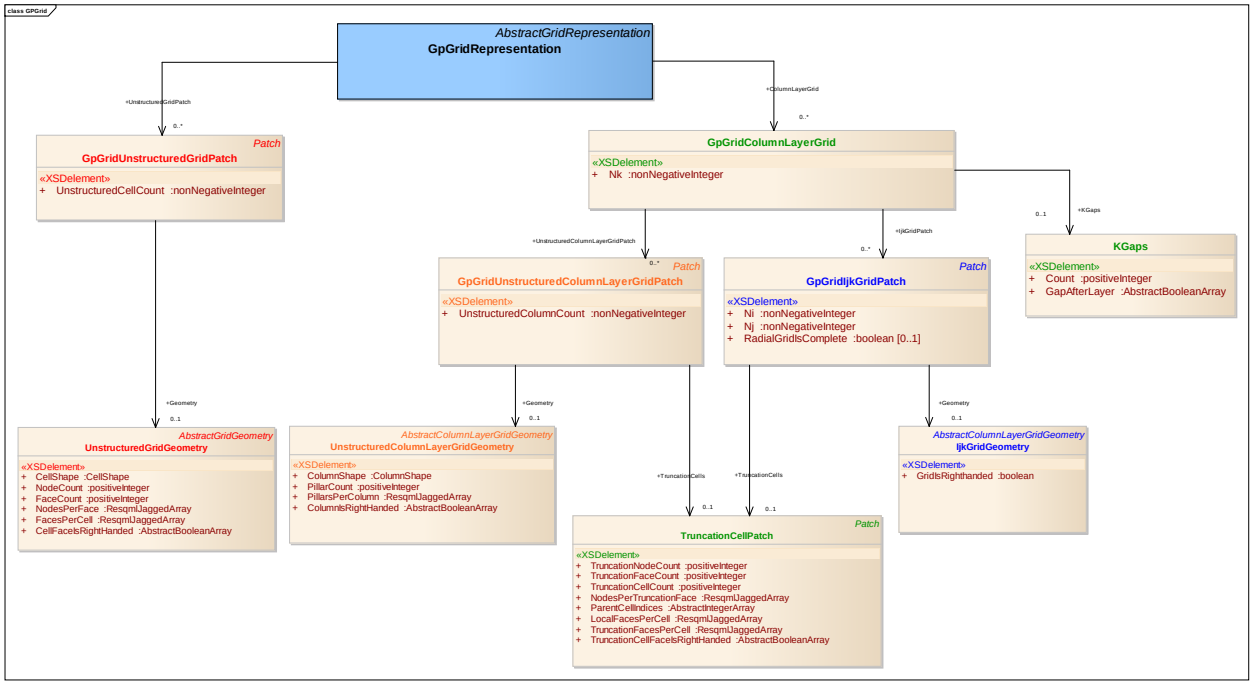


Figure 11-27—General purpose grid representation.

11.16 Grid Connection Set Representation

Just like grids, grid connection sets are RESQML representations (**Figure 11-28**). They replace the more specific non-standard adjacency (NSA) objects of RESQML v1. As with any other representation, they may be used to support properties or relationships. Unlike a grid, geometry as such is never attached to a connection, although geometric properties, i.e., cell face overlap area, may certainly be attached to a connection.

Grid connection sets are the preferred means of representing faults on a grid, and have preference over the use of grid cell-face subrepresentations. The use of cell-face-pairs is more complete than single cell-faces, which are missing a corresponding second cell face identification, and only provide an incomplete representation of the topology of a fault. A grid connection set representation may be associated with a single feature interpretation, e.g., a fault, just as for any other representation. However, it is also possible to associate zero or more interpretations with individual connections to describe more complex structures, e.g., faults or geobody boundaries, potentially merging at below the spatial resolution of a grid.

Unlike what is sometimes the case in reservoir simulation software, RESQML does not distinguish between standard and non-standard connections. Within RESQML if a grid connection corresponds to a "nearest neighbor" as defined by the cell indices, then it replaces and is never additive to the implicit nearest neighbor connection.

BUSINESS RULE: A single cell-face-pair should not appear within more than a single grid connection set. This rule is designed to simplify the interpretation of properties assigned to multiple grid connection sets, which might otherwise have the same property defined more than once on a single connection, with no clear means of resolving the multiple values.

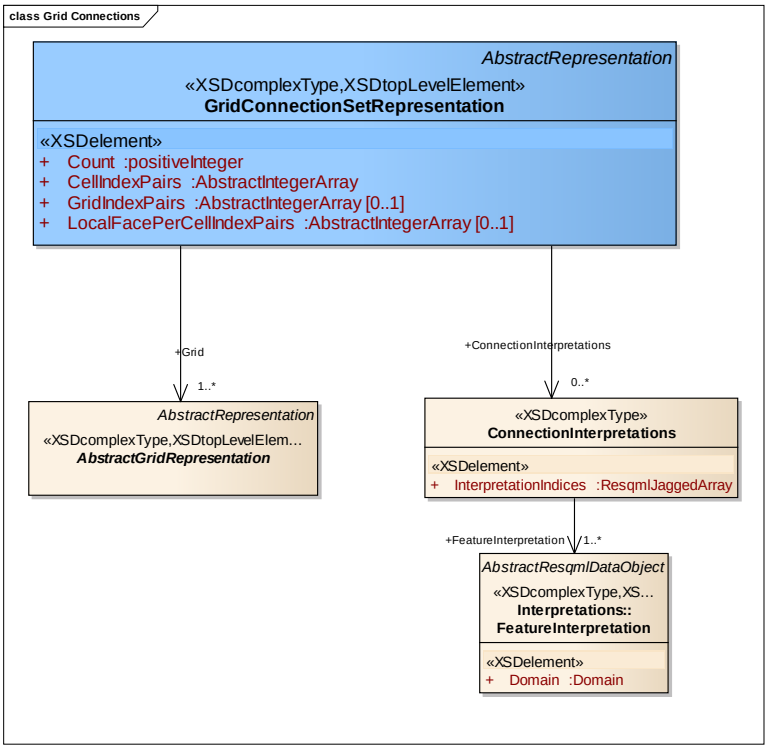


Figure 11-28—Grid connections.

RESQML v1 used a grid-cell-face pair construction for an NSA. The current construction is similar in intent and provides a list of connections between cell pairs. There is no requirement that the two cells are on a shared grid, and so the grid index may need to be provided for each cell. The grid index object is used to convert a list of grid UUIDs to local grid indices, by pairing a (locally) unique index with a reference to a grid. Because directional information is often needed for the use of a connection, the local face per cell index is also included. This is a local index, which, for example, would take on the values of 0…5 for an IJK grid cell.

The connection interpretations provides the feature-interpretations, and hence the feature's name. Notice that the interpretation data structure allows more than one interpretation to be associated with a single connection, which may be required depending upon the spatial resolution of a grid. In engineering terms, the implications are that the transmissibility multiplier for a connection may need to be computed as the product of transmissibility multipliers for each fault or feature-interpretation.

The interpretation cardinality of the grid representation set may be used to support different levels of granularity in the representation. As with any representation, the grid representation set may correspond to a single feature, e.g., provide a list of all of the cell-face-pairs for a fault or for a geobody boundary. In addition, the optional connection interpretations object may be used to associate feature-interpretations with individual connections. The ordered list of feature-interpretations defines a 0-based index for each interpretation, which are then referenced from the interpretation indices array so that each connection has zero, one, or many associated interpretations.

11.17 Grid Examples

This section contains several simple grid examples. Each example consists of:

- One or more class diagrams, which show the objects used to describe the grid.
- One or more instance diagrams, which show the attribute and element data values.

In each diagram, the blue object is the grid representation. Green objects identify the top level objects referenced in the construction.

11.17.1 Eclipse GRDECL File as an IJK Grid

An Eclipse GRDECL grid consists of an NX x NY x NY corner-point grid described by these keywords (**Figure 11-29**):

- COORD defines straight coordinate lines, which correspond to the RESQML pillars.
- ZCORN provides the parametric Z-values, which are used to specify the corner nodes for each cell, using the COORD data as a linear lookup from Z to XY. Adjacent columns share pillars (no IJ Gaps), but the top and base of cells need not be continuous: a GRDECL grid supports NZ-1 K Gaps.
- ACTNUM is an array, which is used to specify whether the geometry and/or properties of a cell are defined.
- Properties are attached to the cells of the grid.

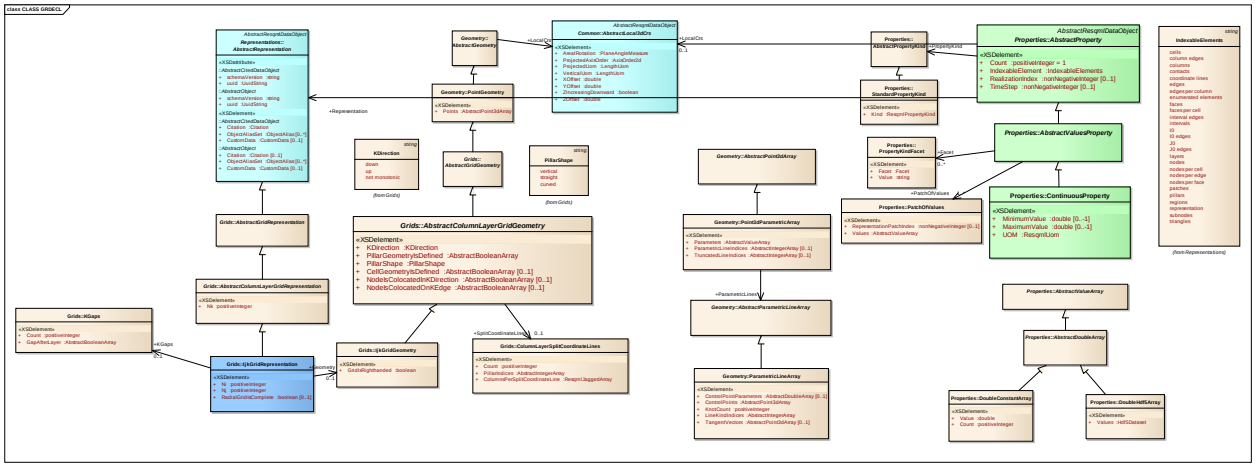


Figure 11-29—Class diagram for an Eclipse grid, including geometry/topology, parametric lines/points, and properties.

This figure is split into its major components in **Figure 11-30, Figure 11-31** and **Figure 11-32,** which are explained below.

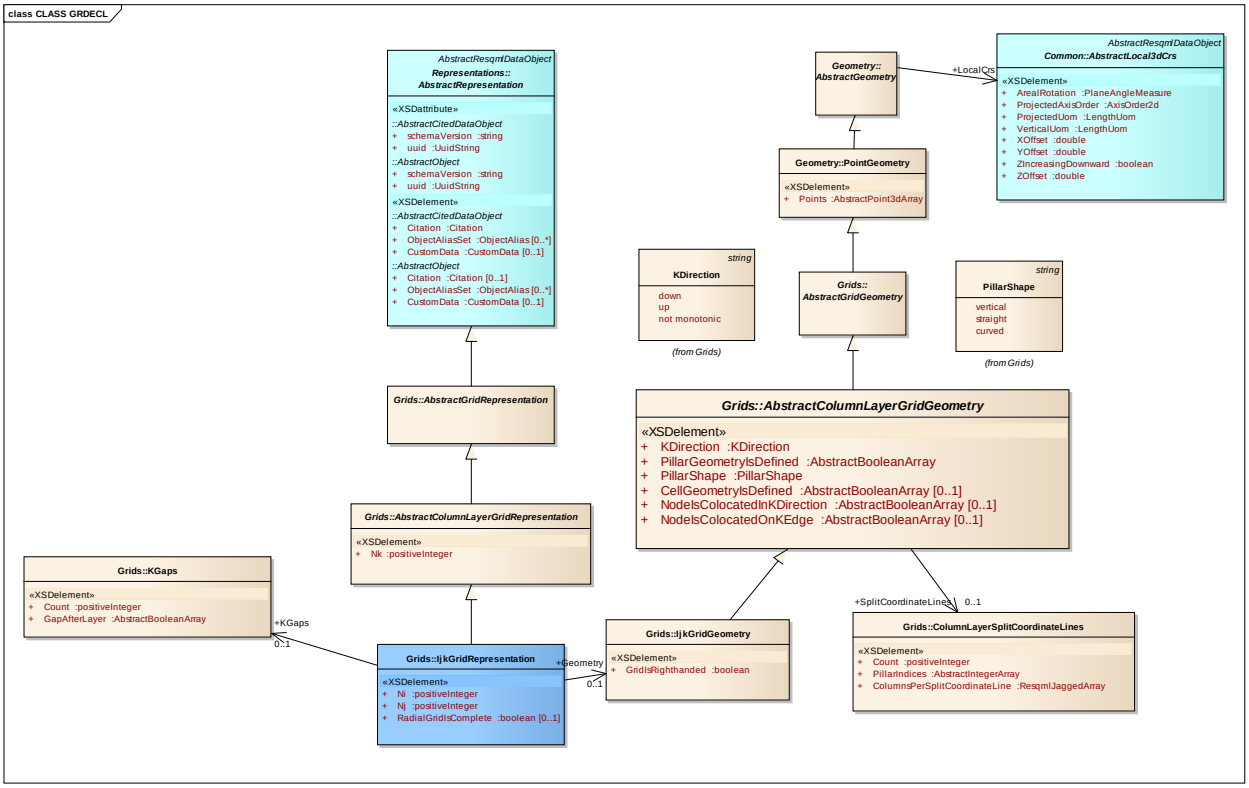


Figure 11-30—Class diagram for the geometry of an Eclipse grid.

The IJK grids have three indices and inherit a UUID as an abstract data object. An Eclipse grid implicitly assumes that all cells are faulted and includes redundant geometric information when they are not. In contrast, RESQML only introduces split coordinate lines and split coordinate line nodes when faults are present, if any. However, in this example, no analysis of the data within the GRDECL file has been performed, and so the cell geometry is stored as if each cell were faulted.

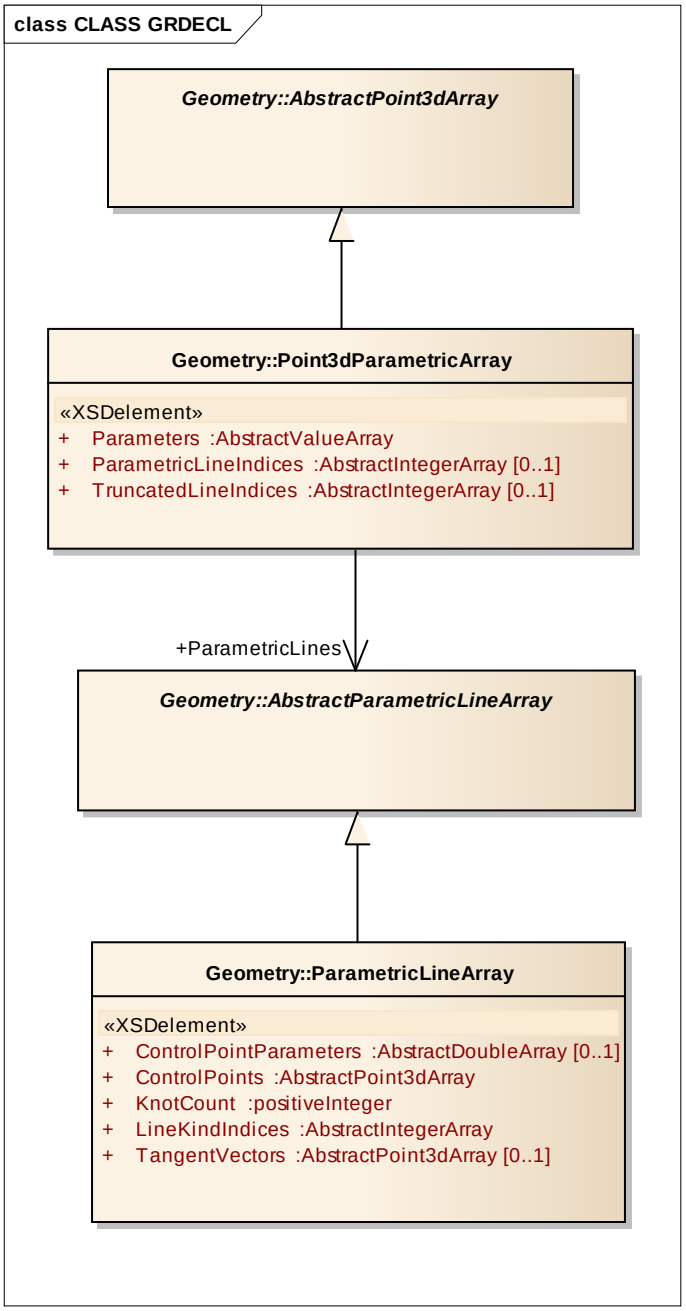


Figure 11-31—Class diagram for the parametric points and lines of an Eclipse grid.

The COORD data from the GRDECL file are used to define a (NX+1) x (NY+1) array of straight parametric lines, i.e., linear parametric lines with two control points per line. The control points are the XYZ values from the COORD data and the control point parameters are the COORD Z values. The ZCORN data from the GRDECL file are used to describe the cell corner nodes. The array of parametric points will be referenced for all of the 4*NX*NY coordinate lines, which themselves reference the (NX+1) x (NY+1) parametric lines, once for each pillar.

There is one subtly in this construction. The parametric line indices array in the points 3D parametric array does not need to be specified because it is identical to the pillar indices array in the column layer split coordinate lines. This is an example of the mapping from array index of the parametric points to the parametric line index already being known in context so that it does not need to be specified a second time. The optional parametric line indices array is available for when this mapping is not otherwise known.

A GRDECL file assumes that Z is monotonic and uses the Z coordinate to provide a linear lookup to X and Y. In contrast, the parametric representations in RESQML parameterize the XYZ coordinates to an arbitrary parameter, P. This parameterization removes all restrictions on the shape of the reservoir, for example, to support overturned reservoirs. This flexibility also allows for simplification in the grid description for specific layering schemes. For example, a parametric value that varies between 0 and NK may be used to naturally describe a proportional layering scheme.

Property treatment is common to all RESQML representations. Properties are attached to the IJK grid representation and follow the indexing of the selected attachment kind, which in this case are cells. The abstract class of values may be instantiated in several ways, including a constant array or an explicit array of values stored as an HDF5 dataset.

Interestingly, the ACTNUM keyword of the GRDECL file does not have a standard interpretation in the industry; its usage will vary from application to application. For some applications a zero value of ACTNUM implies that all properties have been nulled for that cell while for others a zero value implies that both properties and geometry are null. To avoid any ambiguity, RESQML does not utilize “ACTNUM” as such. Instead, there is an explicit Boolean array: CellGeometryIsDefined, which indicates exactly that. The GRDECL file has no provision for null values of properties and so needs to use ACTNUM for this purpose. In contrast, RESQML always has a well-defined null value, and so a special treatment of nulls is not required.

In some reservoir simulation applications, ACTNUM or a minimum pore volume array, may be used to mask away inactive cells, and properties are then stored in a reduced size array. In RESQML, the size of a property array is uniquely specified by the representation itself. For instance, an array associated with the cells of an IJK grid will always be stored as an NI x NJ x NK array. If it is desirable to achieve the effect of masking away cells and changing array storage to a reduced size 1D array following the values of ACTNUM, then a subrepresentation must be built from the IJK grid using ACTNUM to define the corresponding indexable grid cell elements. However, a single representation (IJK grid or subrepresentation) has only a single indexing of the cells, so no ambiguity in the number of cells on which properties are defined should ever arise in RESQML.

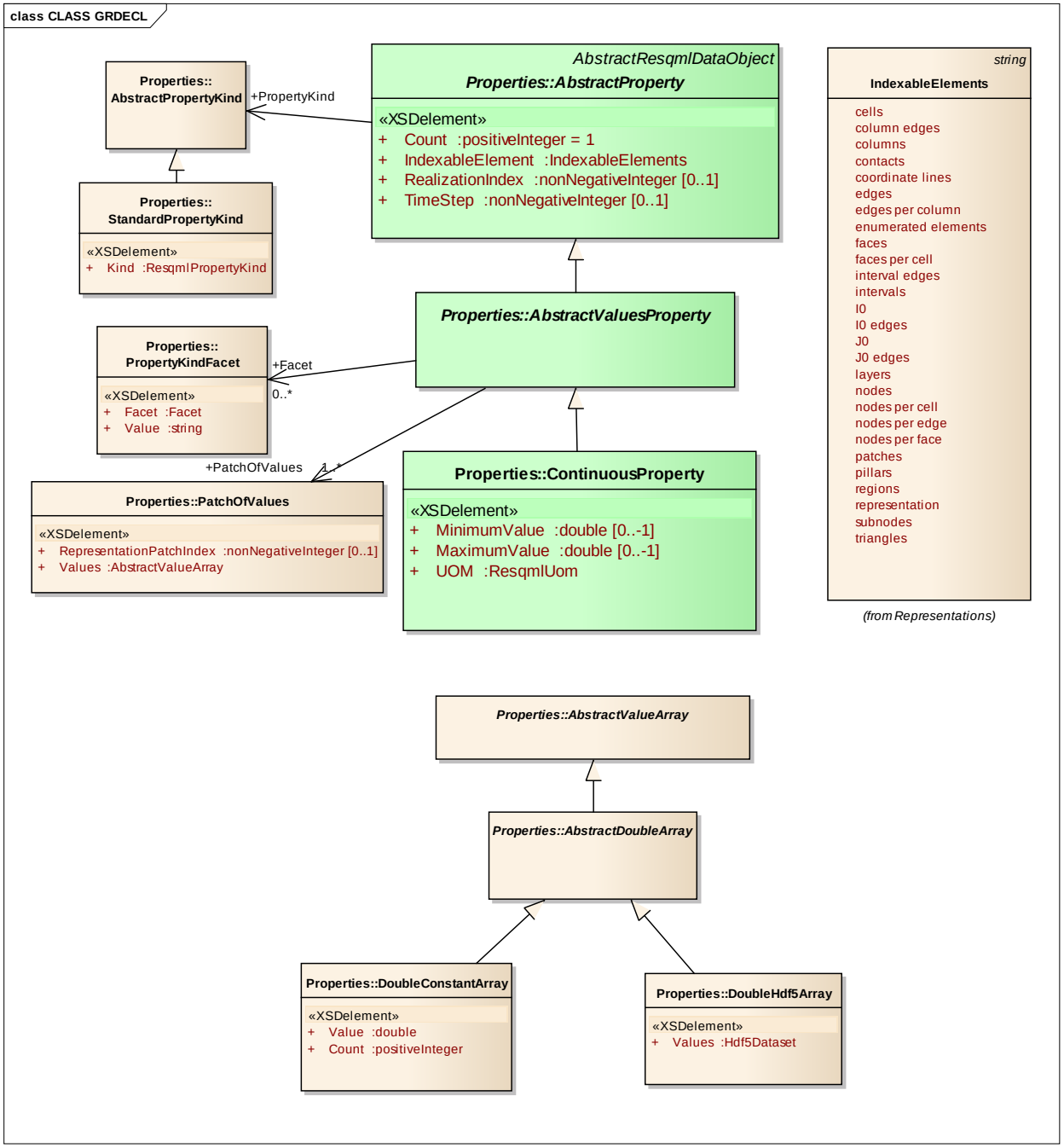


Figure 11-32—Class diagram for the cell properties of an Eclipse grid.

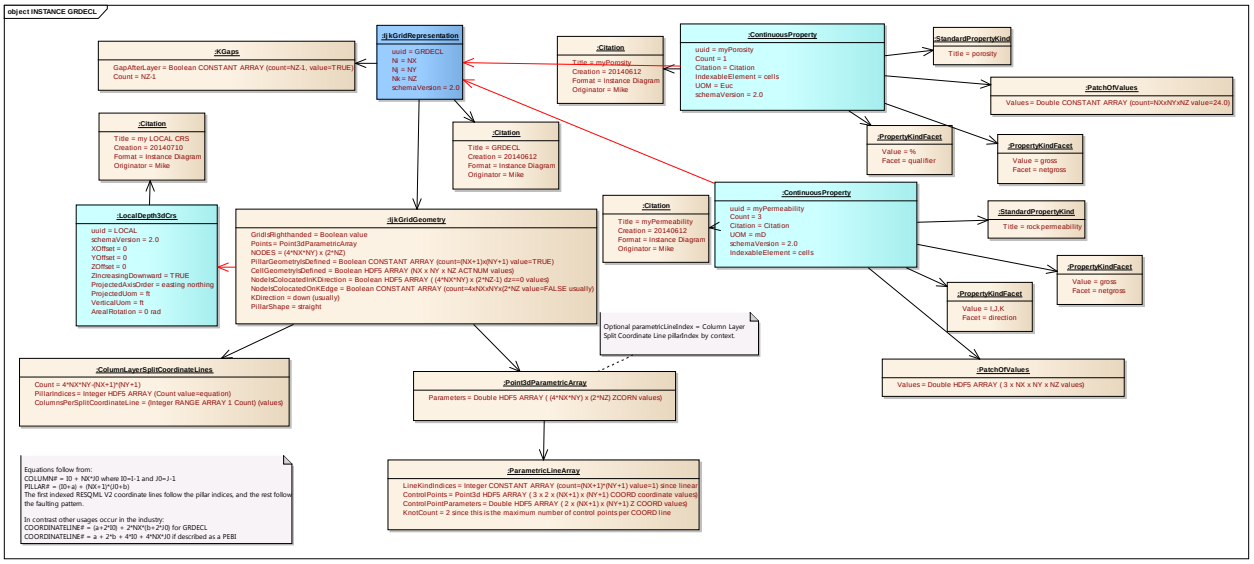


Figure 11-33—Instance diagram of an Eclipse GRDECL file, including properties.

Grid name (UUID) is GRDECL with indices NI=NX, NJ=NY and NK=NZ. The remaining indices are NIL=NX+1, NJL=NY+1, NKL=2*NZ and #Intervals=2*NZ-1. Properties are attached to the IJK grid representation by reference, with an attachment kind of cells. One property (porosity) shows the use of a constant array. The other property (permeability) shows the use of the property count to store the three directional permeability arrays as a single 4D array. The use of property facets allows more details about the property values to be stored, e.g., that these are both gross properties, that the porosity is expressed in percentage, and that the three permeabilities are in the I, J, and K directions.

The IJK grid contains the geometry of the coordinate line nodes, and in this case, the data from the ACTNUM array within the omit cells object. The nodes are defined parametrically using the COORD parametric lines. Because the model is faulted, the coordinate lines need an array, which is used to implicitly describe which columns of the model follow the split coordinate lines and which do not. This is the array of pillar indices. This array also indicates how to map from the 4*NX*NY coordinate lines to the (NX+1) x (NY+1) pillars, and is used as part of the parametric points construction.

Coordinate lines may be indexed using a 4D set of indices: (α,β,I,J). The Eclipse GRDECL file and RESQML each reduce this index to a single 1D index, or equivalently choose an order for the coordinate lines. RESQML v2 specifies that the index of each unsplit coordinate line is identical to its corresponding pillar index. Each split coordinate line is defined explicitly by the column per split coordinate line jagged array and the corresponding pillar indices. In contrast, GRDECL does not distinguish between split and unsplit coordinate lines and will have a different, and longer, list of coordinate lines than will RESQML.

11.17.2 4x3x2 Faulted IJK Grid

Figure 11-34 and **Figure 11-35** show an example of a simple grid with regularly spaced vertical coordinate lines and a single fault. The grid has no gaps in IJ or in K.

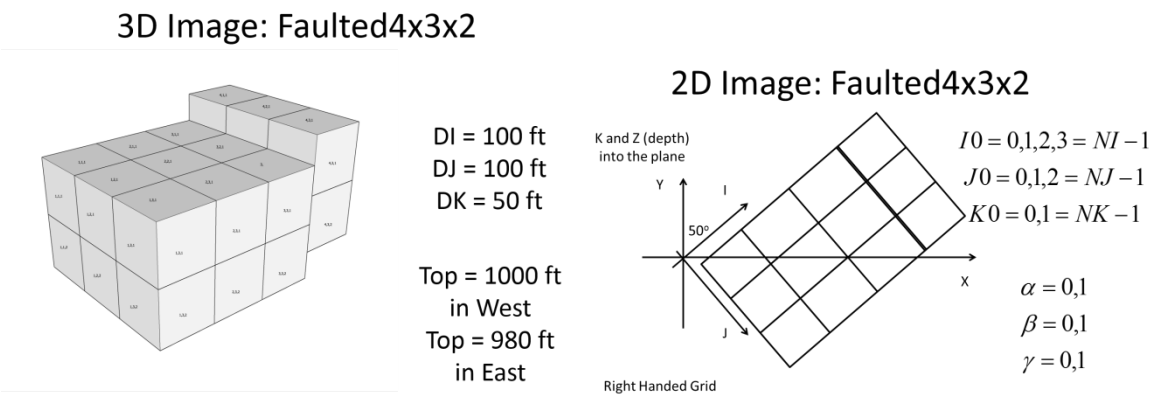


Figure 11-34—4x3x2 faulted corner-point grid.

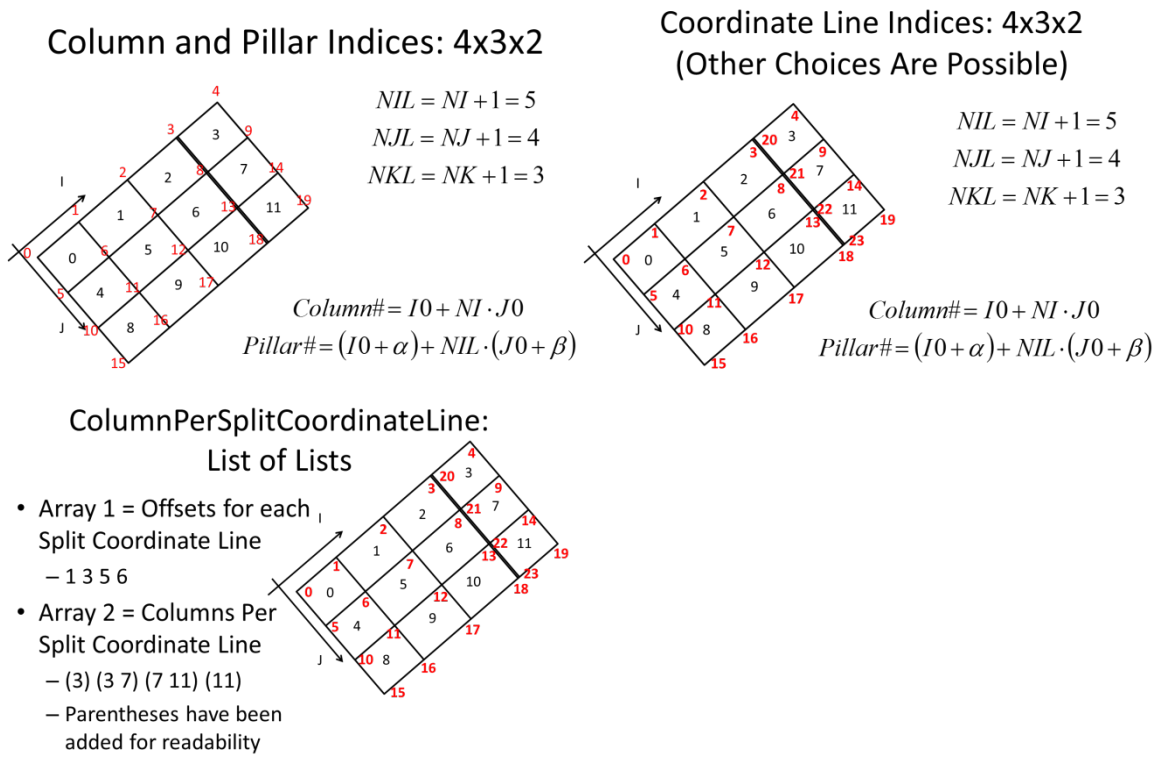


Figure 11-35—Indexing of the elements for the 4x3x2 faulted corner-point grid.

In **Figure 11-35**, the split coordinate lines are specified using a jagged array construction, which consists of two arrays. The first provides the offset into the second array for each element and the second array provides the values. There are 20 pillars in this grid and 4 split coordinate lines. The first 20 coordinate lines correspond to the pillars, and the remaining lines are the split coordinate lines. Because there are no IJ gaps in this grid, the split coordinate lines share the same pillars as the unsplit coordinate lines.

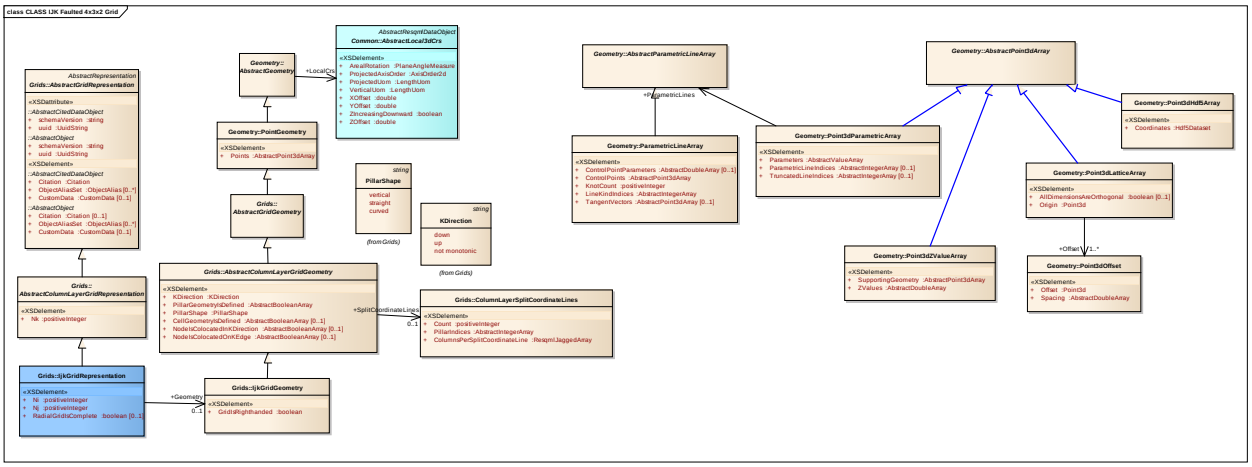


Figure 11-36—Class diagram of an IJK Grid Representation of the 4x3x2 Faulted corner-point grid

The class diagram for this grid (**Figure 11-36**) is similar to that of the GRDECL grid (**Figure 11-29**), although with fewer options. The grid description has neither IJ nor K gaps, the grid spacing is regular with vertical pillars, and all cells have their geometry defined. Property attachment is not part of this example. Because of the regularity of this grid, we can demonstrate implicit parameterizations for the nodes. For this example, values for the cell dimensions and nodal positions are available.

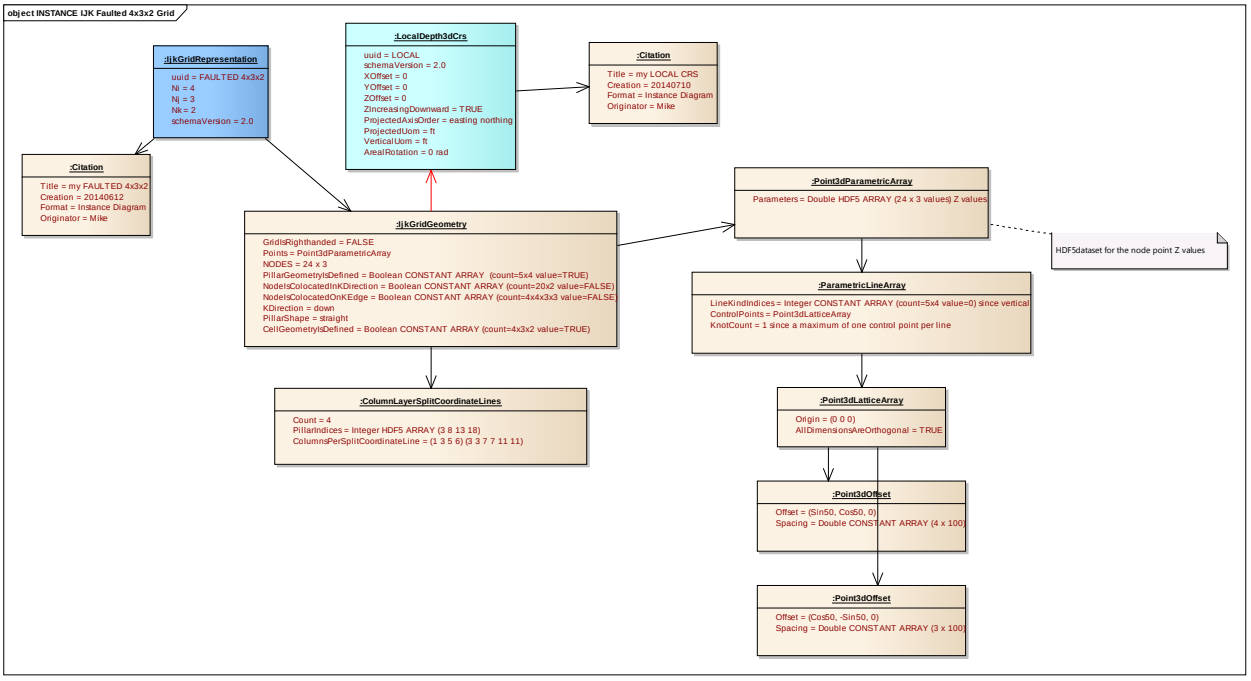


Figure 11-37—Instance diagram for an IJK Grid Representation of the 4x3x2 Faulted corner-point grid.

The parametric line indices, or equivalently the pillar indices, provide the mapping from the coordinate lines to the parametric lines. In this case, the parametric lines are vertical with a regular XY spacing. They are specified using the array of lattice points 3D for an orthogonal lattice. The Z coordinate of each node is given explicitly on a 24x3 array. For this simple grid, the values are (1000 1050 1100) or (980 1030 1080) per coordinate line, depending on which fault block of the grid the line is positioned within.

11.17.3 Fault Representations on the 4x3x2 Faulted IJK Grid

There are two recommended ways of creating a representation of a fault given a grid. If the fault is a pillar fault, i.e., follows the pillars of a structure through the structure without stair-stepping, then the fault may be represented using a pillar-based subrepresentation of the structure, which in this case is a faulted grid. This places the fault in the grid, but does not explicitly specify the topological support of the fault on the grid. The latter can be constructed using a grid connection set representation, which is based upon all of the cell-face-pairs of the grid which intersect the fault. **Figure 11-38** is a class diagram which contains both the grid subrepresentation, the grid connection set representation, and the fault feature and interpretation. **Figure 11-39** (page 176) is the instance diagram for the same objects.

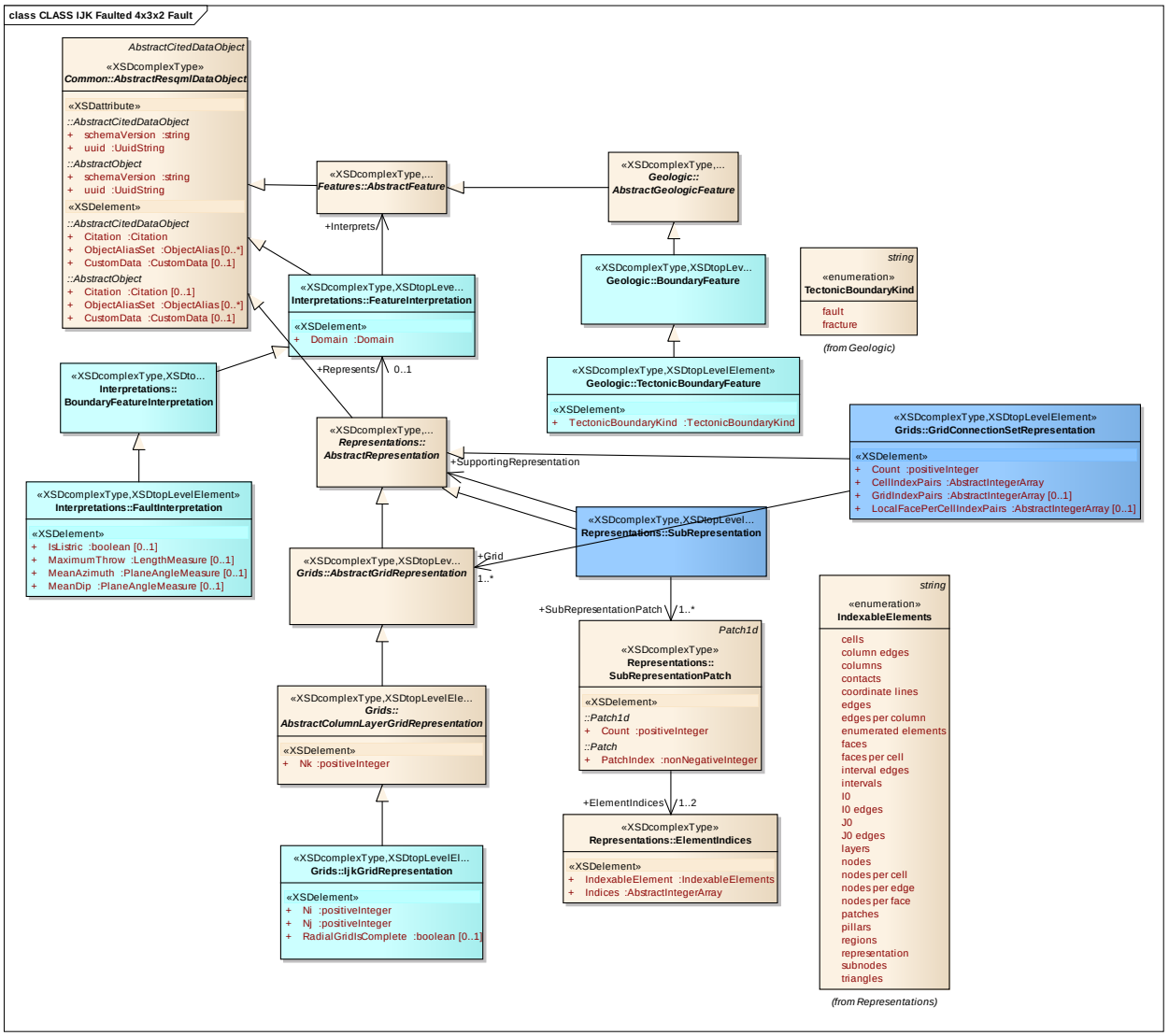
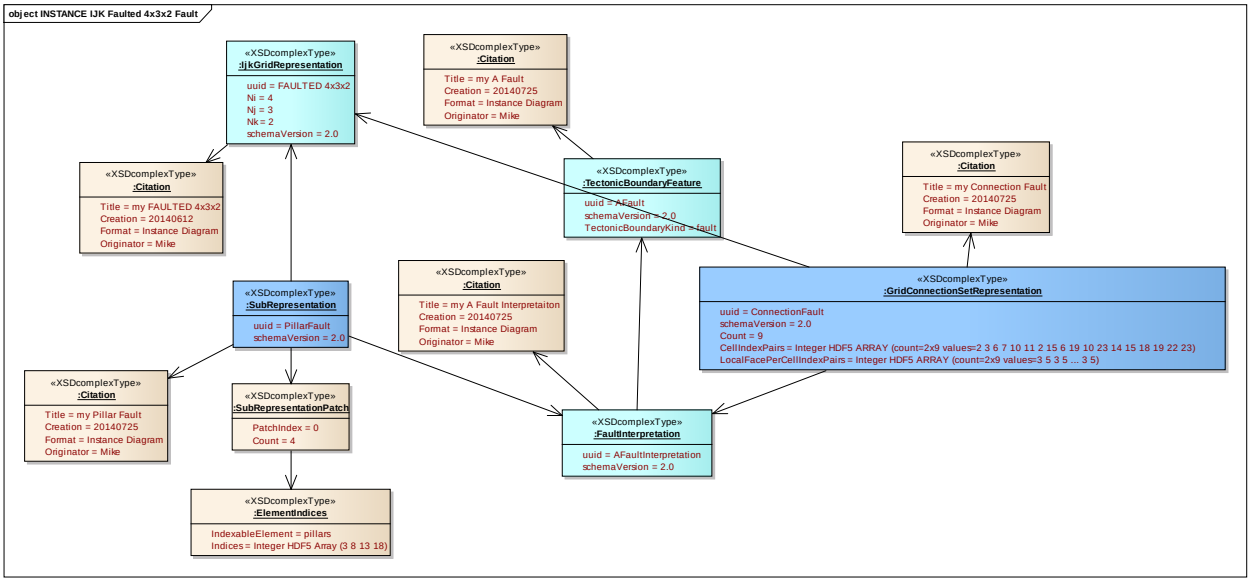


Figure 11-38—Class diagram for a subrepresentation and a grid connection set representation which provide the recommended representations for a fault.


object INSTANCE IJK Faulted 4x3x2 Fault
«XSDcomplexType»
:ijkGridRepresentation
uuid = FAULTED 4x3x2
Ni = 4
Nj = 3
Nk = 2
schemaVersion = 2.0
«XSDcomplexType»
:Citation
Title = my A Fault
Creation = 20140725
Format = Instance Diagram
Originator = Mike
«XSDcomplexType»
:Citation
Title = my FAULTED 4x3x2
Creation = 20140612
Format = Instance Diagram
Originator = Mike
«XSDcomplexType»
:TectonicBoundaryFeature
uuid = AFault
schemaVersion = 2.0
TectonicBoundaryKind = fault
«XSDcomplexType»
:Citation
Title = my Connection Fault
Creation = 20140725
Format = Instance Diagram
Originator = Mike
«XSDcomplexType»
:SubRepresentation
uuid = PillarFault
schemaVersion = 2.0
«XSDcomplexType»
:Citation
Title = my A Fault Interpretaiton
Creation = 20140725
Format = Instance Diagram
Originator = Mike
«XSDcomplexType»
:GridConnectionSetRepresentation
uuid = ConnectionFault
schemaVersion = 2.0
Count = 9
CellIndexPairs = Integer HDF5 ARRAY (count=2x9 values=2 3 6 7 10 11 2 15 6 19 10 23 14 15 18 19 22 23)
LocalFacePerCellIndexPairs = Integer HDF5 ARRAY (count=2x9 values=3 5 3 5 ... 3 5)
«XSDcomplexType»
:Citation
Title = my Pillar Fault
Creation = 20140725
Format = Instance Diagram
Originator = Mike
«XSDcomplexType»
:SubRepresentationPatch
PatchIndex = 0
Count = 4
«XSDcomplexType»
:FaultInterpretation
uuid = AFaultInterpretation
schemaVersion = 2.0
«XSDcomplexType»
:ElementIndices
IndexableElement = pillars
Indices = Integer HDF5 Array (3 8 13 18)

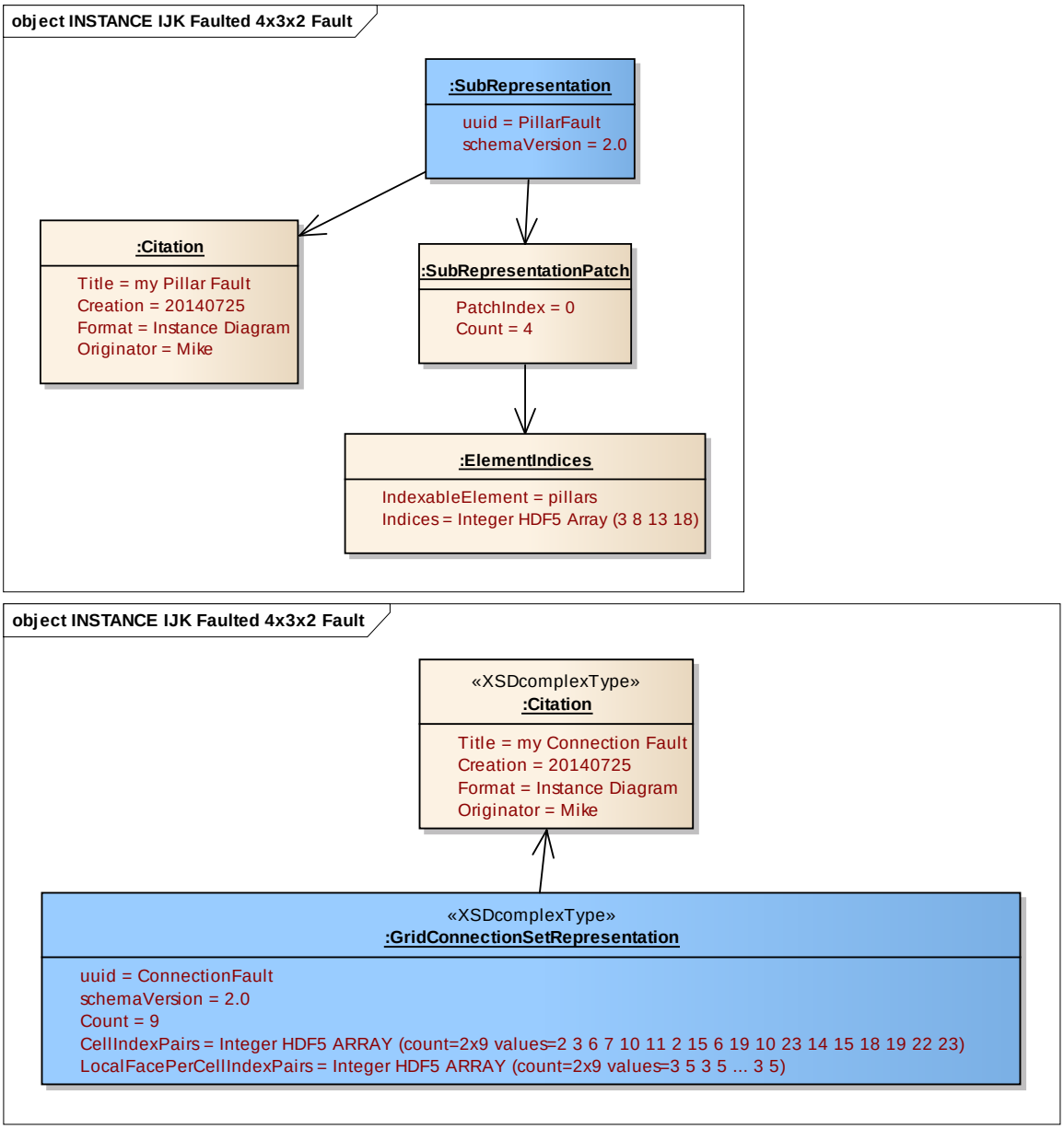


Figure 11-39—Instance diagram for a subrepresentation and for a grid connection set representation for the fault of the Faulted 4x3x2 grid (a) Overview (b) Subrepresentation (c) Grid connection set representation.

In the instance diagram, it can be seen that the pillar-based subrepresentation provides a very simple fault representation, based upon the four pillars that support the fault. The grid connection set representation is a much more detailed representation, with, in this case, 9 connections. For instance, the first connection is from the J+ face of cell (I,J,K) = (1,3,1) to the J- face of cell (I,J,K) = (1,4,1). Cell indices are 2 and 3. Local cell face indices are 3 for J+ and 5 for J-. These are listed in detail in the instance diagram.

11.17.4 Stratigraphic Column Representations on an IJK Grid

The following example (**Figure 11-40, Figure 11-41, Figure 11-42**) is used to demonstrate how to specify a relationship between the interval edges of a grid and the horizons of a stratigraphic column. In this specific example there are three stratigraphic units (Unit A, Unit B, Unit C) bounded by four horizons (H1, H2, H3, H4). The reservoir grid has been built only for Unit B, which in this case, is the only unit with appreciable productivity. This example shows how to use a stratigraphic column to express the relationship between the top and base of the reservoir grid and horizons H2 and H3, which bound Unit B. For the grid this involves constructing a subrepresentation of the two interval edges of the grid. For the stratigraphic column this involves constructing a column of stratigraphic rank two, consisting of Unit B and horizons H2 and H3. A more complete stratigraphic column of rank one also exists, consisting of all three units and all four horizons. However, the rank one stratigraphic column is not referenced directly, other than implicitly through the shared horizon interpretations and the statement of the differing ranks of the stratigraphic columns.

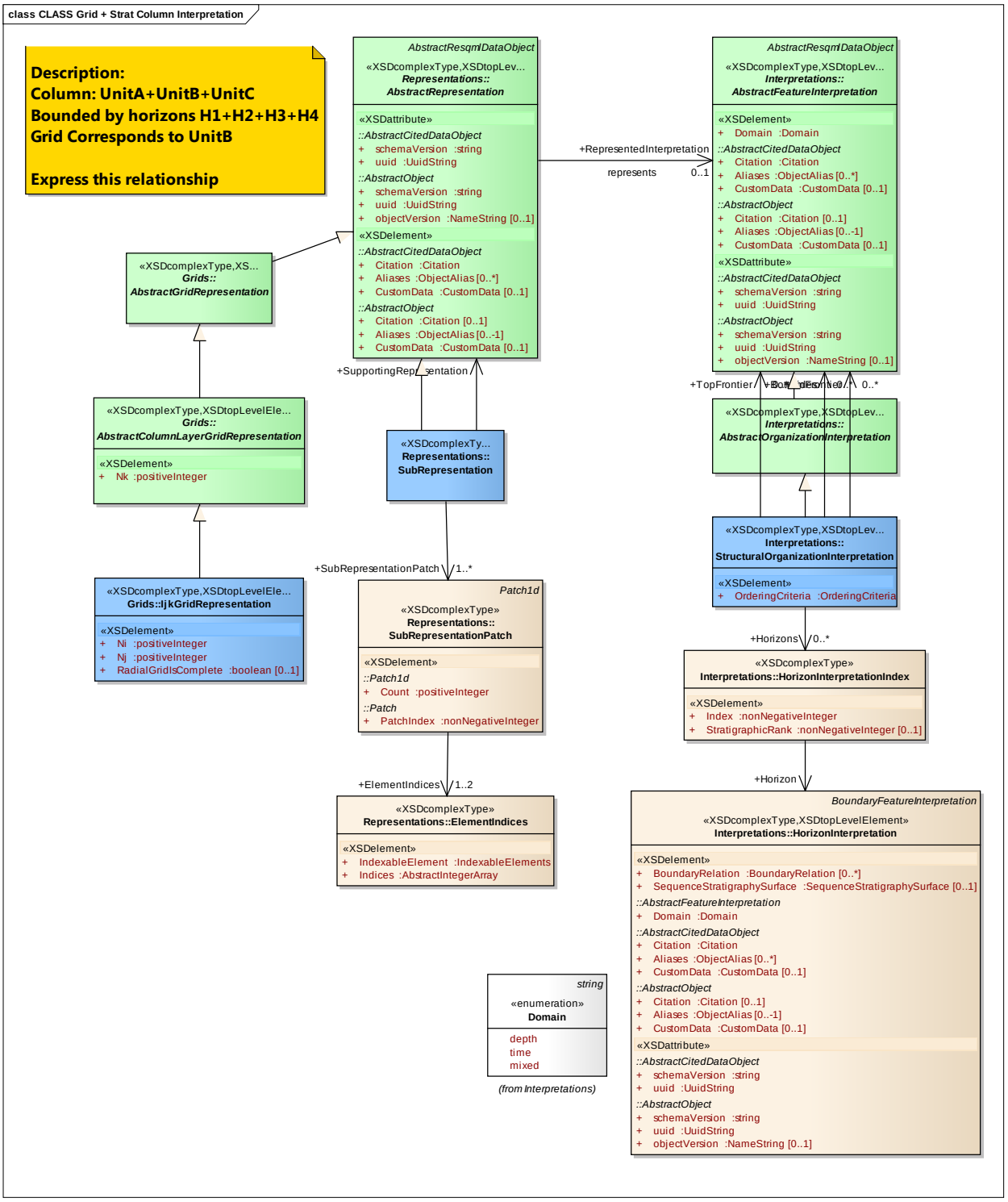


Figure 11-40—Class diagram for a grid, a subrepresentation and stratigraphic column.

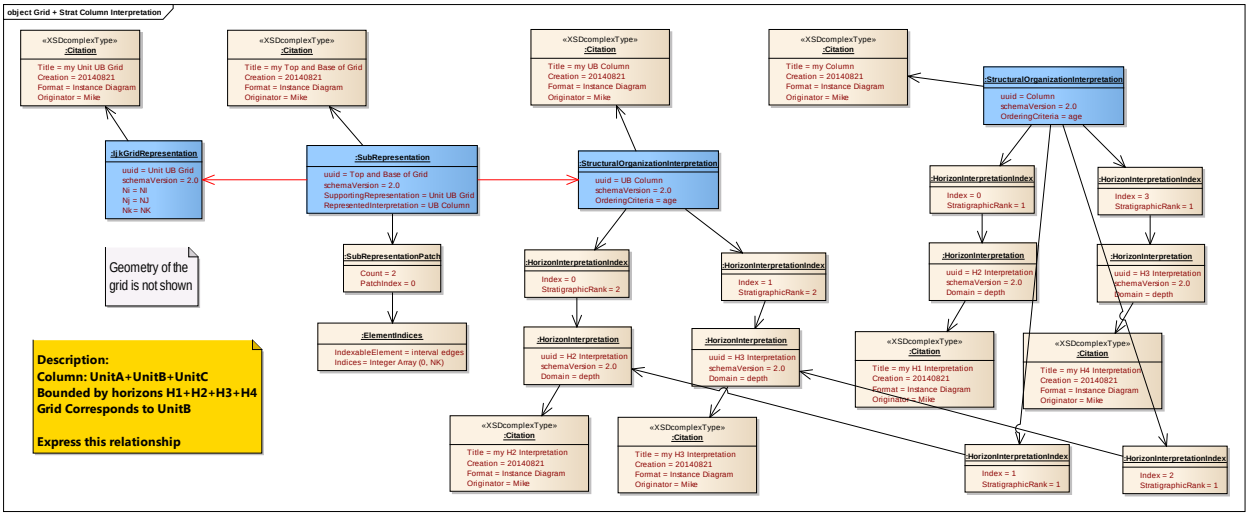


Figure 11-41—Instance diagram showing an IJK grid, a subrepresentation and two stratigraphic columns.

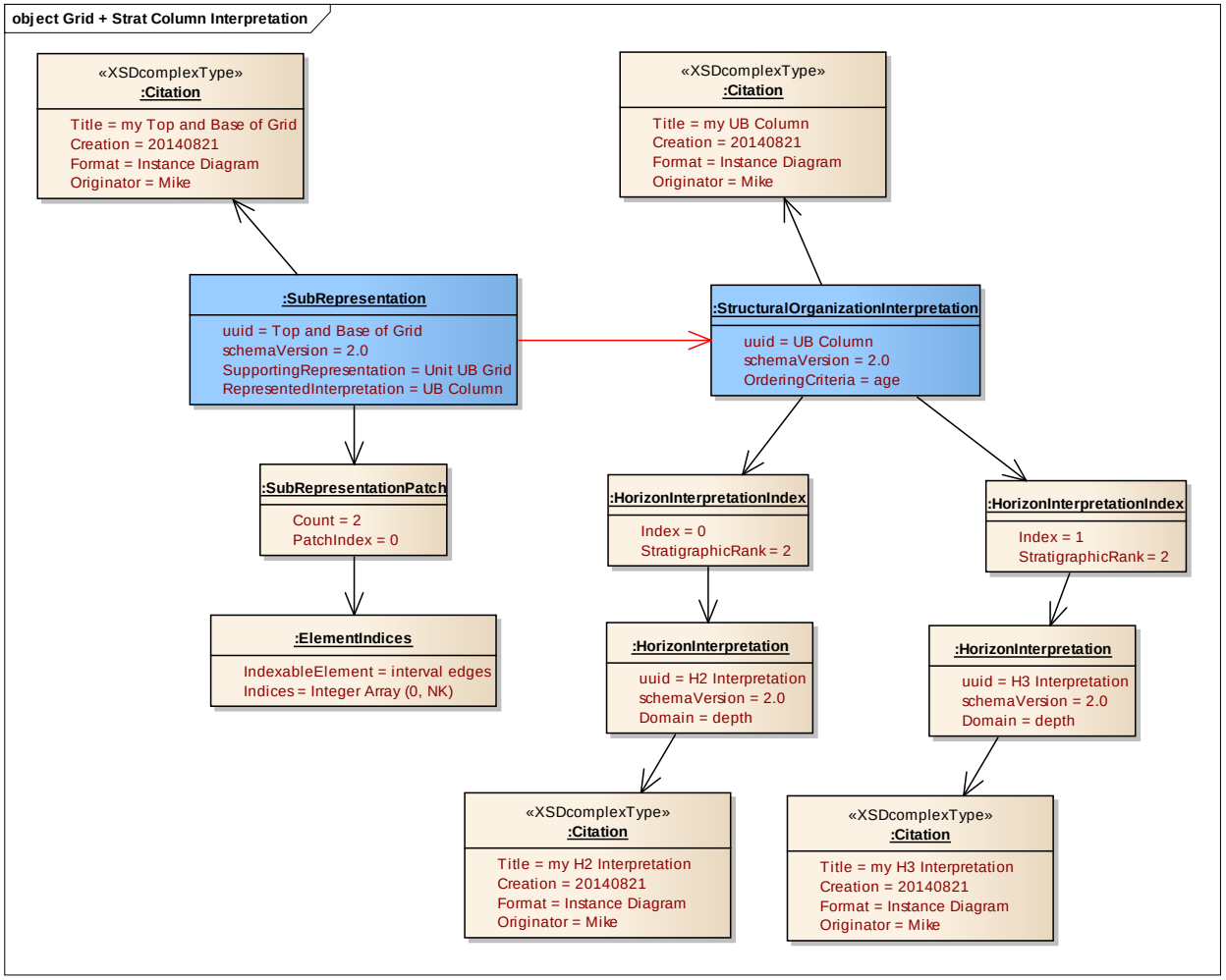


Figure 11-42—Instance diagram showing only the subrepresentation of the grid and the rank two stratigraphic column.

11.17.5 Small IJK Grid with Nested Local Grid Refinement

Figure 11-43 and **Figure 11-44** is a grid example that shows the use of grid parentage and local grids. Grid parentage allows one grid to inherit geometry and properties from a parent grid, but has no immediate impact on the parent grid. Local grid sets are used to "activate" local grids and replace portions of the parent grid by the corresponding child grid or grids. (For more information on local grids, see Section 11.8 (page 141).) The RESQML construction is sufficiently general to allow both nested and irregularly shaped local grids. It is also sufficiently general to support refinement, coarsening, or combinations of the two.

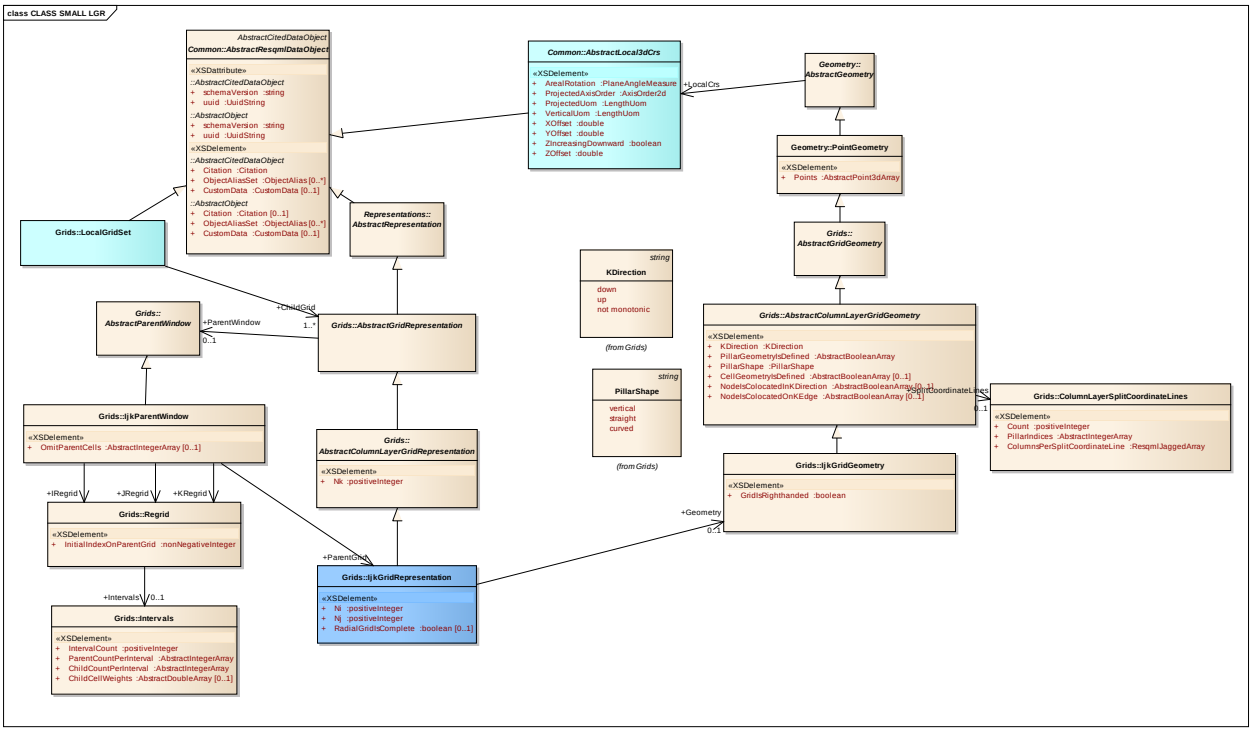


Figure 11-43—Class diagram for the nested LGR example.

Figure 11-43 is similar to the IJK grids examined previously, with the exception of the grid parentage construction. No properties are included within this example.

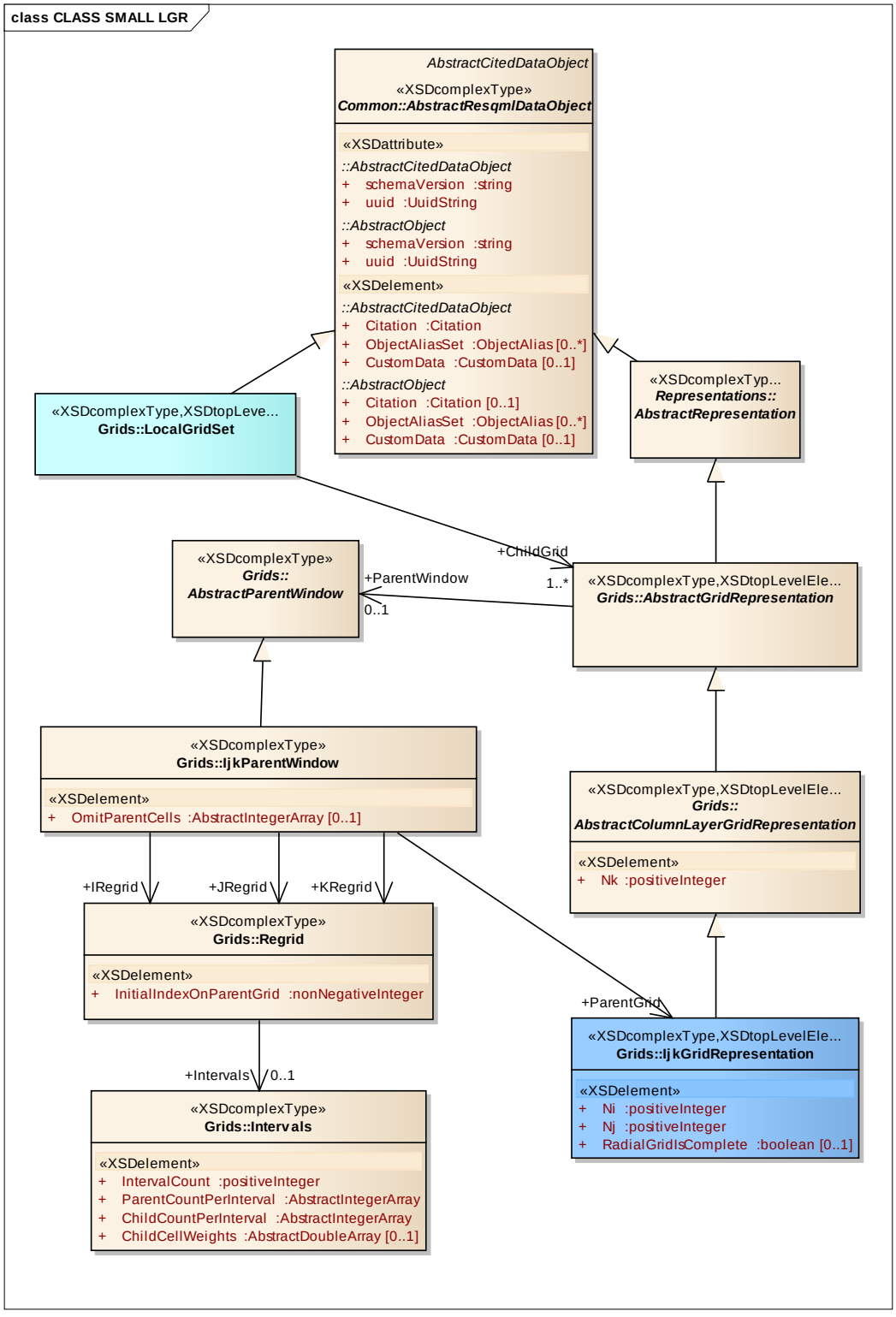
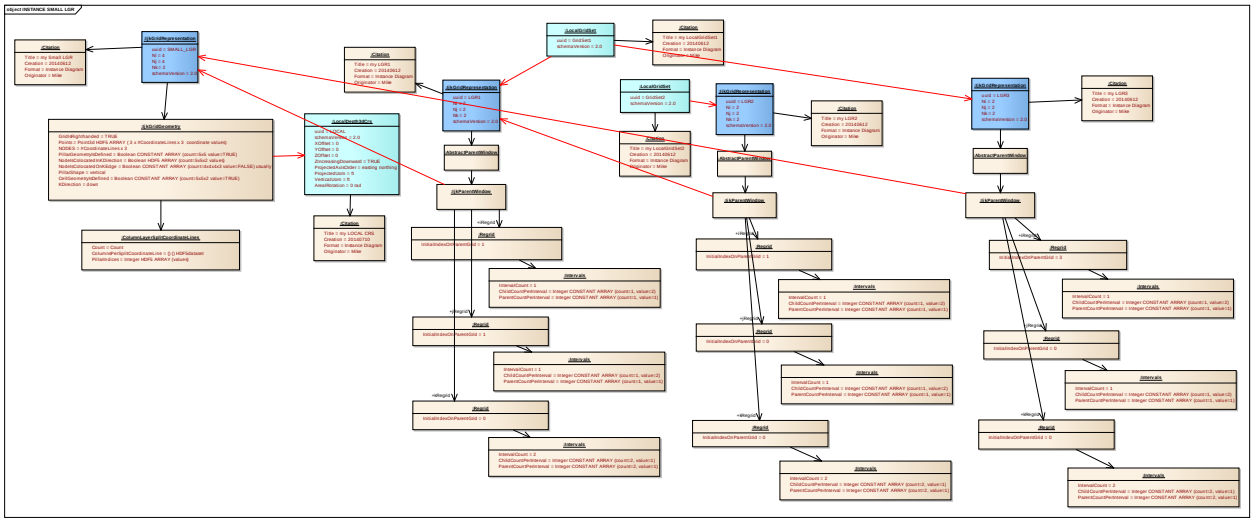
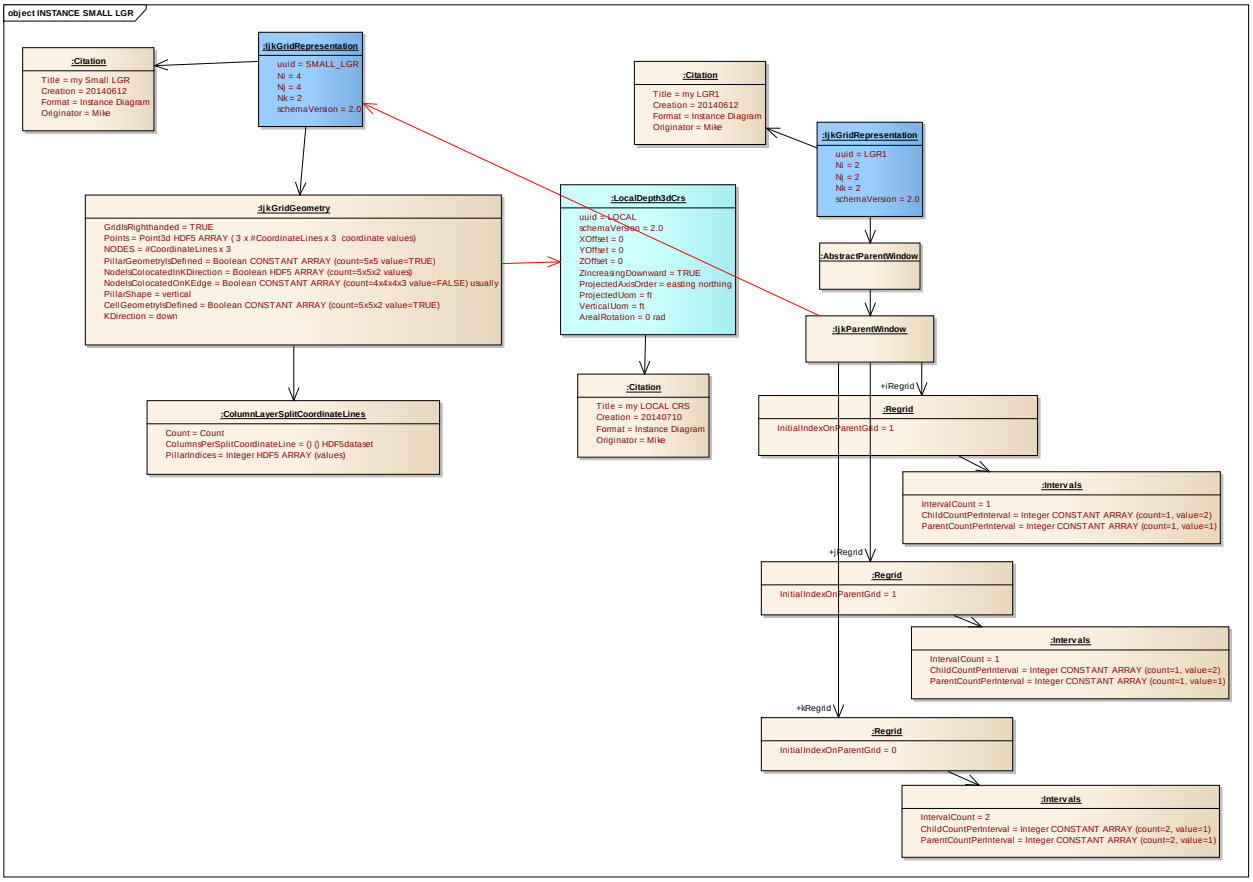


Figure 11-44—Class diagram showing only the parent-child grid specification.

Figure 11-44 shows the portion of the grid parentage construction based on an IJK grid parent. It supports I, J, and K regrid specifications.




object INSTANCE SMALL LGR
:Citation
Title = my Small LGR
Creation = 20140612
Format = Instance Diagram
Originator = Mike
:ijkGridRepresentation
uuid = SMALL_LGR
Ni = 4
Nj = 4
Nk = 2
schemaVersion = 2.0
:ijkGridGeometry
GridIsRighthanded = TRUE
Points = Point3d HDF5 ARRAY (3 x #CoordinateLines x 3 coordinate values)
NODES = #CoordinateLines x 3
PillarGeometryIsDefined = Boolean CONSTANT ARRAY (count=5x5 value=TRUE)
NodeIsColocatedInKDirection = Boolean HDF5 ARRAY (count=5x5x2 values)
NodeIsColocatedOnKEdge = Boolean CONSTANT ARRAY (count=4x4x4x3 value=FALSE) usually
PillarShape = vertical
CellGeometryIsDefined = Boolean CONSTANT ARRAY (count=5x5x2 value=TRUE)
KDirection = down
:ColumnLayerSplitCoordinateLines
Count = Count
ColumnsPerSplitCoordinateLine = () () HDF5dataset
PillarIndices = Integer HDF5 ARRAY (values)
:LocalDepth3dCrs
uuid = LOCAL
schemaVersion = 2.0
ZOffset = 0
ZIncreasingDownward = TRUE
ProjectedAxisOrder = easting northing
ProjectedUom = ft
VerticalUom = ft
ArealRotation = 0 rad
:Citation
Title = my LOCAL CRS
Creation = 20140710
Format = Instance Diagram
Originator = Mike
:Citation
Title = my LGR1
Creation = 20140612
Format = Instance Diagram
Originator = Mike
:ijkGridRepresentation
uuid = LGR1
Ni = 2
Nj = 2
Nk = 2
schemaVersion = 2.0
:AbstractParentWindow
:ijkParentWindow
+iRegrid
:Regrid
InitialIndexOnParentGrid = 1
:Intervals
IntervalCount = 1
ChildCountPerInterval = Integer CONSTANT ARRAY (count=1, value=2)
ParentCountPerInterval = Integer CONSTANT ARRAY (count=1, value=1)
+jRegrid
:Regrid
InitialIndexOnParentGrid = 1
:Intervals
IntervalCount = 1
ChildCountPerInterval = Integer CONSTANT ARRAY (count=1, value=2)
ParentCountPerInterval = Integer CONSTANT ARRAY (count=1, value=1)
+kRegrid
:Regrid
InitialIndexOnParentGrid = 0
:Intervals
IntervalCount = 2
ChildCountPerInterval = Integer CONSTANT ARRAY (count=2, value=1)
ParentCountPerInterval = Integer CONSTANT ARRAY (count=2, value=1)

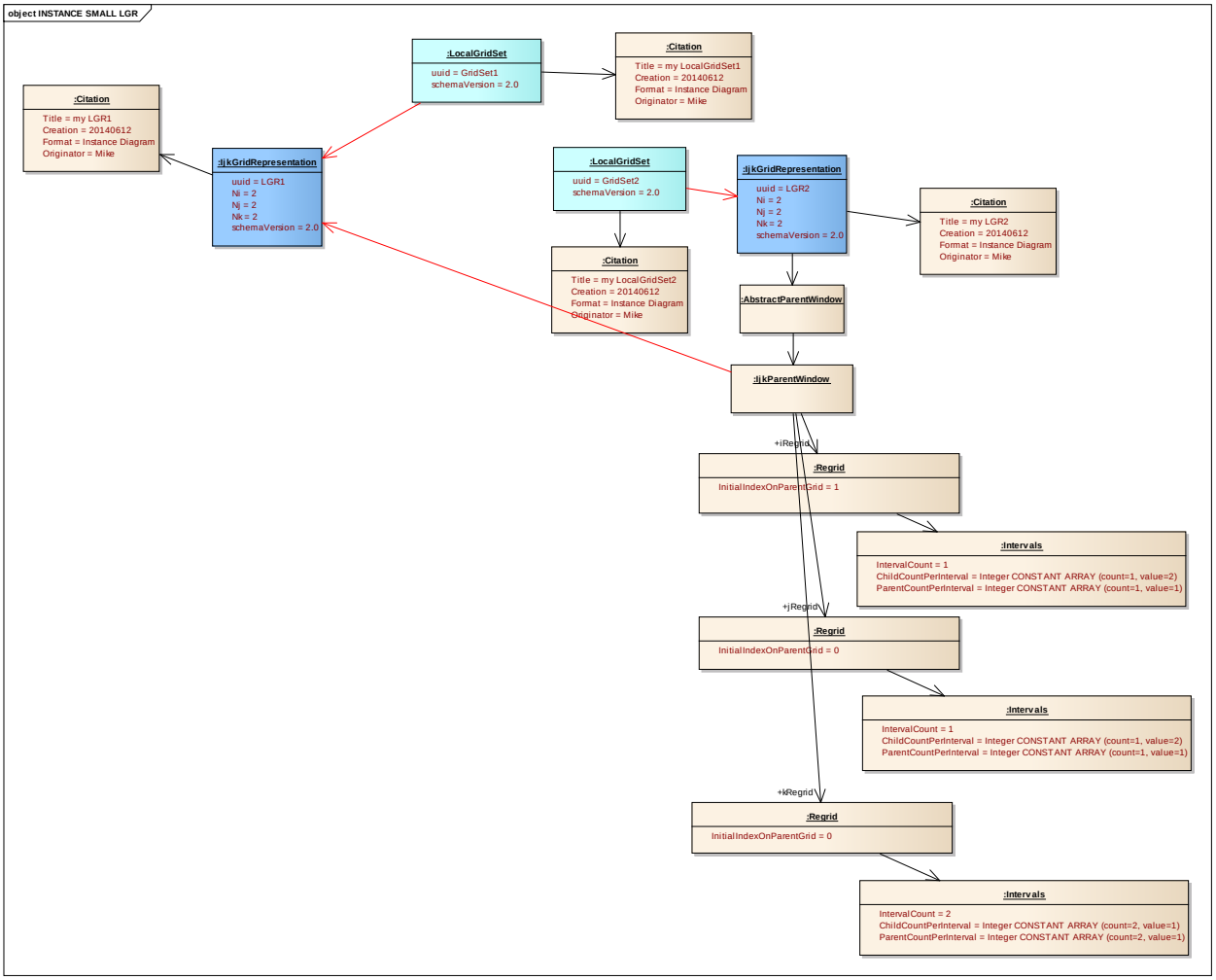


Figure 11-45—Instance diagram for the small nested LGR IJK grid example showing grid parentage and local grid set definitions. The constructions for LGR1 and the nested LGR (LGR2) are shown in more detail.

In **Figure 11-45**, the grid on the far left of the top diagram (SMALL_LGR) is a grid with explicit specification of its geometry. Local grid set 1 activates grids LGR1 and LGR3. Local grid set 2 activates grid LGR2. LGR1 and LGR3 have SMALL_LGR as their parent. LGR2 is nested in LGR1.

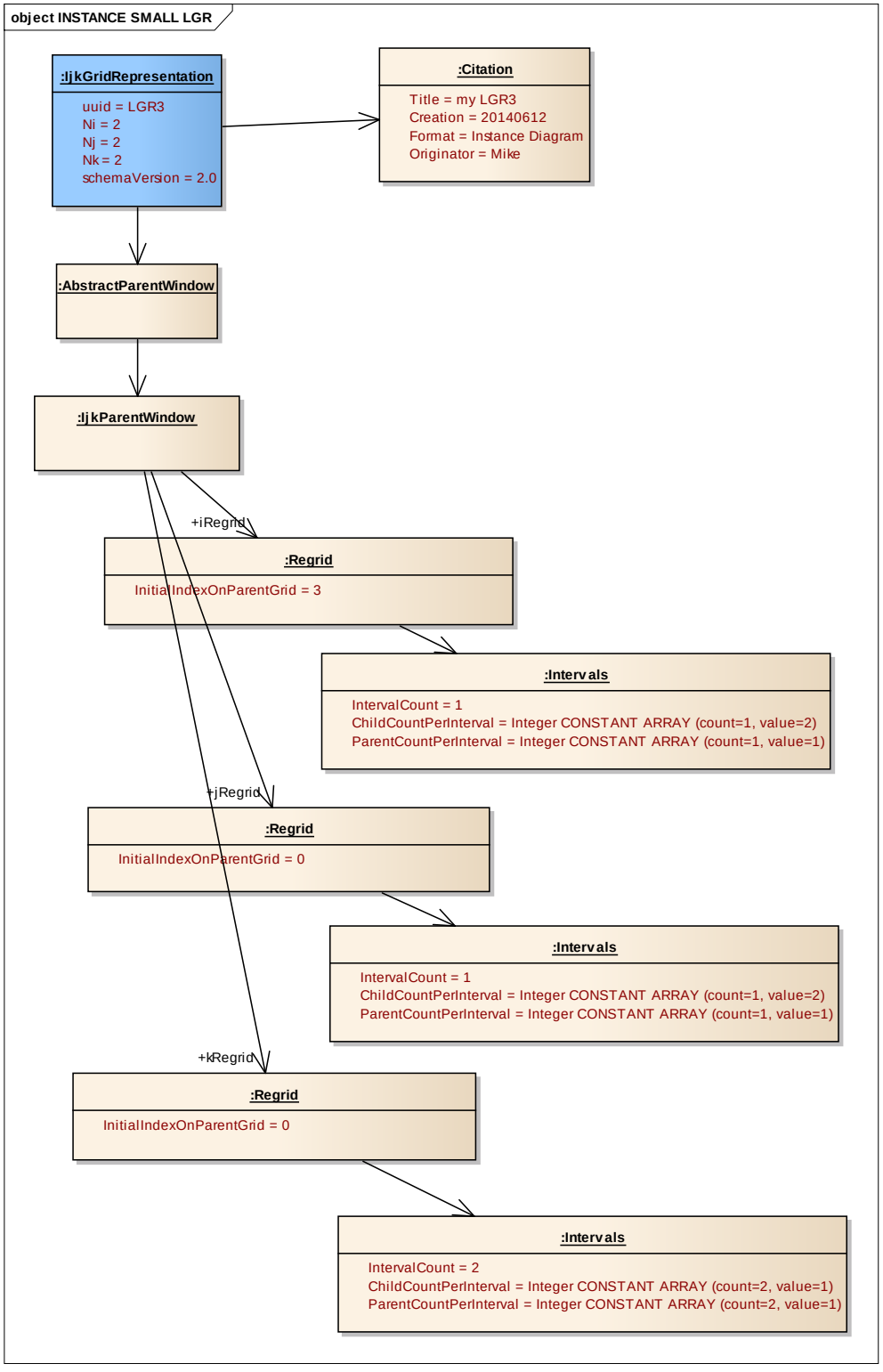


Figure 11-46—Regrid construction for grid LGR3.

In **Figure 11-46**, we examine the regrid construction for grid LGR3. The parent window is positioned starting at parent cell (I,J,K)=(4,1,1). The I and J regrids are identical and represent a factor of 2 grid refinement. The K regrid uses two intervals to indicate that K=1 is mapped to K=1 and that K=2 is mapped to K=2.

11.17.6 IJK Grid with Proportional Layering

In **Figure 11-47,** we can see how this example is built on the 4x3x2 faulted IJK grid, but now we take advantage of the parametric form of proportional layering, to convert the two layer model to a two zone model with 6 layers in the first zone and 18 layers in the second zone, for a total of 24 layers.

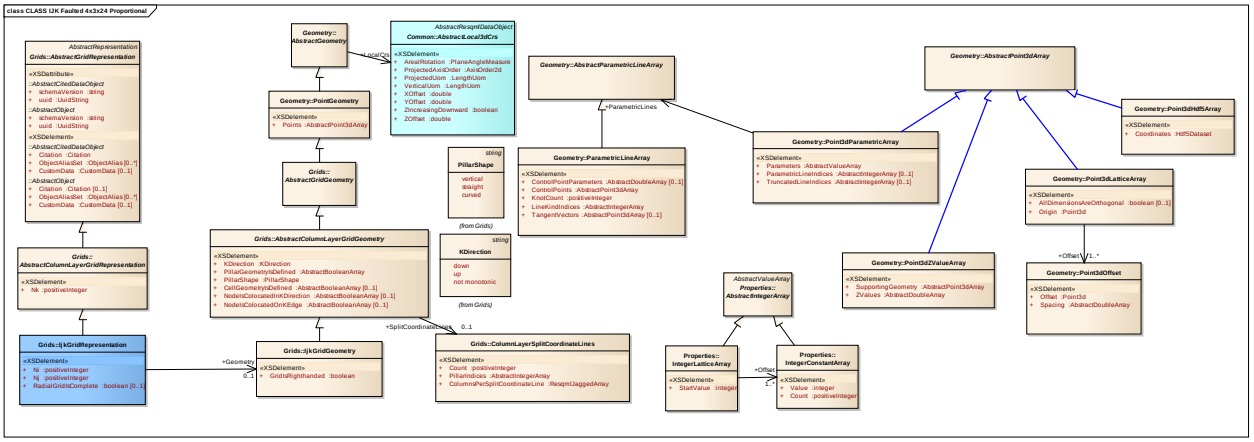


Figure 11-47—Class diagram for the 4 x 3 x 24 layer proportional IJK grid.

Specifically, as can be seen in **Figure 11-48**, the parameterization takes advantage of the interval edge index, which in this case takes on the values of 0…24. Interval edges 0..6 describe the top geologic zone and interval edges 6..24 describe the bottom. Along a single coordinate line it is not necessary to specify all 25 nodes explicitly. Instead nodes 0, 6, and 24 can be specified, and linear interpolation can otherwise be used to define layers within each zone. This is shown in the figure. The original points from the 4x3x2 grid now arise as the control points. There are now two sets of parametric lines. The first set consists of 24 straight lines, with three control points and three parametric values per line (one per coordinate line). The second set consists of 5x4 vertical lines, with one control point per line (one per pillar). To minimize any ambiguity in indexing, the second set of parametric lines now includes the explicit parametric line indices, although they are not strictly necessary.

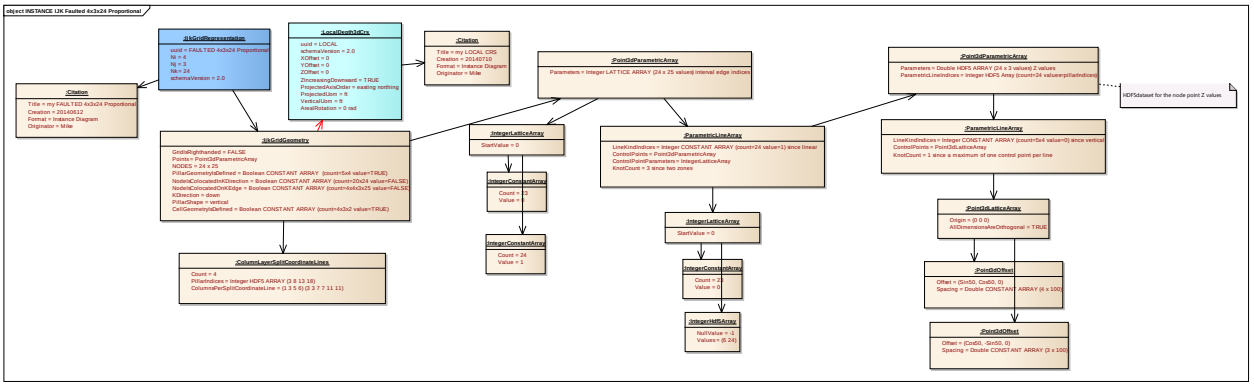


Figure 11-48—Instance diagram for the 4 x 3 x 24 layer proportional IJK grid.

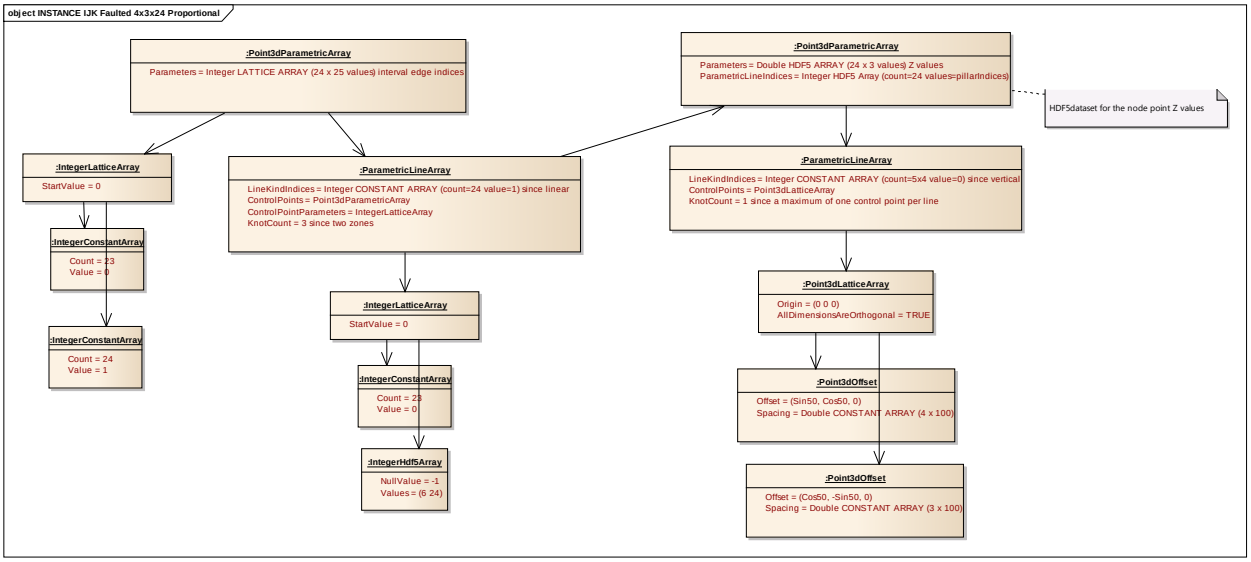


Figure 11-49—Instance diagram showing proportional layering (6+18 layers).

Notice in **Figure 11-49** that the integer lattice constructions, which have two dimensions, only have the second dimension (dimension=1) in the instance diagram. This is because the parameters for proportional layering depend only on the interval indices. In contrast, the generalization of this construction to eroded and truncated layering would, in general, require explicit parametric values that vary from line to line.

11.17.7 Higher Order Finite Element Prism24 Unstructured Column-layer Grid

This example demonstrates an unstructured column-layer grid representation and the use of higher order subnode geometry to create a distorted prism cell shape. For simplicity, this example is of an unfaulted grid.

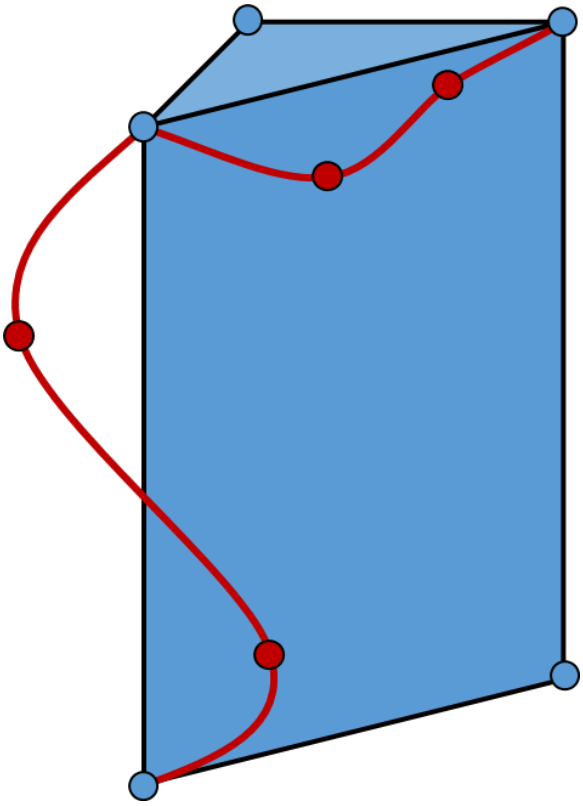


Figure 11-50—Description of a single lower order (blue prism) and higher (distorted prism) grid cell. All nine edges are distorted but not all are shown.

As shown in **Figure 11-50**, there are six blue nodes, defining the shape of the lower order triangular prism. There are two additional higher order nodes per edge, for each of the nine edges, which describe the distortion of each edge away from linearity. (Only two edges are shown.) The resulting distorted prism is described by a total of 24 nodes.

The description of the lower order aspects grid is similar to that of the IJK grid except that the grid uses an unstructured column-layer cell geometry (**Figure 11-51**). The unstructured column-layer cell geometry inherits from the column-layer cell geometry used for the IJK grid, but includes additional elements that explicitly describe the pillars and columns of the model. The higher order finite element grid is a simple kind, with two subnodes defined for each edge. The edges and the nodes per edge must be defined explicitly before they can be referenced by the subnode construction.

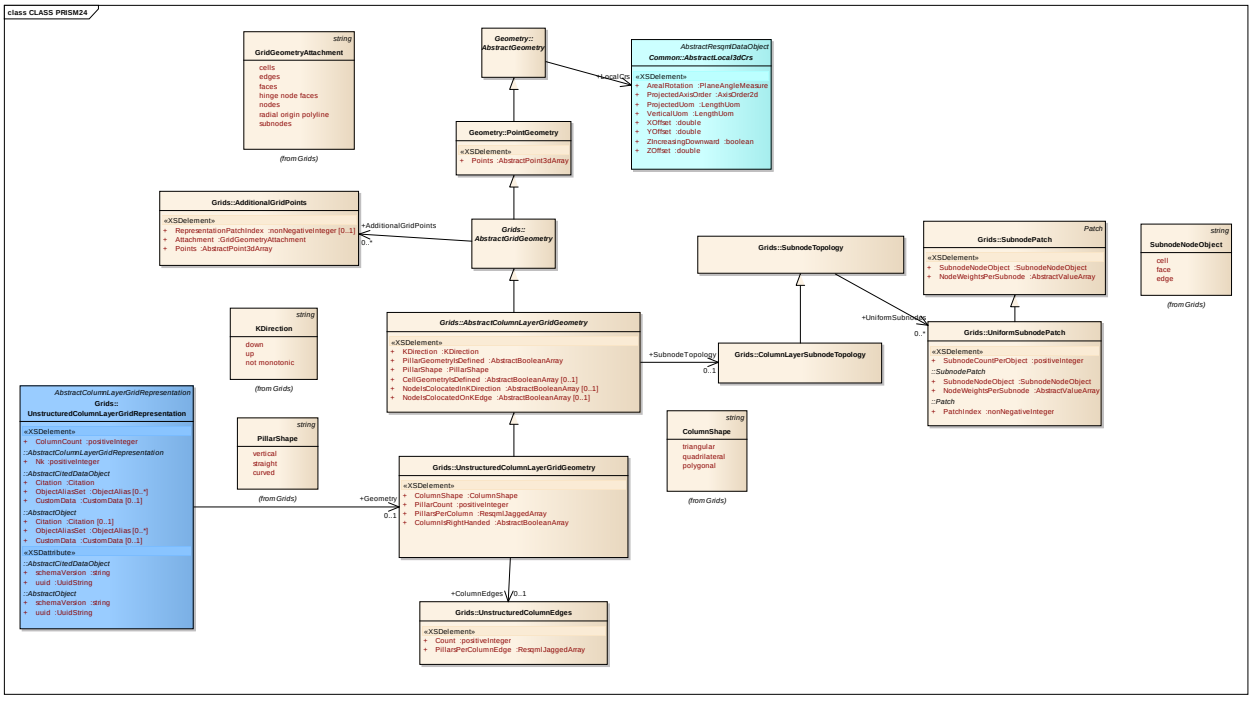


Figure 11-51—Class diagram for the Prism24 grid.

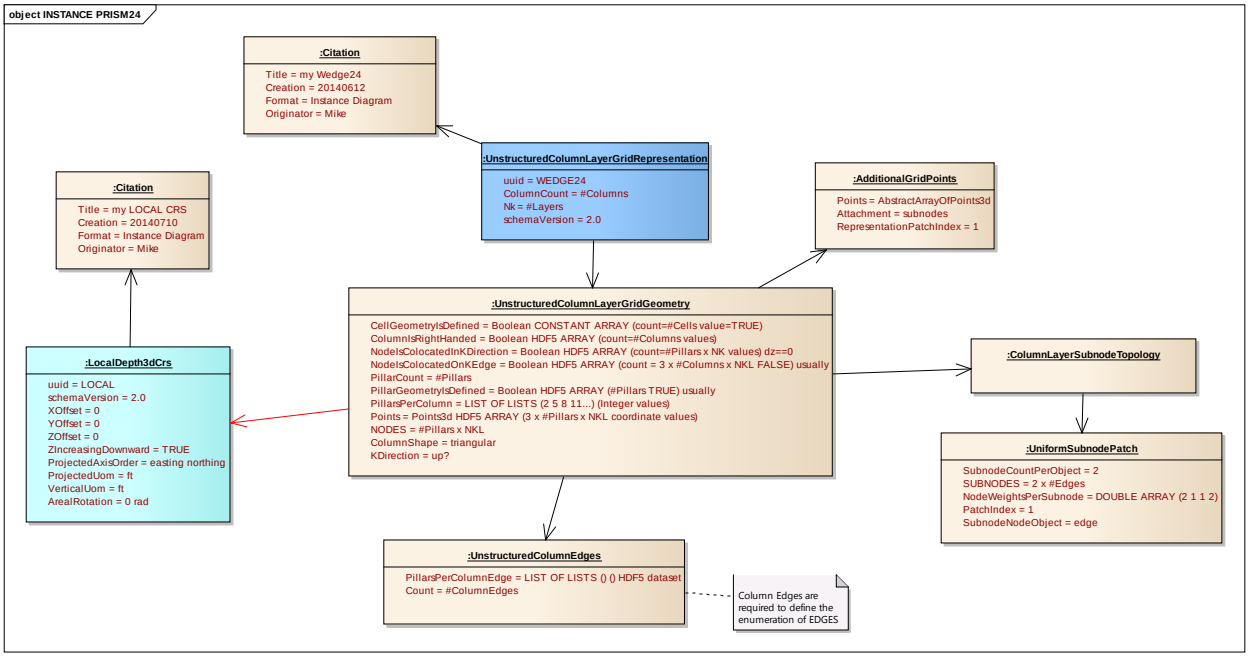


Figure 11-52—Instance diagram for the Prism24 grid.

Section 11.13.3 (page 160) explains the edge indexing for an unstructured column-layer grid is given by "ColumnEdgeCount x NKL + CoordinateLineCount x NK + SplitEdgeCount". In **Figure 11-52**, the column edges are defined explicitly using a jagged array construction. Because the grid is unfaulted, the coordinate line count is identical to the pillar count. This model has no split edges, hence the edge indexing is known. There are two subnodes per edge, defined using the uniform subnode patch. Each subnode is defined parametrically by the two nodes per edge: the first with weights of (2 1) and the second with weights of (1 2). In other words, subnode1 = (2/3)*edgenode1 + (1/3)*edgenode2 while subnode2 = (1/3)*edgenode1 + (2/3)*edgenode2. Once defined, these subnodes may be used to provide

topological support for higher order properties or geometry. In this example, the positions of the subnodes are modified when higher order geometry points are attached, giving the distorted shape. As a reminder, the schema itself does not describe the method of geometric interpolation between the subnodes on an edge or between the subnodes on a face, although natural interpolation algorithms do arise. For instance, in this figure, edge interpolation follows a natural cubic spline and face interpolation follows the iso-parametric mapping of the lowest order object.

11.17.8 Block-Centered General Purpose Grid

Figure 11-53 (class diagram) is a very simple example, which is included to show the use of grid patches in the general purpose grid. **Figure 11-54** (instance diagram) consists of four grid patches (1, 2, 3, and 6). Because this is a block-centered grid with no explicit geometry, the local 3D CRS does not appear as part of the representation. Instead, it may appear as part of the geometry valued properties attached to this grid.

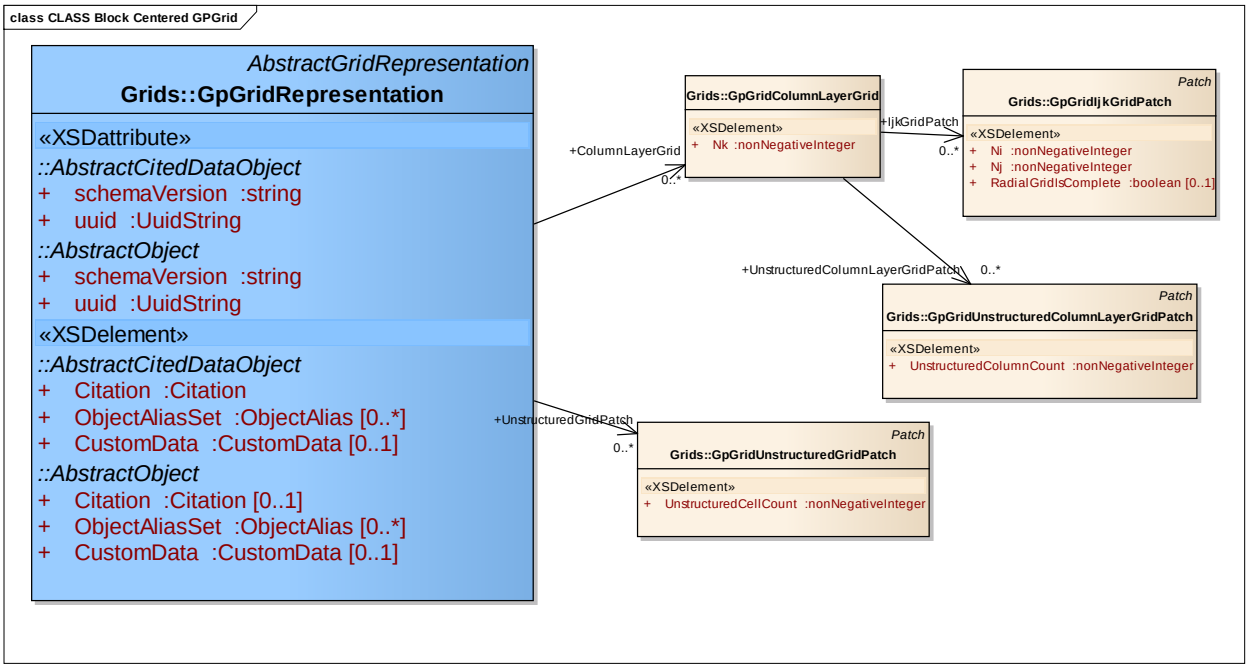


Figure 11-53—Block-centered general purpose grid class diagram.

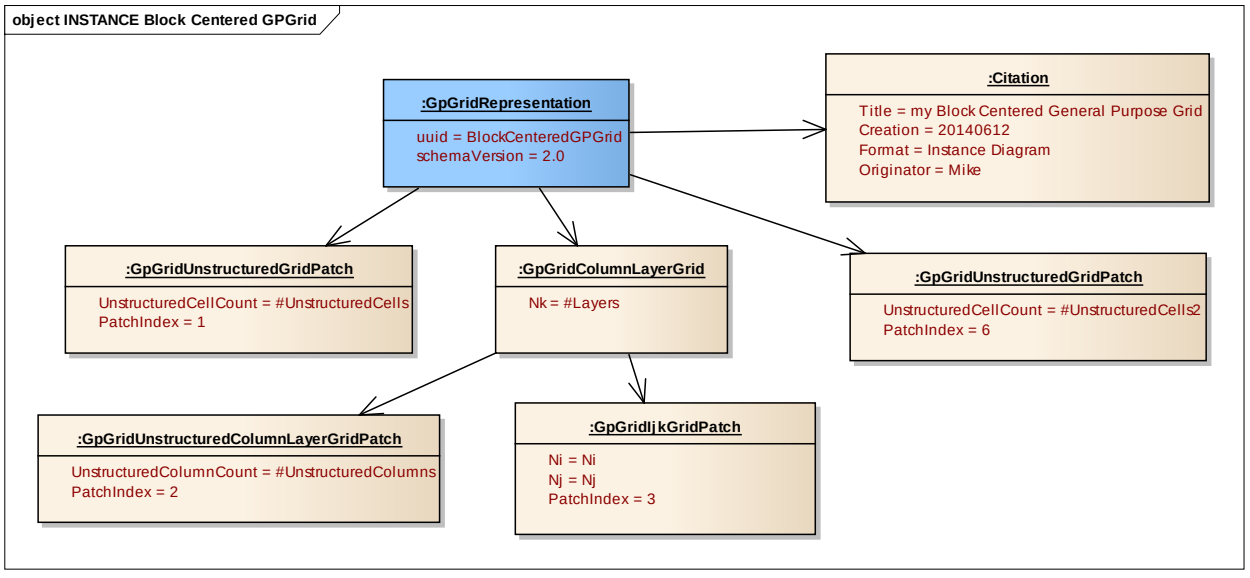


Figure 11-54—Block-centered general purpose grid instance diagram.

11.17.9 Unstructured Grid with Discontinuous Properties

This example shows an unstructured grid representation, and the use of a subrepresentation to support a cell-node property which is discontinuous from cell to cell, despite the underlying grid being unfaulted. **Figure 11-55** shows a very simple grid; **Figure 11-56**, **Figure 11-57**, **Figure 11-58** are the class diagrams and **Figure 11-60**, **Figure 11-61**, and **Figure 11-62** are the instance diagrams showing the data.

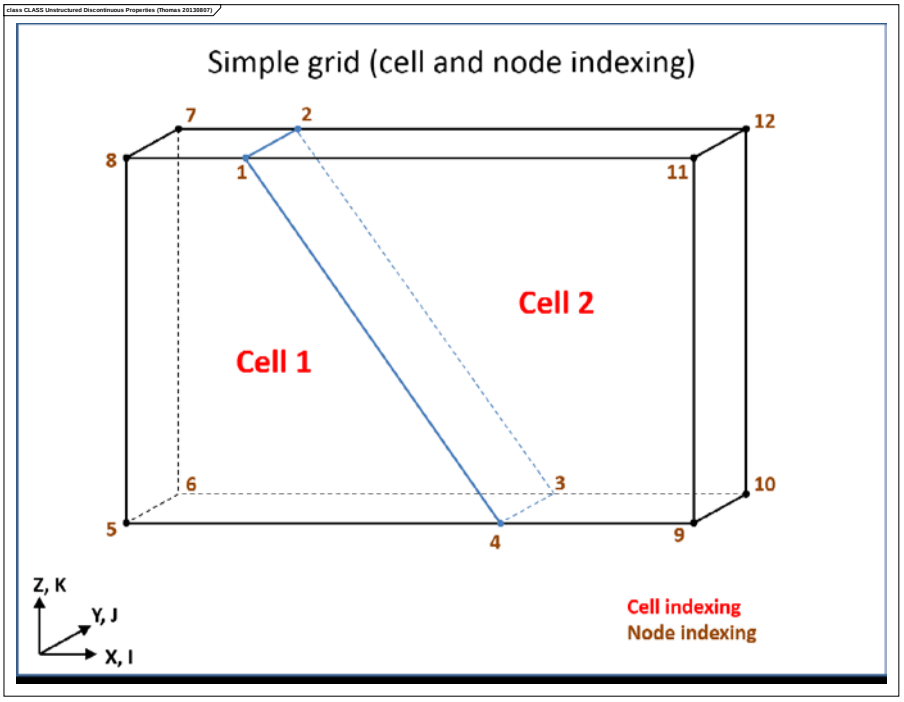


Figure 11-55—Unfaulted unstructured grid, with discontinuous properties.

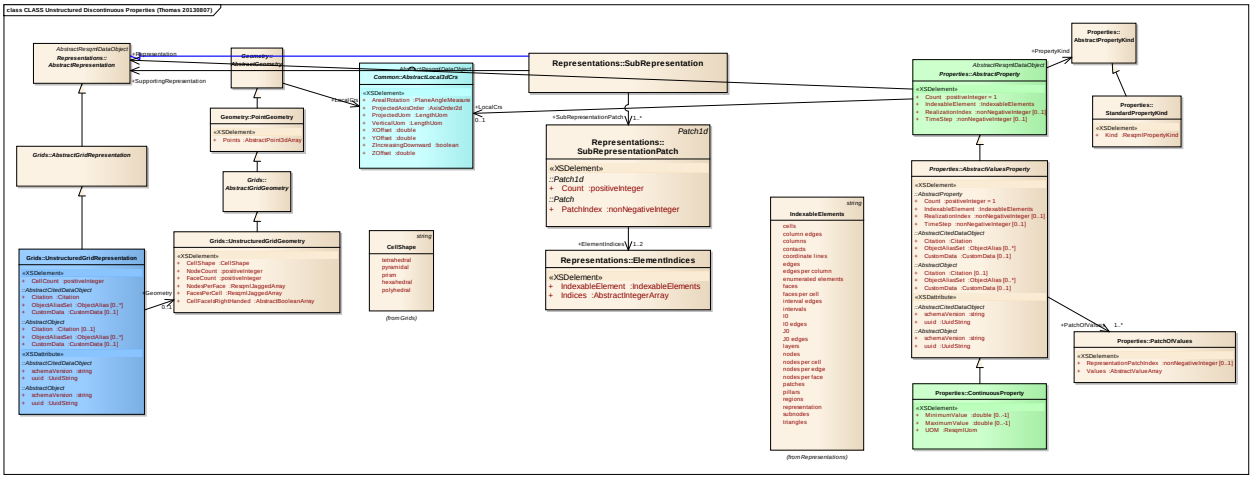


Figure 11-56—Class diagrams of an unfaulted unstructured grid, with a subrepresentation to support discontinuous properties (1 of 4).

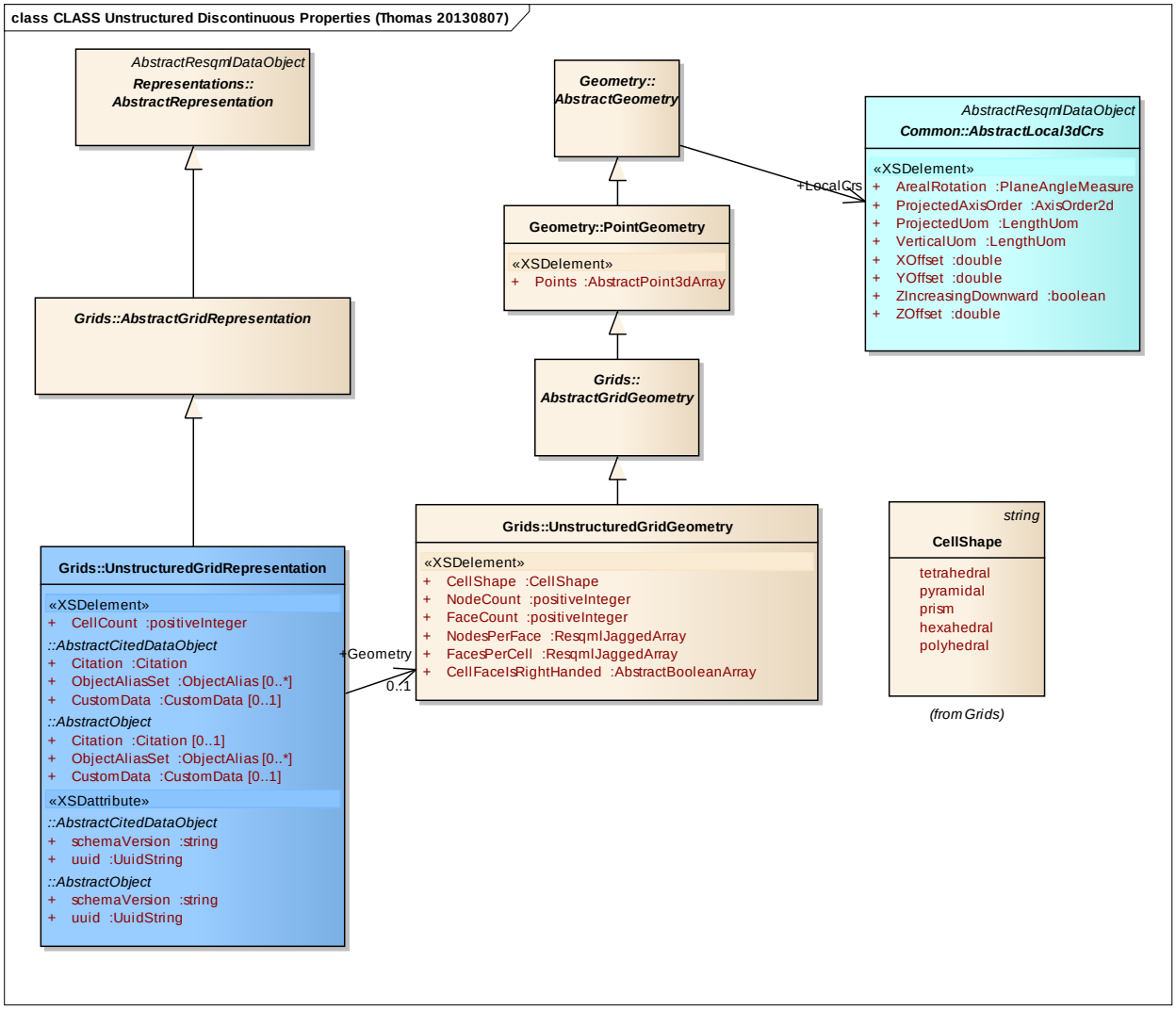


Figure 11-57—Class diagrams of an unfaulted unstructured grid, with a subrepresentation to support discontinuous properties (2 of 4).

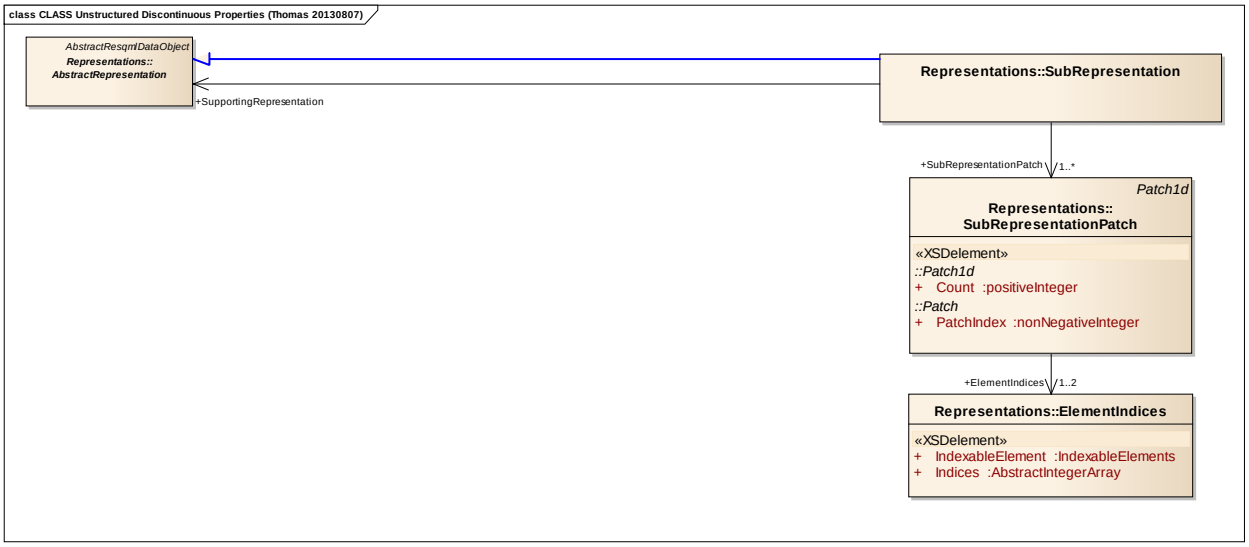


Figure 11-58—Class diagrams of an unfaulted unstructured grid, with a subrepresentation to support discontinuous properties (3 of 4).

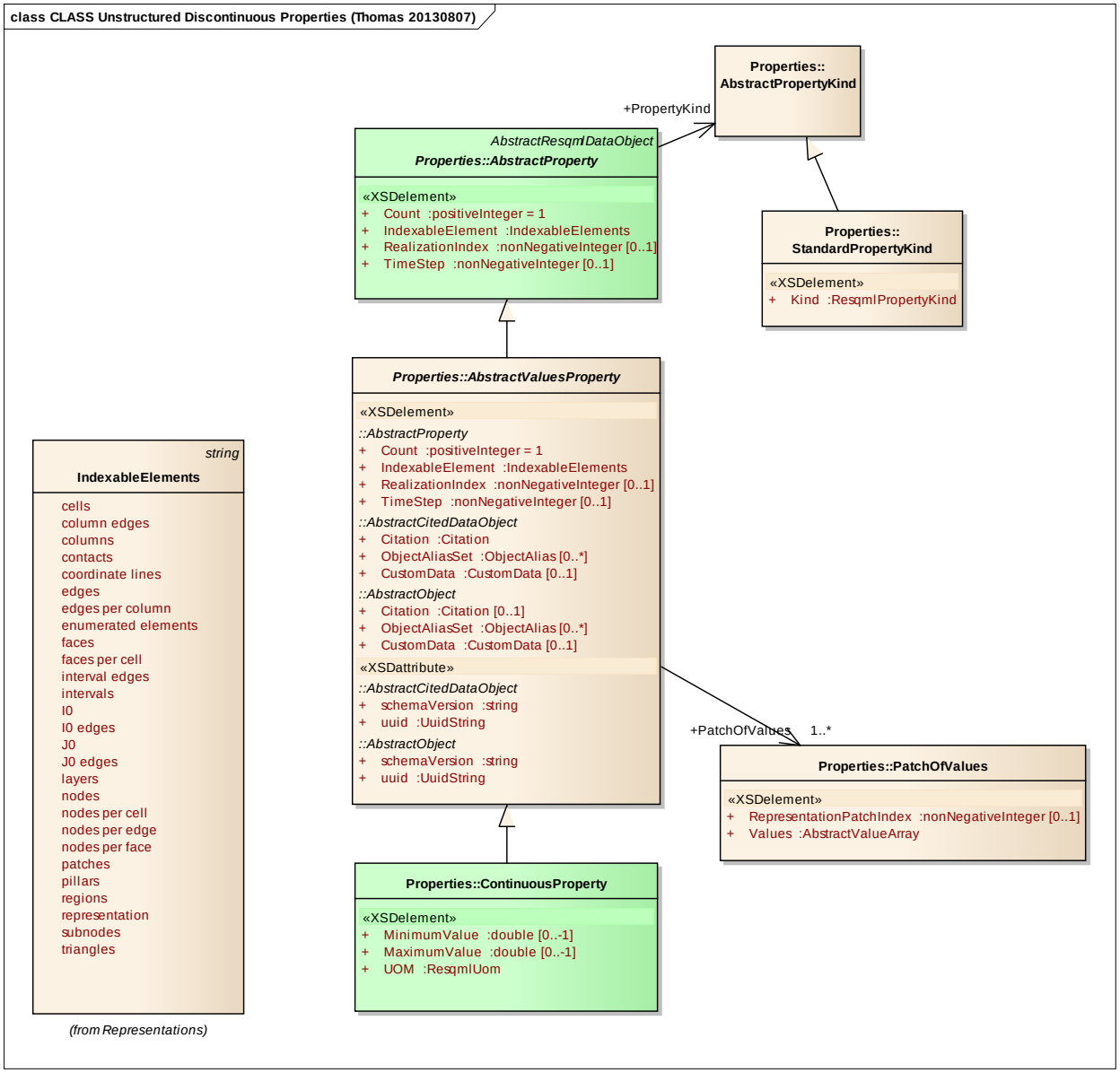


Figure 11-59—Class diagrams of an unfaulted unstructured grid, with a subrepresentation to support discontinuous properties (4 of 4).

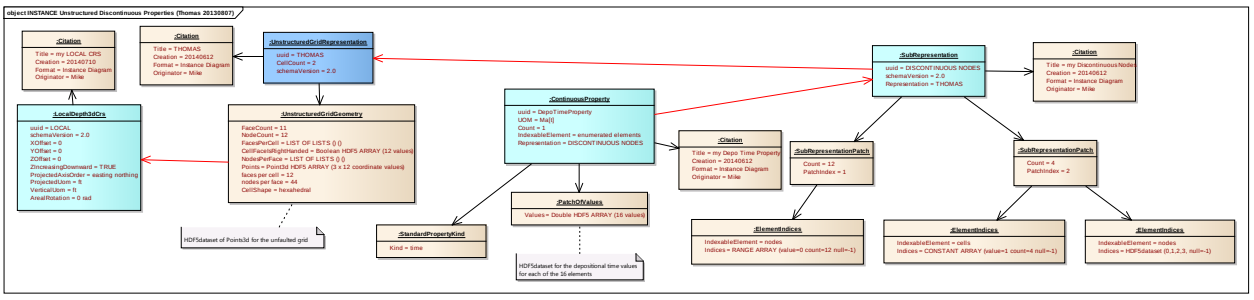


Figure 11-60—Instance diagrams of an unfaulted unstructured grid, with a subrepresentation to support discontinuous properties (1 of 3).

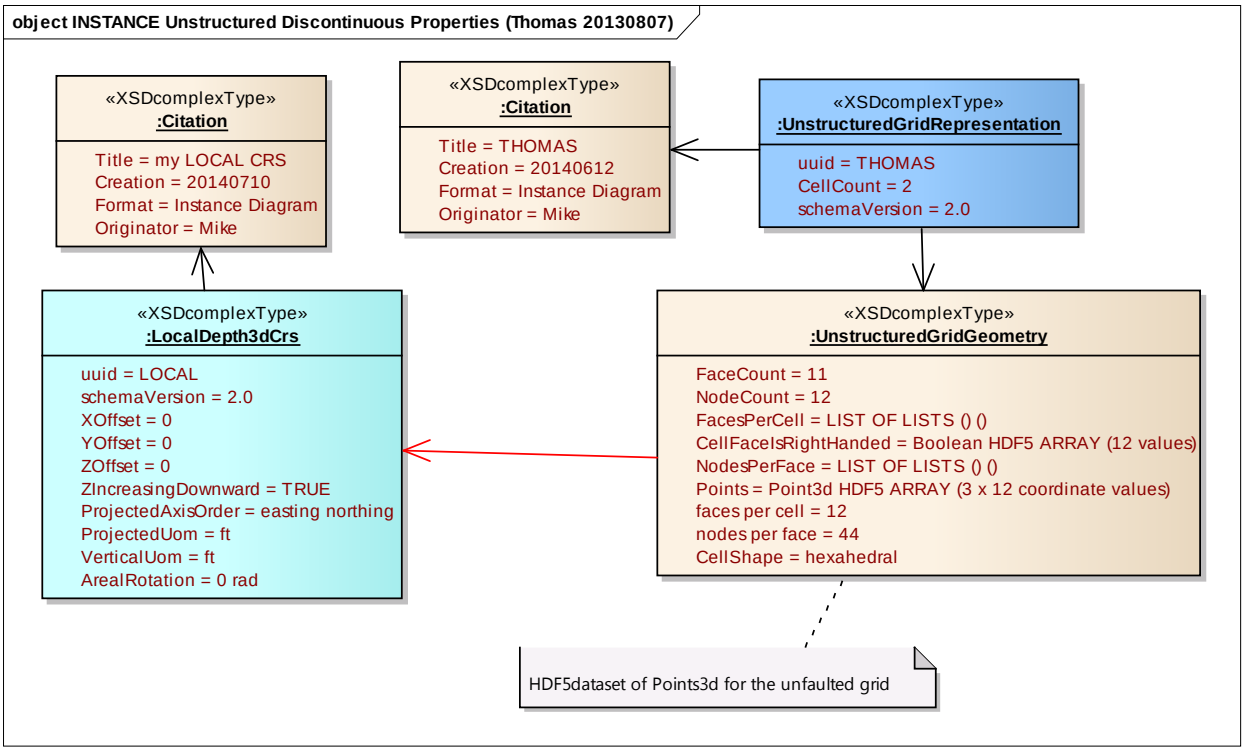


Figure 11-61—Instance diagrams of an unfaulted unstructured grid, with a subrepresentation to support discontinuous properties (2 of 3).

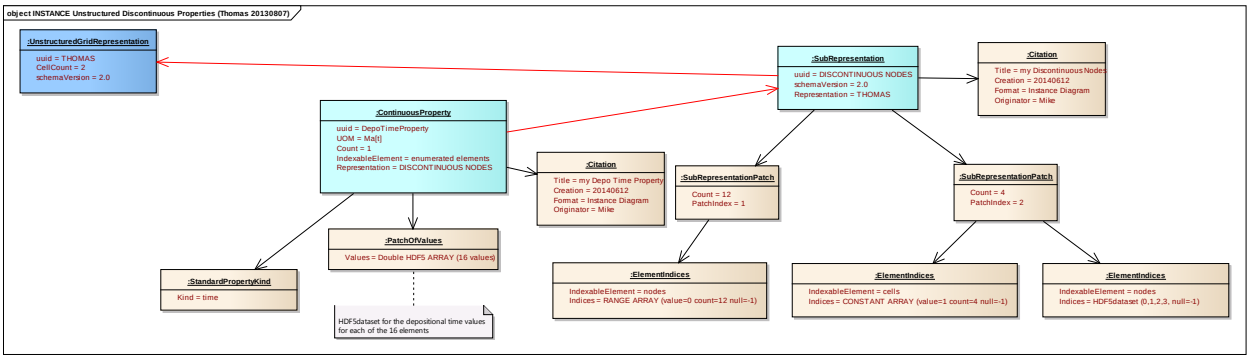


Figure 11-62—Instance diagrams of an unfaulted unstructured grid, with a subrepresentation to support discontinuous properties (3 of 3).

11.18 References

Jenny, P., Lee, S. H., & Durlofsky, L. J. (2001). Modeling Flow in Geometrically Complex Reservoirs Using Hexahedral Multi-Block Grids. Society of Petroleum Engineers. doi: **http://dx.doi.org/10.2118/66357-MS.** Copyright 2001, Society of Petroleum Engineers. Further reproduction prohibited without permission.

Lasseter, T.J. (2004). Improving integrated interpretation accuracy and efficiency using a single consistent reservoir model from seismic to simulation. *The Leading Edge* (2004), 23(11):1118. http://dx.doi.org/10.1190/1.1825932. Used with permission from SEG/standard re-use policy.

Martin, K., Macdonald, C., The Schiehallion field: applying a geobody modelling approach to piece together a complex turbidite field, presented at the DEVEX conference held in Aberdeen, Scotland, 12-13 May, 2010. Permission for reuse given by personal communication from author.

Perrin, M., Rainaud, J-F, et al. 2013. *Shared Earth Modeling: Knowledge driven solutions for building and managing subsurface 3D geological models*. p123. Paris: Editions Technip ISBN 98-207108-1002-5

Zhang, Y., King, M. J., & Datta-Gupta, A. (2011). Robust Streamline Tracing Using Intercell Fluxes in Locally Refined and Unstructured Grids. Society of Petroleum Engineers. doi: **http://dx.doi.org/10.2118/140695-MS.** Copyright 2011, Society of Petroleum Engineers. Further reproduction prohibited without permission.

12 Wells

One of the long-term goals for RESQML is to leverage other Energistics standards, such as WITSML and PRODML, to link the well-related information with the reservoir. However at the date of the release, the main well standard, WITSML v1.4.1, does not yet require use of a UUID, which limits the elements of WITSML which may currently be re-used.

Unlike WITSML, which is used to represent actual drilled wells, RESQML must be able to represent wellbores and associated information during the planning phase, before any administrative information (such as legal names, precise locations, etc.) about the well is available.

To fill these gaps, RESQML has adopted its own well-related data objects. These data objects have enough information to meet RESQML needs and can also be used as proxies for existing WITSML data objects.

These data objects are also compatible with the "What is a Well" approach as defined by PPDM (https://www.ppdm.org/ppdm-standards/what-is-a-well-definitions).

12.1 Special Requirements for Using WITSML 1.4.1 Data Objects with RESQML (in an EPC File)

Because it was developed several years earlier, the currently most-used version of WITSML, 1.4.1.1, has different requirements for identifying and storing data objects. (For rules on WITSML data object identification, see Section 2.2 of the *WITSML STORE Application Programming Interface* specification.) Therefore, the following additional rules must be observed when using WITSML data objects in an EPC file:

- Each file created in WITSML must contain only one business object, e.g., a single well, wellbore, log, etc. This rule is so that these individual business objects can each be correctly referenced in an EPC file.
- WITSML UIDs are mandatory for each data object. In an EPC file, the WITSML UID serves the role of a UUID as specified in the *Energistics Packaging Conventions Specification* (for a link to this document, see Section 1.4.1 (page 14)). Currently use of UUIDs in WITSML is recommended but not required. For EPC files, use of UUIDs is strongly recommended.

12.2 Wellbore Organization Overview

In WITSML, data objects are organized into a single hierarchy, with the well data object at the top. The well data object is the parent of one or more wellbore data objects (child data object); a wellbore data object can have one or more children, such as logs and trajectories.

In RESQML, the wellbore is the core data object. Because the well data object information is mainly administrative, no reservoir-specific requirements are needed. Thus, for this administrative information, RESQML relies on the WITSML link between a wellbore and its well.

Figure 12-1 shows an overview of the wellbore organization, which is based on the RESQML knowledge hierarchy (see Chapter 5 (page 51). The sections below the figure explain it.

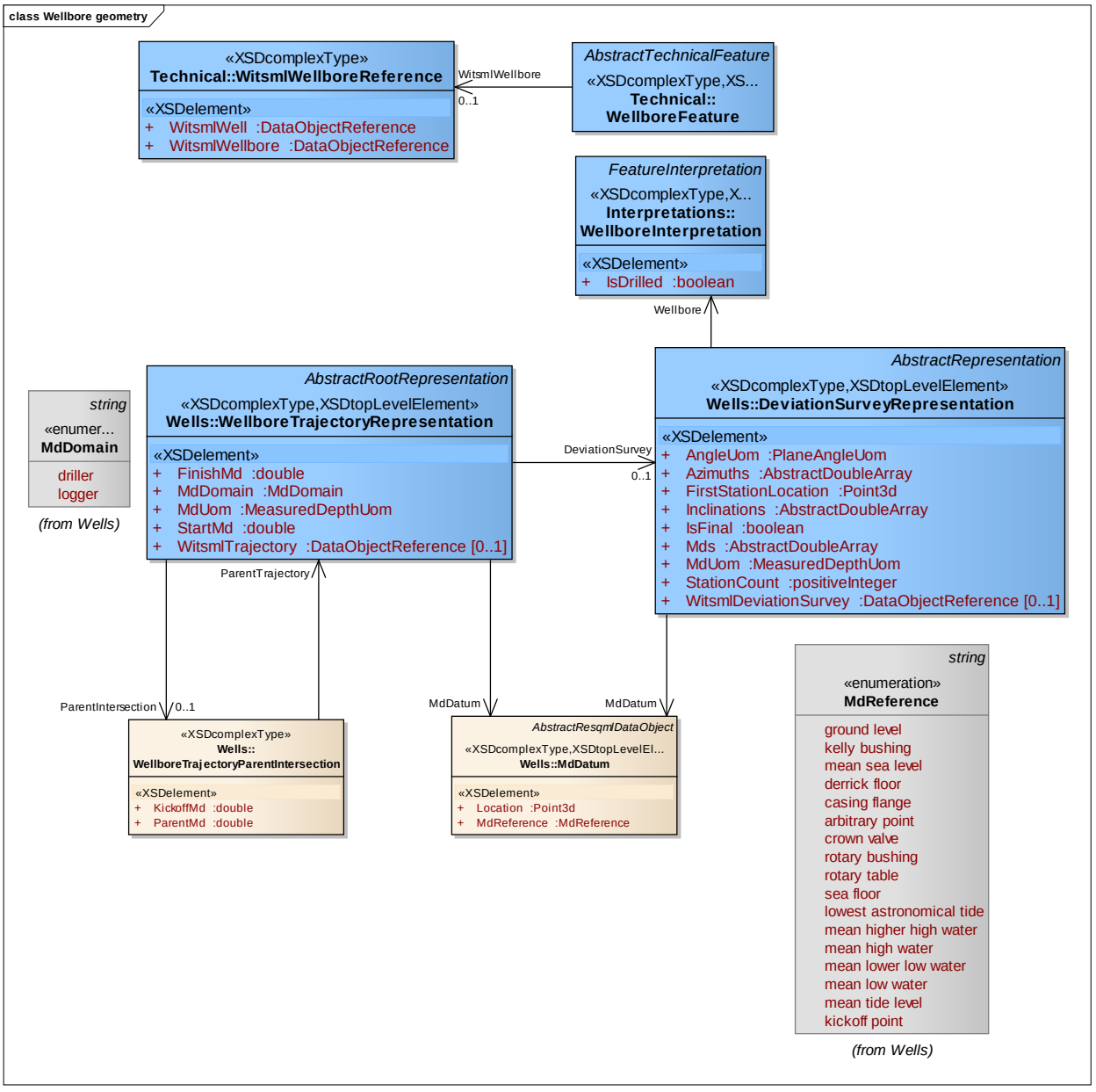


Figure 12-1—Main wellbore data object organization based on the RESQML "FIRP" knowledge hierarchy.

12.2.1 Wellbore Feature

Because the location of a wellbore can continually evolve between planning and drilling, it is important to be able to link all of these evolutions. RESQML provides the ability to do this using a wellbore technical feature. The wellbore technical feature provides a consistent identification of a wellbore through all of its different phases and provides the reference to a potential WITSML representation of the same wellbore.

12.2.2 Wellbore Interpretation

A wellbore interpretation is an opinion about a wellbore trajectory. It typically represents an actual drilled wellbore or any version of a planned wellbore trajectory. This “drilled” information is part of the data object.

The wellbore interpretation is used as an umbrella for all the representations of a specific trajectory, such as:

- Different types of representations: directional survey versus point discretization
- Different sampling used during logging or marker interpretation
- Different computation mode or refinement

12.2.3 Wellbore Location

A wellbore location is defined using a wellbore trajectory representation and MD datum, which are explained in this section.

12.2.3.1 Wellbore Trajectory Representation

The wellbore trajectory representation has these main uses:

- **Defines the geometry of the trajectory inside a RESQML coordinate system**, so that geometrical interactions between its wellbore and other elements of a model are unambiguous. A wellbore trajectory representation can be associated with a WITSML trajectory, but it also must be able to stand by itself, so that it can represent wellbores during planning. The wellbore trajectory representation object includes sufficient information to uniquely define the location of a vertical well. However, all other wells should contain geometry described as a parametric line. (For more information, see Section 7.3 (page 69).)
- **Serves as the reference for all the measured depth information captured along the wellbore**. It references one MD datum (explained below), which provides information about the location of the measured depth datum and its type.
- **Indicates the unit of measure and the range of measured depths covered by the trajectory**. In the simple case, the range goes from zero to total depth. But for multi-lateral wells, the range may begin at kickoff points. A driller or logger domain is also included to indicate which measured depth reference was used.
- If a trajectory is based on a deviation survey, it can indicate the survey it originated from.

For multi-lateral wells, wellbores can have additional parentage information to indicate:

- Which wellbore trajectory it is kicked off from.
- The kickoff measured depth, both in the current wellbore trajectory and its parent wellbore trajectory. Each value is expressed in the measured depth unit of measure of its trajectory.
- If a trajectory is based on a deviation survey, it can indicate the survey it originated from.

12.2.3.2 MD Datum

Because the RESQML data model does not extend beyond the wellbore see Section12.1 (page 197), the MD datum is a mandatory component of the wellbore. It includes an MD reference enumeration that is identical to that of WITSML, with one exception: it also has an “arbitrary point” to support reservoir modeling workflows for well planning and field development.

The MD datum is a top-level data object so that it may be shared among multiple wellbores (e.g., in multi-lateral wells) or several versions of trajectories. The MD datum exists independently of the wellbore trajectory representation and needs to have a uniquely defined local 3D coordinate reference system (CRS), though the datum and the trajectory must refer to the same local coordinate system.

In practice, the local 3D CRS used by the MD datum is often the composite of a projected CRS and a vertical CRS, without any translation or rotation. The local 3D CRS is also a top-level data object, which means that it can be shared between the MD datum and the geometry of the wellbore trajectory representation, although there is no requirement that they do so. For example, the CRS of the MD datum may be shared among multiple wellbores from the same wellhead, while the CRS of the wellbore trajectory representation may be chosen to be the same as that of a reservoir modeling grid, to facilitate intersection calculations.

12.2.3.3 Deviation Survey

Before a trajectory can be computed in a model coordinate system, it is usually represented by a deviation survey. It is useful to transfer this survey when a trajectory is not yet computed or for quality control.

The survey references MD datum pointing to a measured depth reference, indicates the location of the first survey station in the model, and then, for each station, specifies a measured depth, azimuth, and inclination. To distinguish it from other intermediate versions of survey, an "is final" tag is used to indicate if this is the currently accepted version of the survey. The deviation survey can be associated with a WITSML survey.

12.3 Well Logs

From a RESQML perspective, well log curves are simply property values assigned on a sampling (a list of measured depths) defined along the trajectory (**Figure 12-2**). The list of measured depths is held in the wellbore frame representation, which corresponds to a WITSML well log.

The wellbore frame represents the wellbore interpretation, references the trajectory on which it is based, and defines a sampling where each node has a given measured depth. The sampling can be defined using either of these methods:

- Explicit list of values, which indicates aperiodic sampling.
- Lattice of values, which indicates periodic sampling.

The property values can be attached to either the nodes or the intervals of the sampling. For more information about properties, see Chapter 8 (page 77).

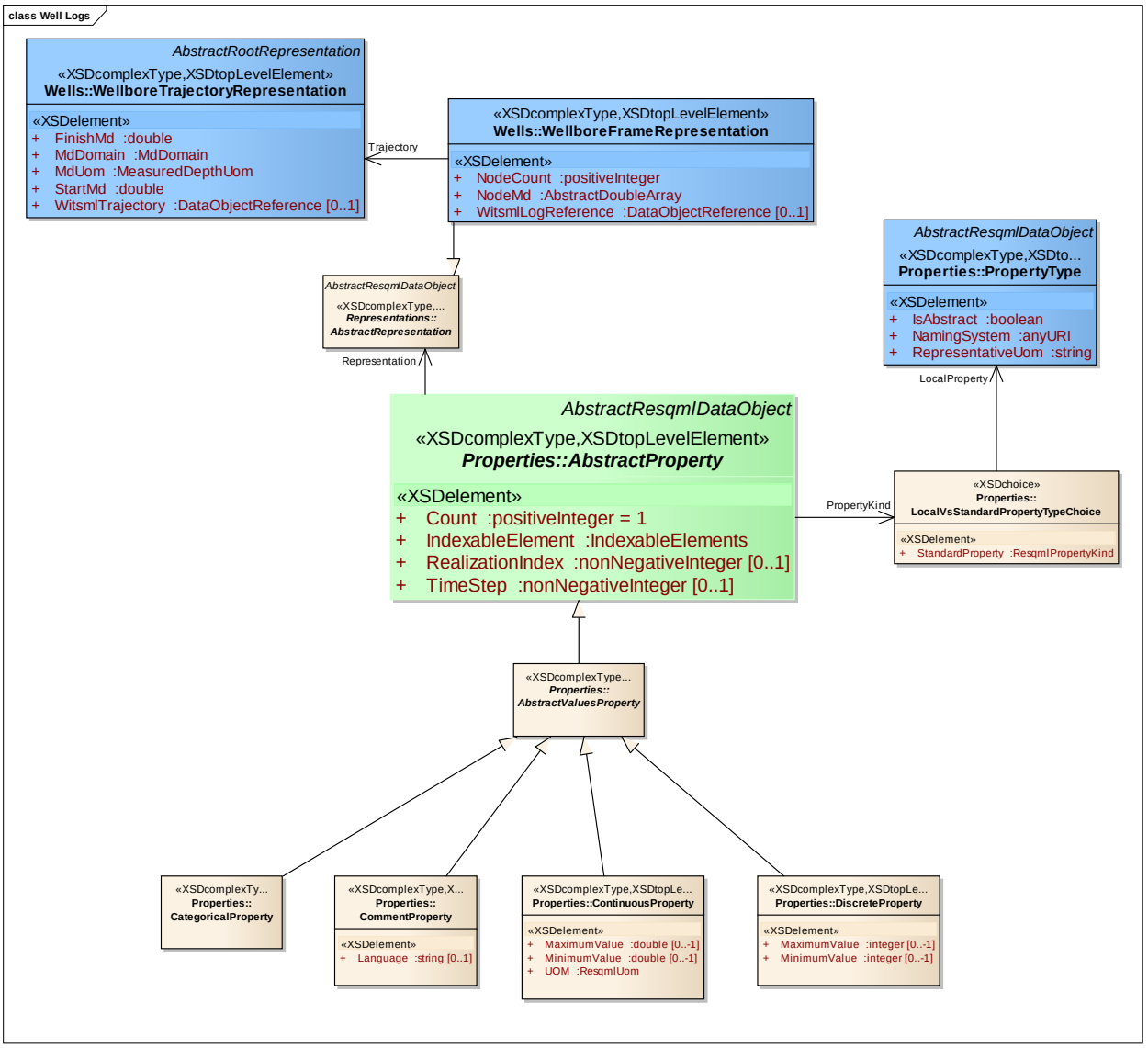


Figure 12-2—RESQML treats well log curves as properties, which are attached to a wellbore trajectory using a wellbore frame.

12.4 Markers and Links to Geological Boundaries

A specialized wellbore marker frame is used to carry marker interpretations along the well (**Figure 12-3**, blue boxes). Each measured depth node can be associated with a marker. Each marker has full traceability through a citation element. Markers can also be associated with individual geological boundary elements through optional references to a geologic, fluid, or contact feature. Markers can also be associated with a WITSML formation marker.

12.5 Interpretations and Links to Organizations

To provide more detailed interpretation information than just a marker list, it is possible to associate a stratigraphic and fluid organization interpretation to an entire marker frame (**Figure 12-3**). Interval stratigraphic units and cell fluid phase units are used to indicate which stratigraphic or fluid organization is represented and which element of the organization interpretation is associated with each interval of the wellbore frame. When an interval is not represented in the organization, -1 is used. For more information about organizations in RESQML, see Chapter 10.3 (page 116).

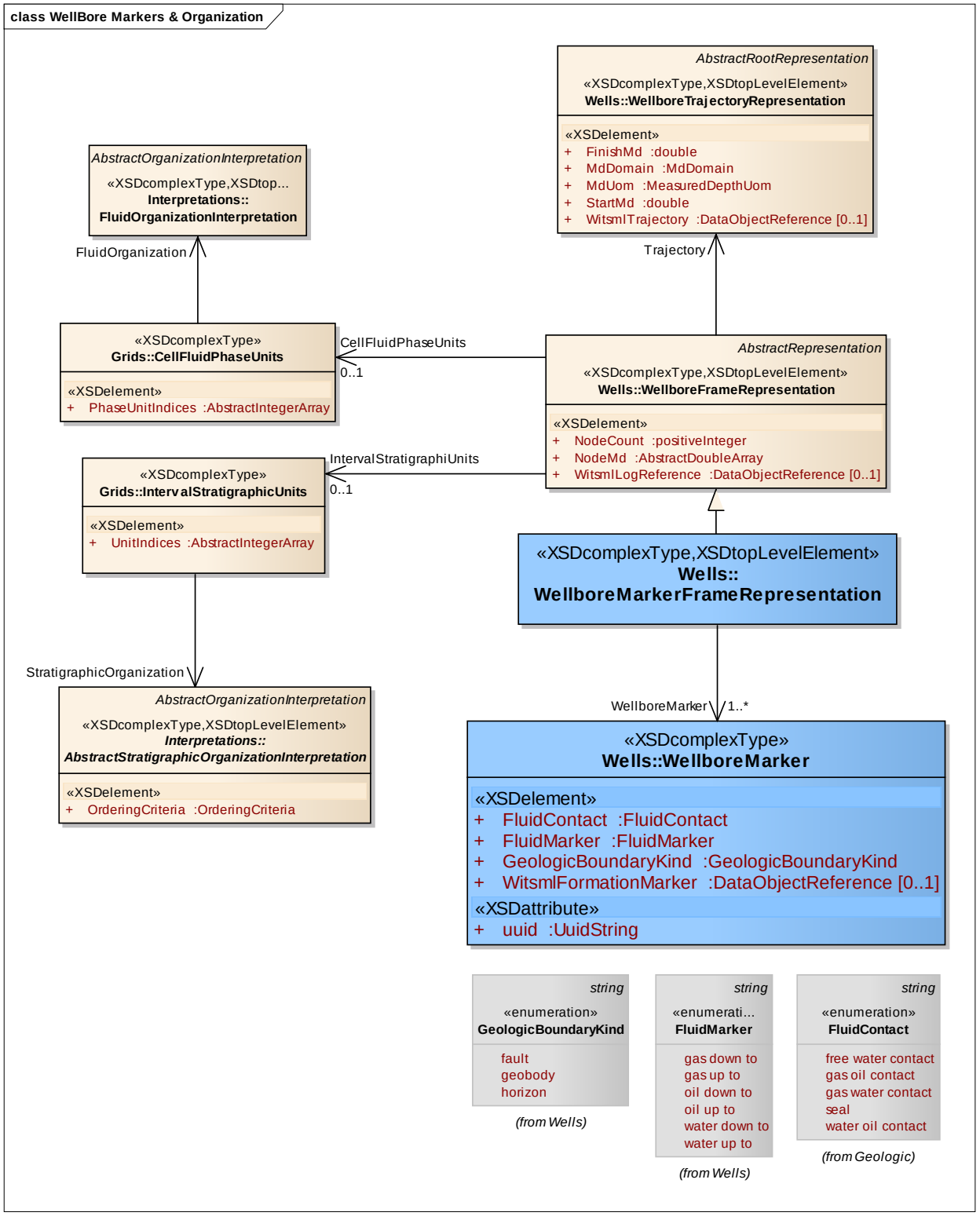


Figure 12-3—A specialized wellbore marker frame representation (blue box) is used to carry marker interpretations along a well. It is also used to link to various types of geologic boundaries (gray boxes) or RESQML stratigraphic and fluid organizations (tan boxes).

12.6 Blocked Wells

Reservoir simulation often requires discretization of a well based on one or several reservoir grids. The blocked wellbore representation (**Figure 12-4**) is the intersection of the grids and a trajectory. It is a well marker frame where each node typically represents a limit between grid cells. It has these characteristics:

- Contains the list of grids on which it has been discretized and the number of grid cells that are intersected.
- For each frame interval corresponding to a grid cell, the corresponding grid index in the list is stored.
- For the intervals between nodes that may not correspond to actual grid cells—for example if the well is outside of any grid or grid geometries have not yet been defined—a value of -1 is used.
- For each actual grid cell, the blocked well contains the cell index and the cell face indices where the trajectory enters and exits. So each cell has a pair of local face indices, and when the trajectory begins or ends within the cell, the entry or exit value is -1.

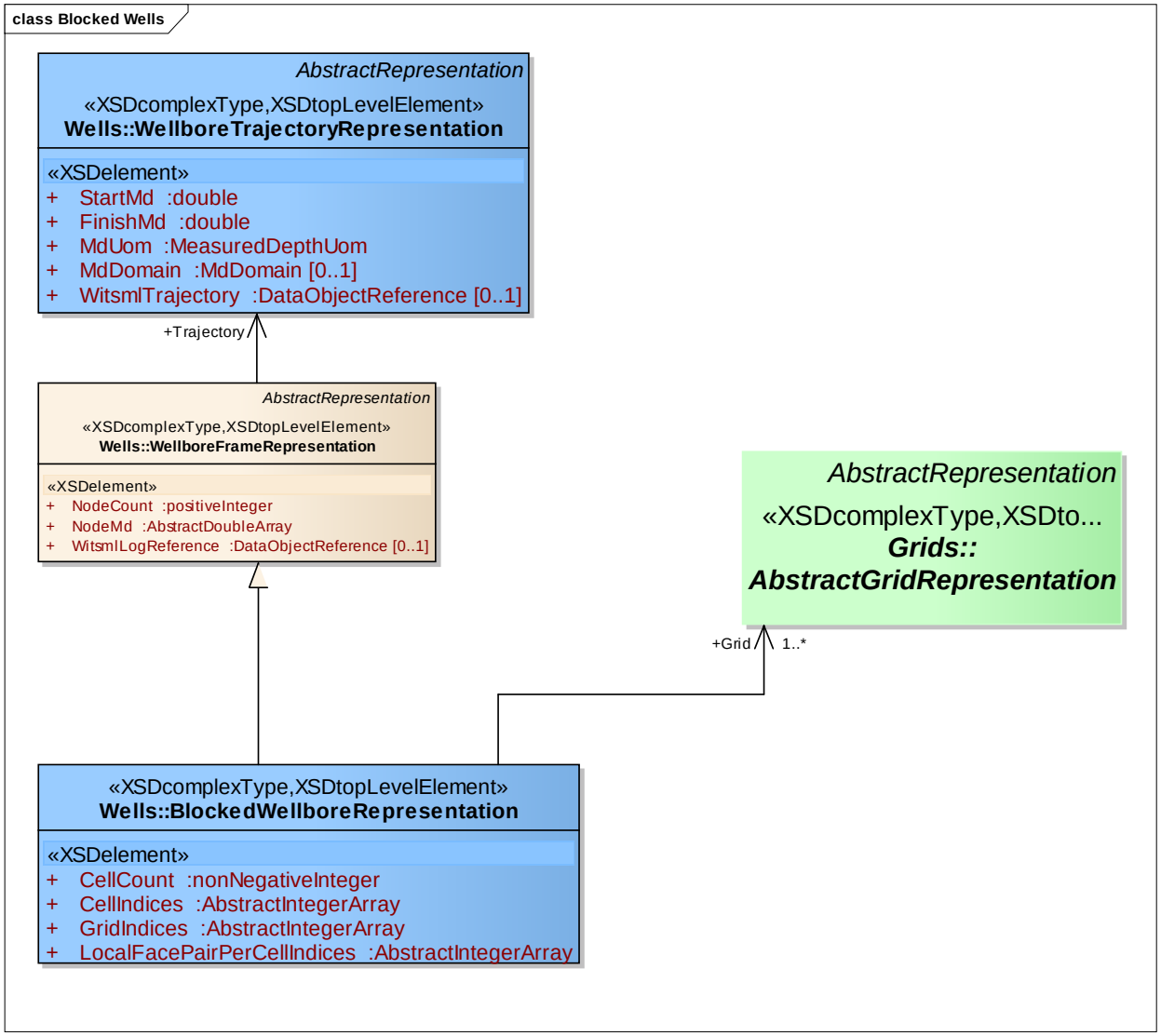


Figure 12-4—The blocked wellbore representation is the intersection of the grids and a trajectory. It is a well marker frame where each node typically represents a limit between grid cells.

12.7 Example: Two Vertical Wells

To show how RESQML works, here's a simple example of two vertical wells:

- **Figure 12-5** shows the well class diagram, which is expanded into four parts (so you can read it) in **Figure 12-6** through **Figure 12-9**.
- **Figure 12-10** (page 209) shows the instance diagram of this two-well example, which is expanded into the two parts of **Figure 12-11** and **Figure 12-12**.

12.7.1 Class Diagram

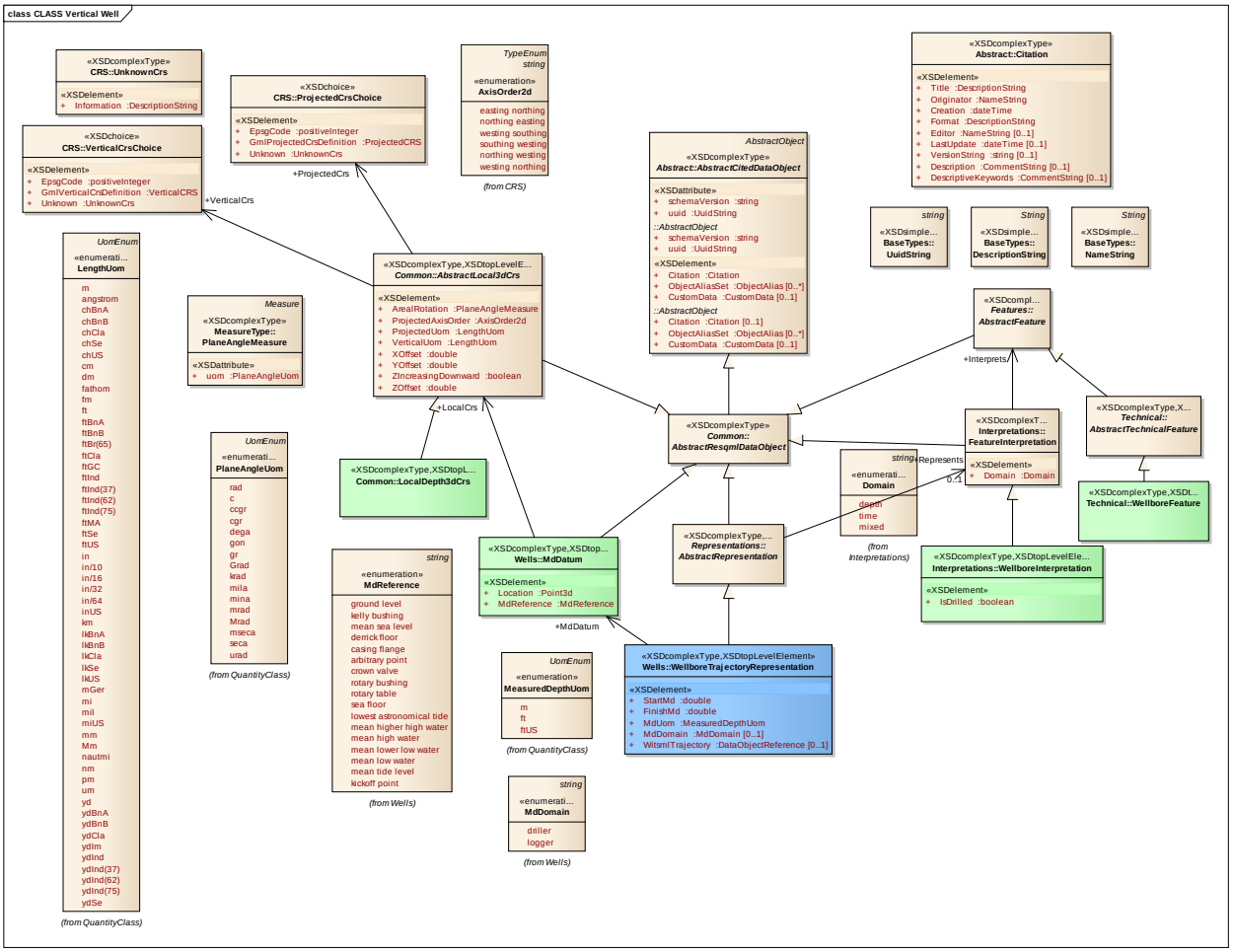


Figure 12-5—Overview of the class diagram for a wellbore trajectory representation. Portions of this figure are expanded in Figure 12-6 through Figure 12-9.

The single major mandatory component of the wellbore trajectory representation is the MD datum **(Figure 12-7**), which corresponds to the wellhead. The MD datum exists independently of the wellbore trajectory representation and needs to have a uniquely defined local 3D coordinate reference system (CRS) (**Figure 12-6**).

The vertical well geometry (highlighted cells and **Figure 12-8**) is known from the location of the MD Datum and the measured depth range (start and finish MD values) of the wellbore trajectory representation. In this specific case, there is no need to specify a parametric line to describe its geometry.

Finally, the use of wellbore interpretations and features (**Figure 12-9)** allows us to document relationships between wellbore trajectory representations. For example, multiple representations with a shared interpretation may arise, if we have three ways of representing nominally the same geometry: a minimum-

curvature trajectory, a piecewise linear trajectory at a low resolution corresponding to the intersections with a coarse reservoir simulation grid, and a piecewise linear trajectory at high resolution corresponding to the intersections with a detailed 3D geologic model. Wellbores that share the same feature but different interpretations may correspond to a single nominal target well and the many well plans for that well.

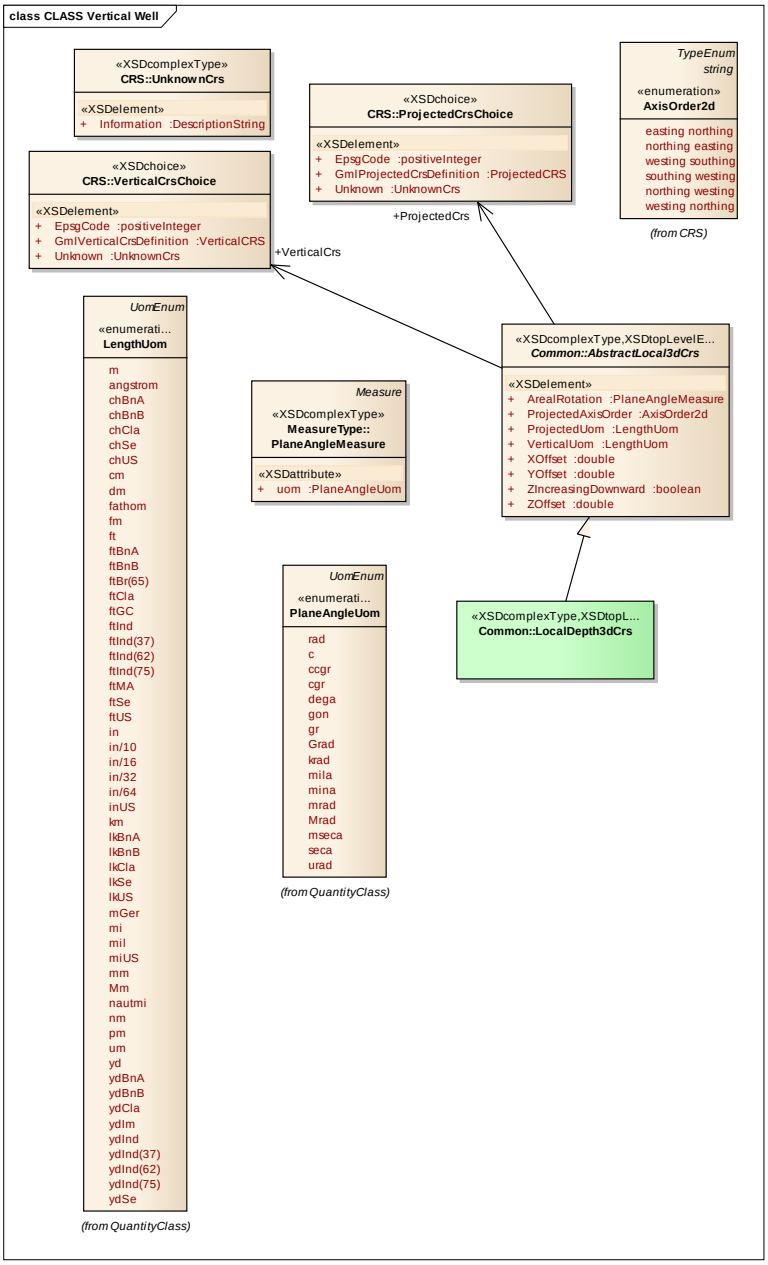


Figure 12-6—(Part 1 of 4) Components of the class diagram for a wellbore trajectory representation, including the description of the local depth 3D CRS, which is used by the MD datum object.

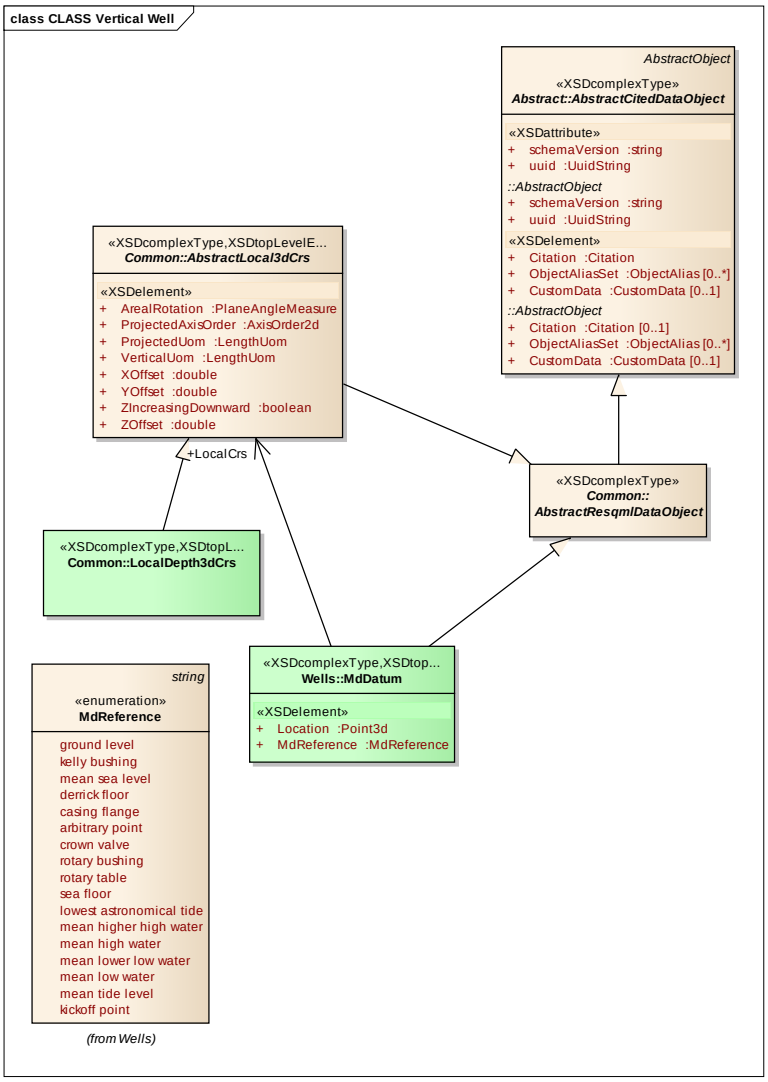


Figure 12-7—(Part 2 of 4) Components of the class diagram for a wellbore trajectory representation: Description of the MD datum data object, which is a mandatory component of the wellbore trajectory representation.

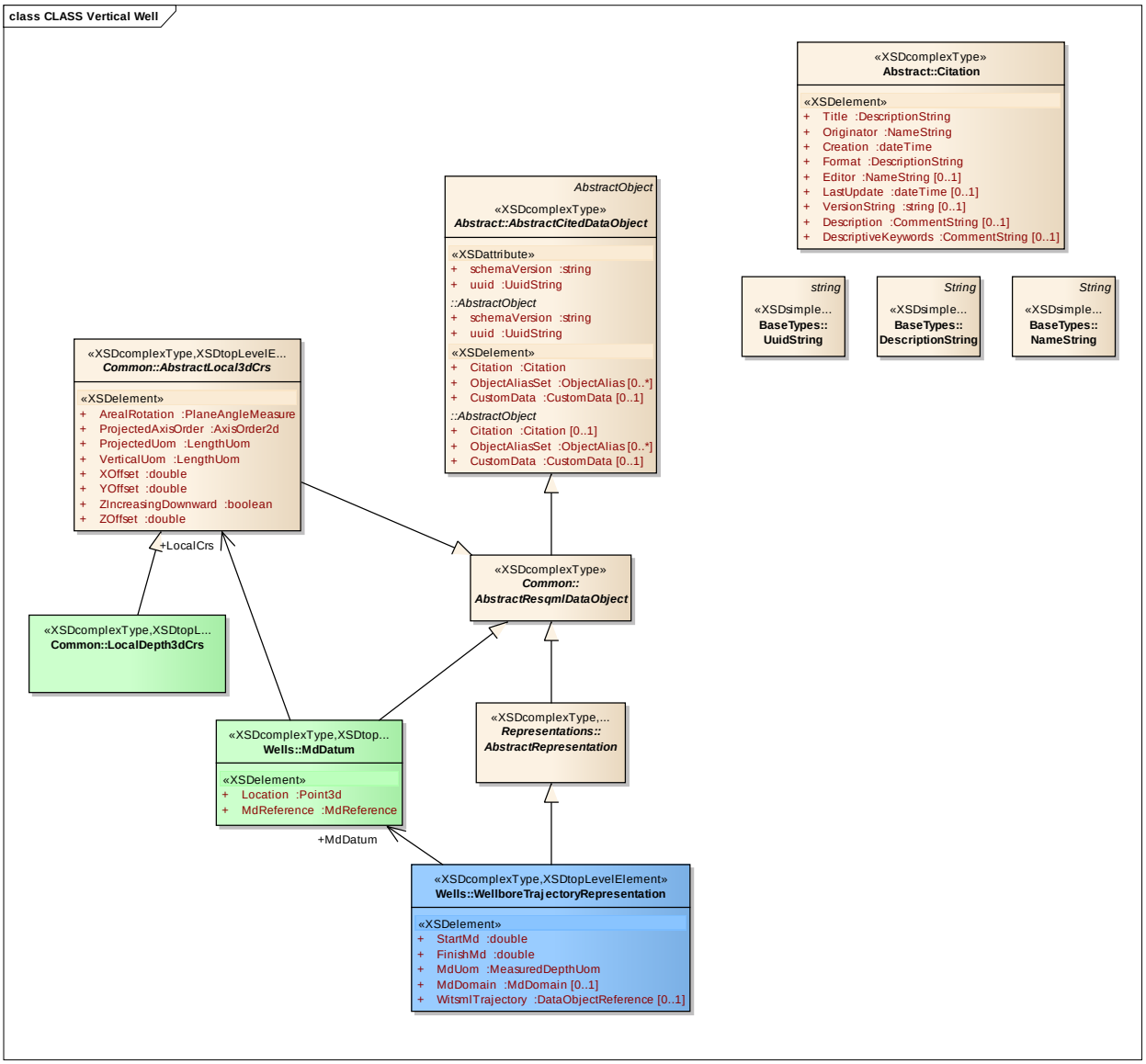


Figure 12-8—(Part 3 of 4) Components of the class diagram for a wellbore trajectory representation: Description of the wellbore trajectory representation includes its implicit geometry.

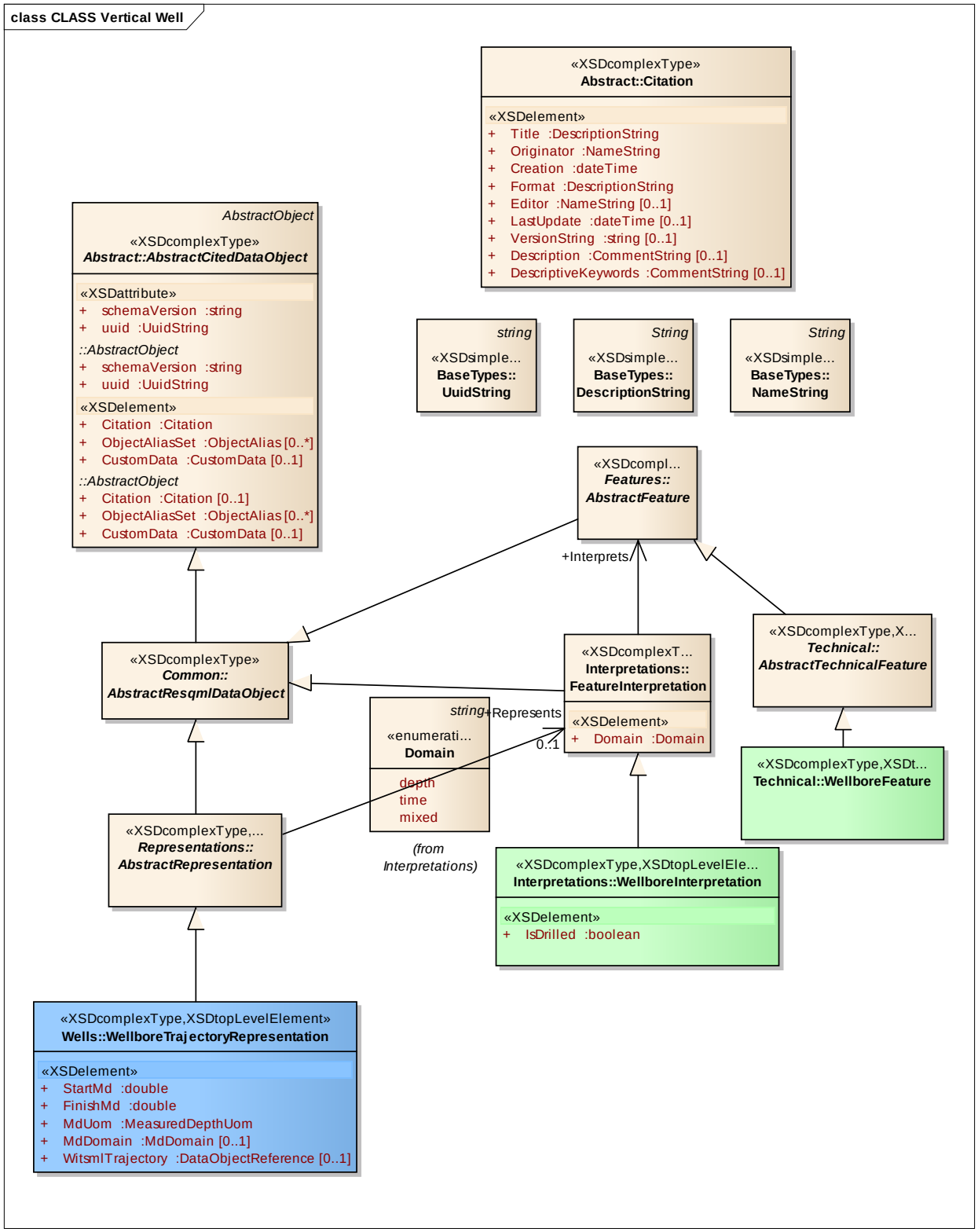


Figure 12-9—(Part 4 of 4) Components of the class diagram for a wellbore trajectory representation: Description of the relationship between the wellbore trajectory representation, the wellbore feature interpretation, and the wellbore feature.

12.7.2 Instance Diagram

Figure 12-10 shows the instance diagram of this two-well example, which is expanded into the two parts of **Figure 12-11** and **Figure 12-12**.

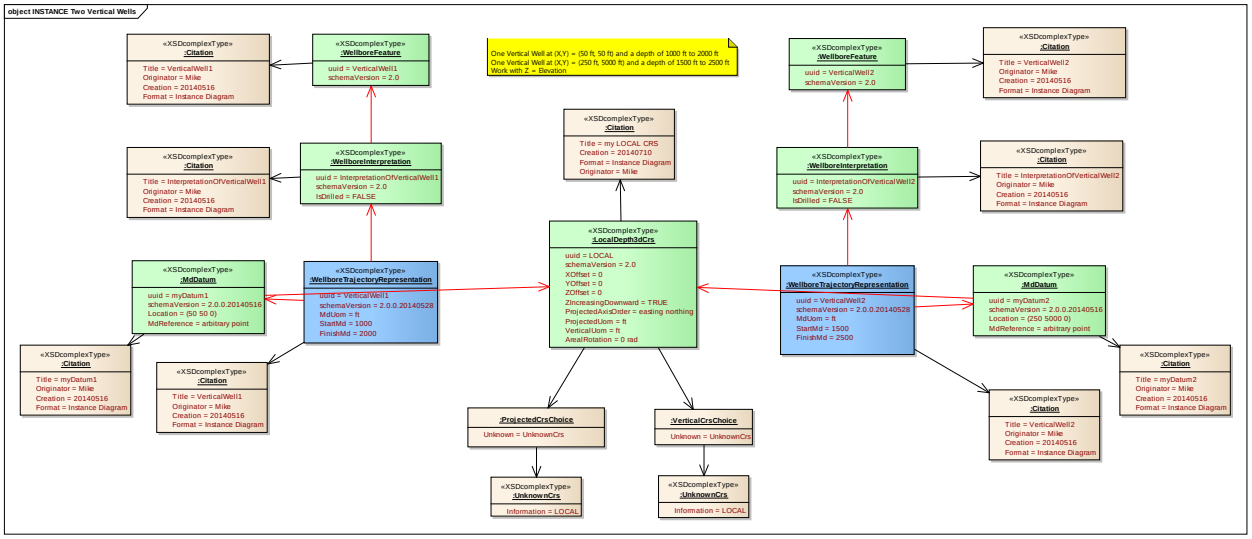


Figure 12-10—Overview of the instance diagram for a wellbore trajectory representation. Portions of this figure are expanded in Figure 12-11 and Figure 12-12.

In **Figure 12-11**, we can see that one well is located at a surface position of (50 ft, 50 ft) in the local coordinate reference system, and extends from a depth of 1000-2000 ft. The other is at a surface position of (250 ft, 5000 ft) and extends from a depth of 1500-2500 ft.

For this specific example (**Figure 12-12)**, the local 3D CRS references an unknown projected CRS and an unknown vertical CRS as their spatial reference. This would be unusual in practice for a drilled well, but may arise in a reservoir simulation well planning workflow in which the simulation applications may not be CRS aware.

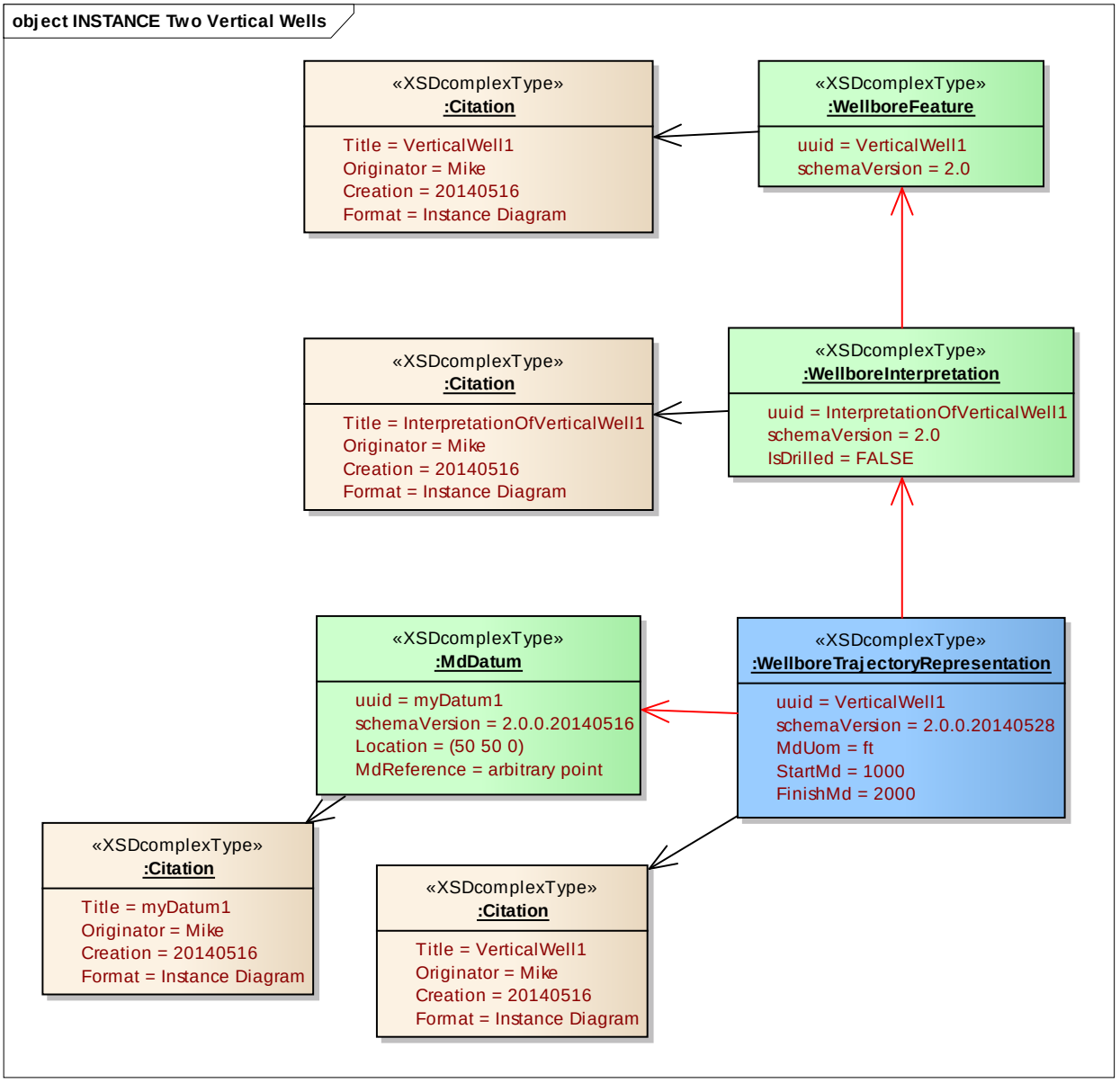


Figure 12-11—(1 of 2) Components of the instance diagram for a wellbore trajectory representation: Instance of the wellbore trajectory representation for the first vertical well.

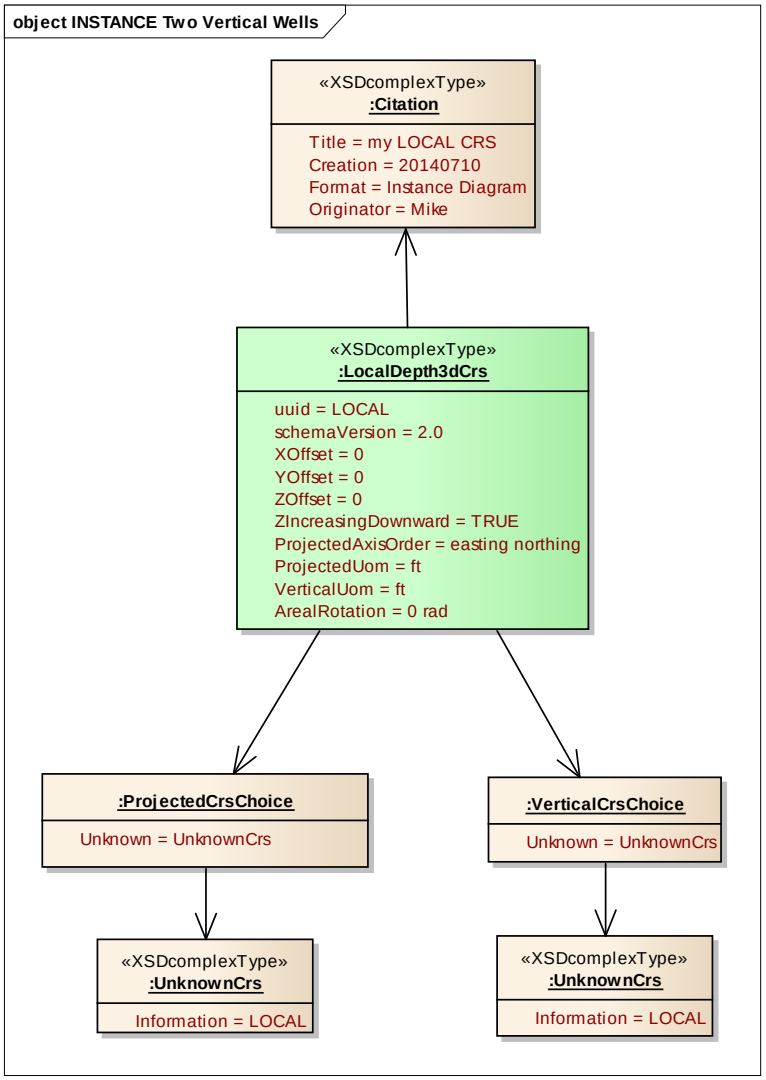


Figure 12-12—(2 of 2) Components of the instance diagram for a wellbore trajectory representation: Instance of the local depth 3D CRS, which is referenced by the MD datum data object.

13 Seismic

A seismic survey is an organization of seismic lines. In the context of RESQML, a seismic survey feature does not refer to any vertical dimension information, but only areally at shot point locations or common midpoint gathers. However, vertical coordinates may be transferred as part of the seismic coordinate geometry.

The seismic traces, if needed by reservoir models, are transferred in an industry standard format such as SEGY. The SEGY format contains information about the number of samples in the seismic traces and whether the vertical domain is in time or depth. This section only discusses the areal aspects of seismic surveys.

RESQML supports two basic kinds of seismic surveys:

- seismic lattice (organization of the traces for the 3D acquisition and processing phases).
- seismic line (organization of the traces for the 2D acquisition and processing phases).

Additionally, to transport several 3D seismic surveys or seismic lines of one or more 2D seismic surveys together:

- 3D Seismic lattices can be aggregated into a seismic lattice set (3D survey set), if needed.
- 2D Seismic lines can be aggregated into a seismic line set (2D seismic survey or surveys) in the same way.

Thus there are four seismic survey features that are represented in RESQML as follows:

- A seismic lattice is generally represented using a grid 2D representation.
- A seismic lattice set is then represented by several grid 2D representations.
- A seismic line is generally represented using a polyline representation.
- The seismic line set is then represented by several polyline representations.

For more information on representations, see Chapter 6 (page 59).

In RESQML seismic surveys are technical features that do not have multiple interpretations. Although it is possible to re-interpret a seismic survey for improved physical properties or for positioning, these types of relationships are not included within the RESQML knowledge hierarchy. (For more information on the knowledge hierarchy, see Chapter 5 (page 51).)

13.1 Seismic Lattice

A seismic lattice defines the seismic trace organization during a 3D acquisition. It is represented by a regular IJ 2D grid (**Figure 13-1**) where each node corresponds to one final common midpoint (CMP) gather.

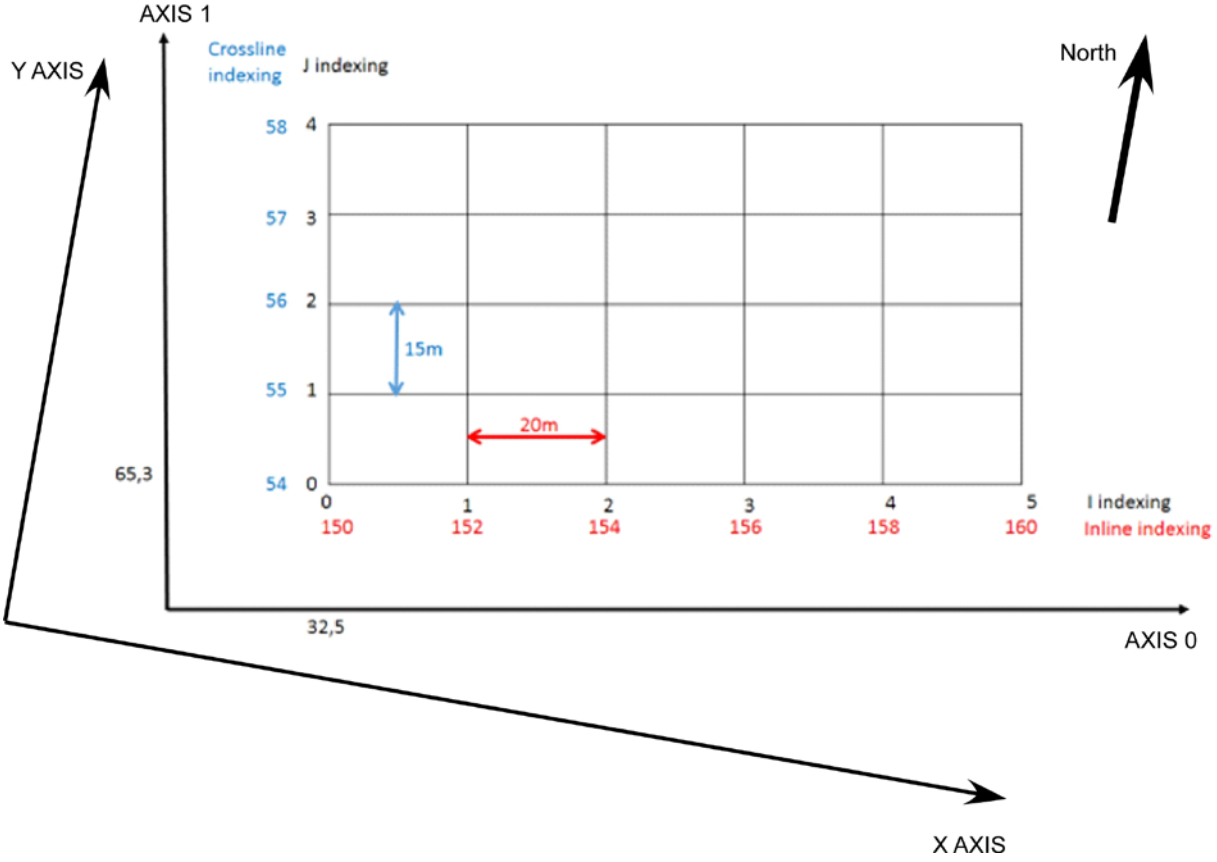


Figure 13-1—A seismic lattice.

At the feature level, the dimensions of seismic lattices are usually oriented along an inline axis and a crossline axis. The indexing of these two dimensions must be regularly incremented along each axis. This is the only constraint; for example, there is no constraint that the origin indices must begin at 0,0.

13.2 Seismic Lattice Representation

As a feature, there is no requirement to define an equivalent 1D index from the inline and crossline indices. However, there is a requirement to do so as a representation. (For more information in grids, see Chapter 11 (page 126).)

Two types of representations may be used to provide the actual geometry of surveys:

- The 2D representation is a grid 2D representation where the geometry is provided by a 2D lattice. When using a grid 2D representation, inline/crossline corresponds to the fastest/slowest indices, respectively.
- The 3D representation is an IJK grid representation where the geometry is provided by a 3D lattice, which corresponds to the geometry of a 3D volume. Because the fast axis (I) in a seismic volume corresponds to vertical traces, inline/crossline typically corresponds to the J/K indices, respectively, although the details will vary depending upon the selection of columns or pillars, as discussed in more detail below.

At the representation level, the dimensions of the seismic lattices are typically regularly spaced. The indexing of these two dimensions is very constrained; the origin indices are always 0,0 and the increment between two node indices is always equal to 1.

Because the lattice geometry is based on axes defined by vectors, the direction of these vectors provides the angular information usually associated with a survey, such as the rotation relative to the local CRS.

Figure 13-1 shows how we use an array lattice of points 3D (ArrayLatticeOfPoints3d) to define the geometry of the representation of the survey. **Figure 13-2** is an example instance diagram of a seismic lattice.

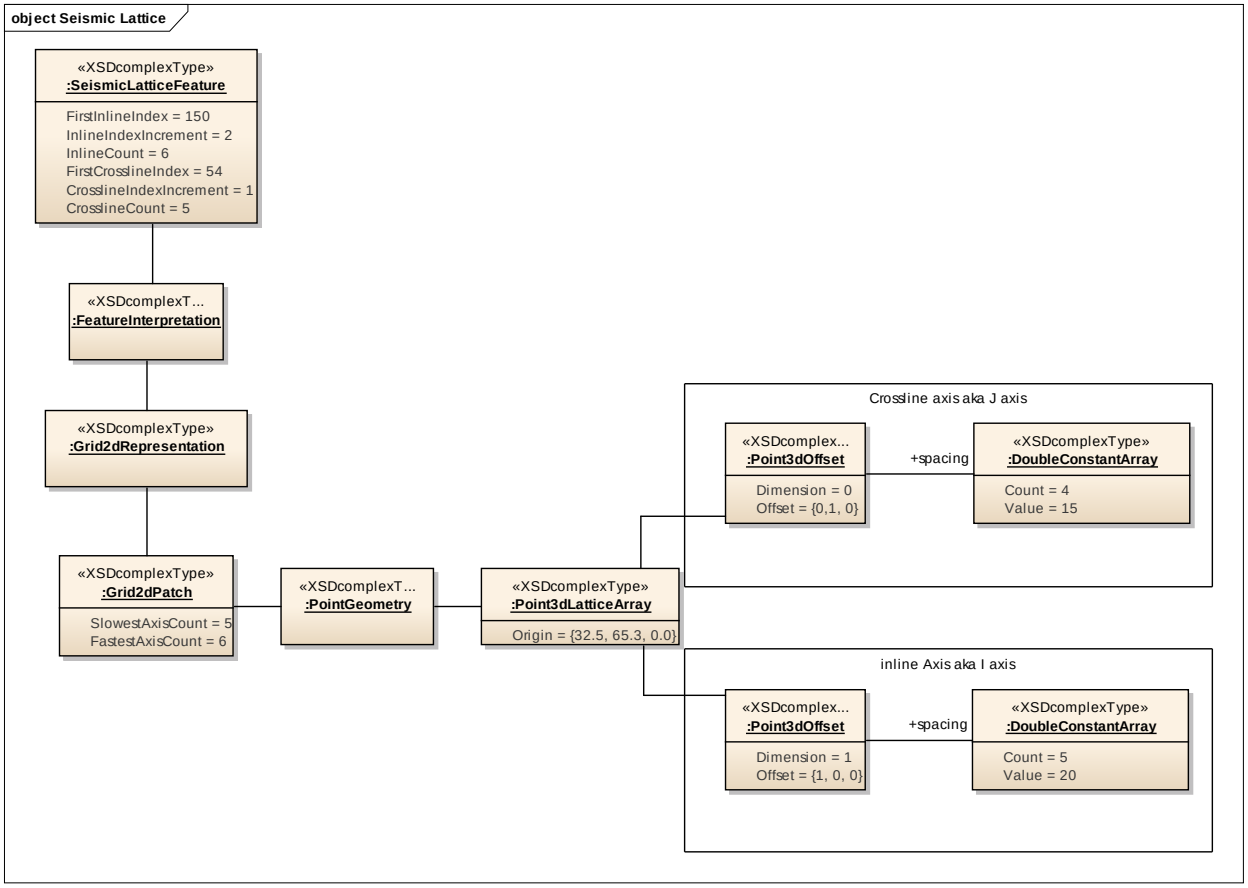


Figure 13-2—Instance diagram of a seismic lattice.

13.3 Seismic Line

A seismic line defines the seismic common midpoint (CMP) organization for the 2D survey acquisition and processing. It is represented by a polyline (**Figure 13-3**) where each node corresponds to one seismic gather location.

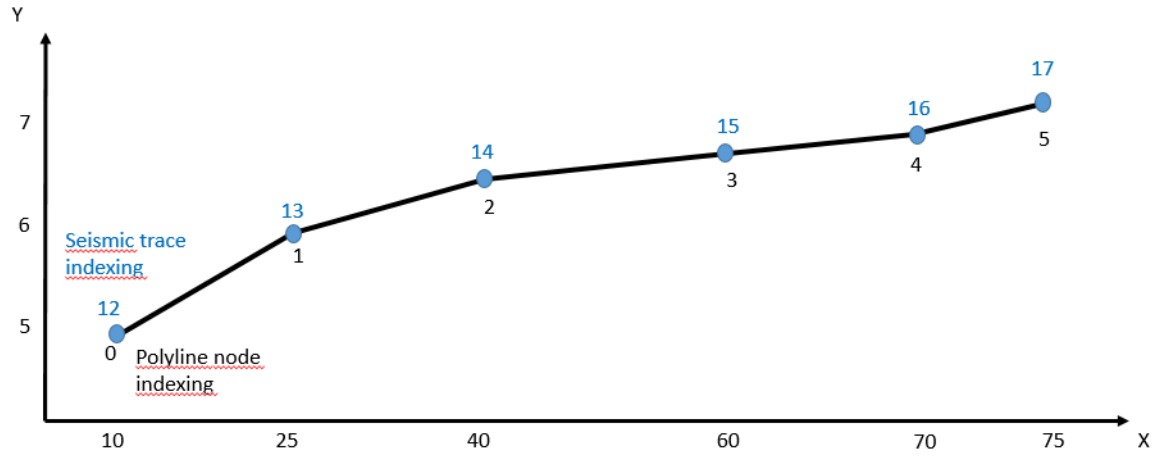


Figure 13-3—A seismic line.

At the feature level, the dimension of a seismic line is the dimension of the seismic traces. The indexing of this dimension must be regularly incremented, but this is the only constraint.

At the representation level, the dimension of a seismic line is geometrically oriented and corresponds to the indexing of the polyline nodes. The indexing of this dimension is very constrained: the origin index is always 0, and the index increment between two nodes is always equal to 1.

Figure 13-4 shows how RESQML uses an array of explicit points 3D (ArrayOfExplicitPoints3d) to define the geometry of the representation of the survey.

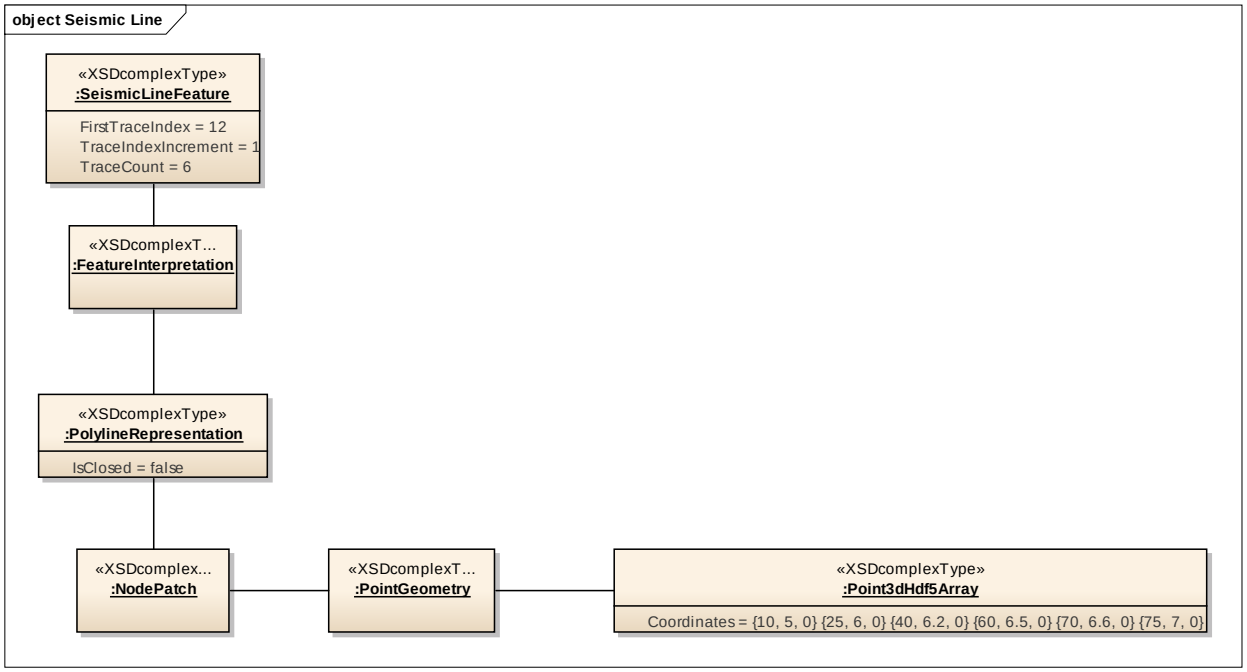


Figure 13-4—Geometry of the representation of a seismic survey.

13.4 Seismic Survey as a Part of the Geometry of the Business Object

Any business object, such as a horizon, can define its geometry by means of Z values. The Z values are then combined with the geometry of a seismic survey to give XYZ points.

This is done using the class point 3D Z value array (Point3dZValueArray) (**Figure 13-5**), which can define Z values on a subset or on the whole of an existing representation indicated in the attribute supporting geometry.

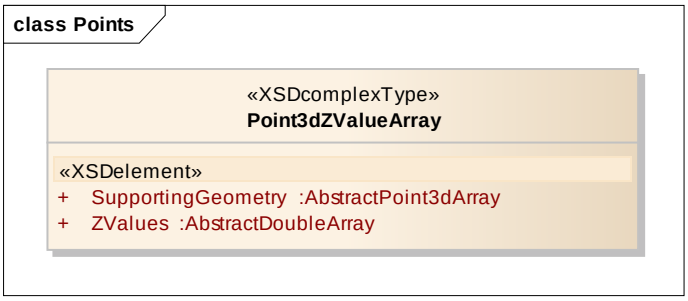


Figure 13-5—Point3dZValueArray is used to define a Z point for a business object; when it's combined with a seismic survey it gives the XYZ points.

The subset or the whole of an existing geometry (attribute supporting geometry above) is generally handled by the class Point3dFromRepresentationLatticeArray, where we use an integer lattice array to select the nodes where the Z values are applied (**Figure 13-6**).

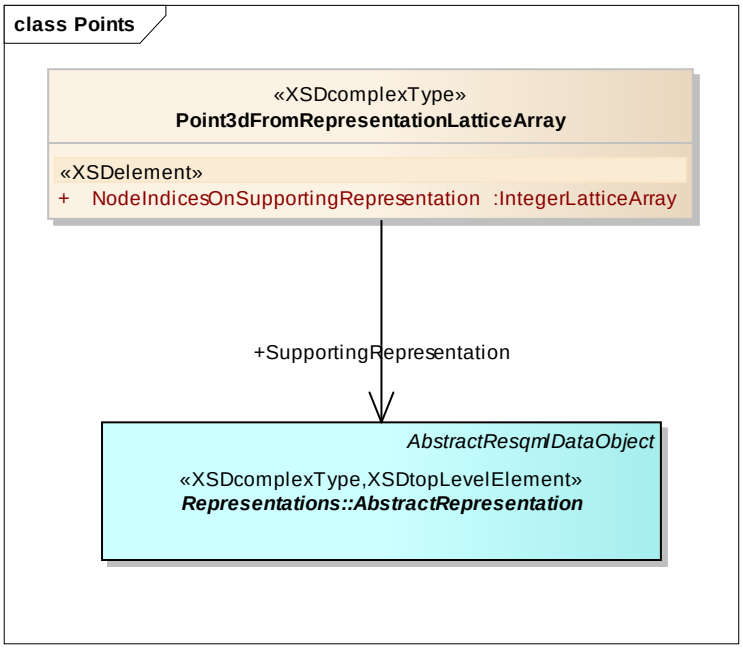


Figure 13-6—Point3d from representation using a lattice array construction.

The subset of nodes is given by means of (**Figure 13-7**):

- A start value (origin): linearized index of the origin node of the subset.
- For each lattice dimension defined by its order in the XML instance, the list of the offset between selected nodes.

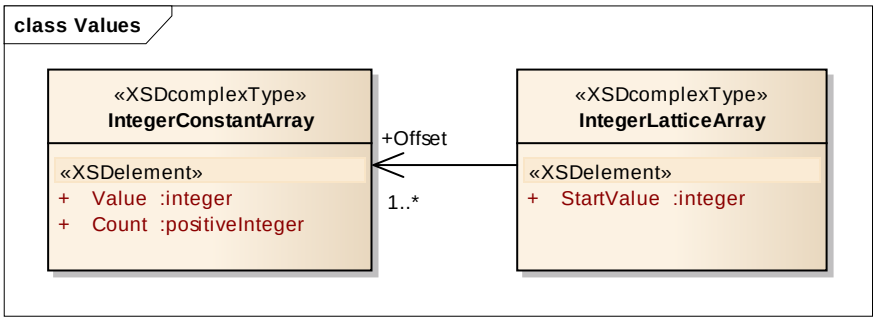


Figure 13-7—Integer lattice array construction.

13.4.1 Example

Figure 13-8 shows an example survey. **Figure 13-9** shows how the green and red 2D grid patched are defined.

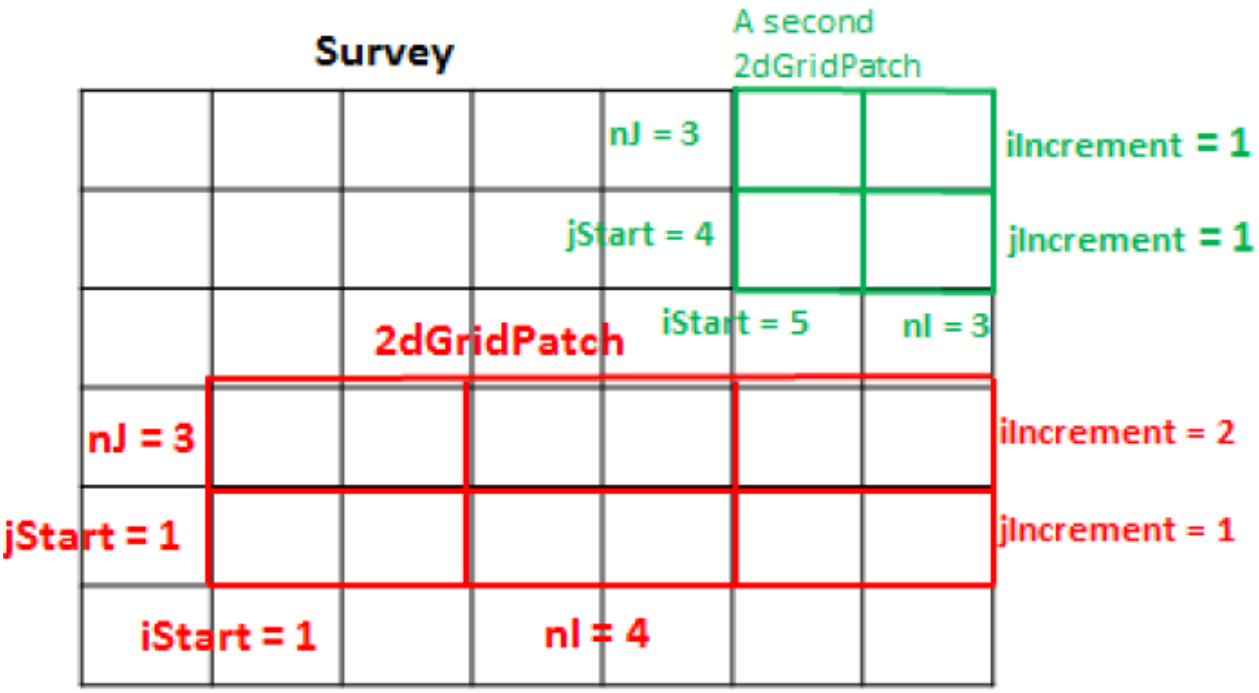


Figure 13-8—An example survey.

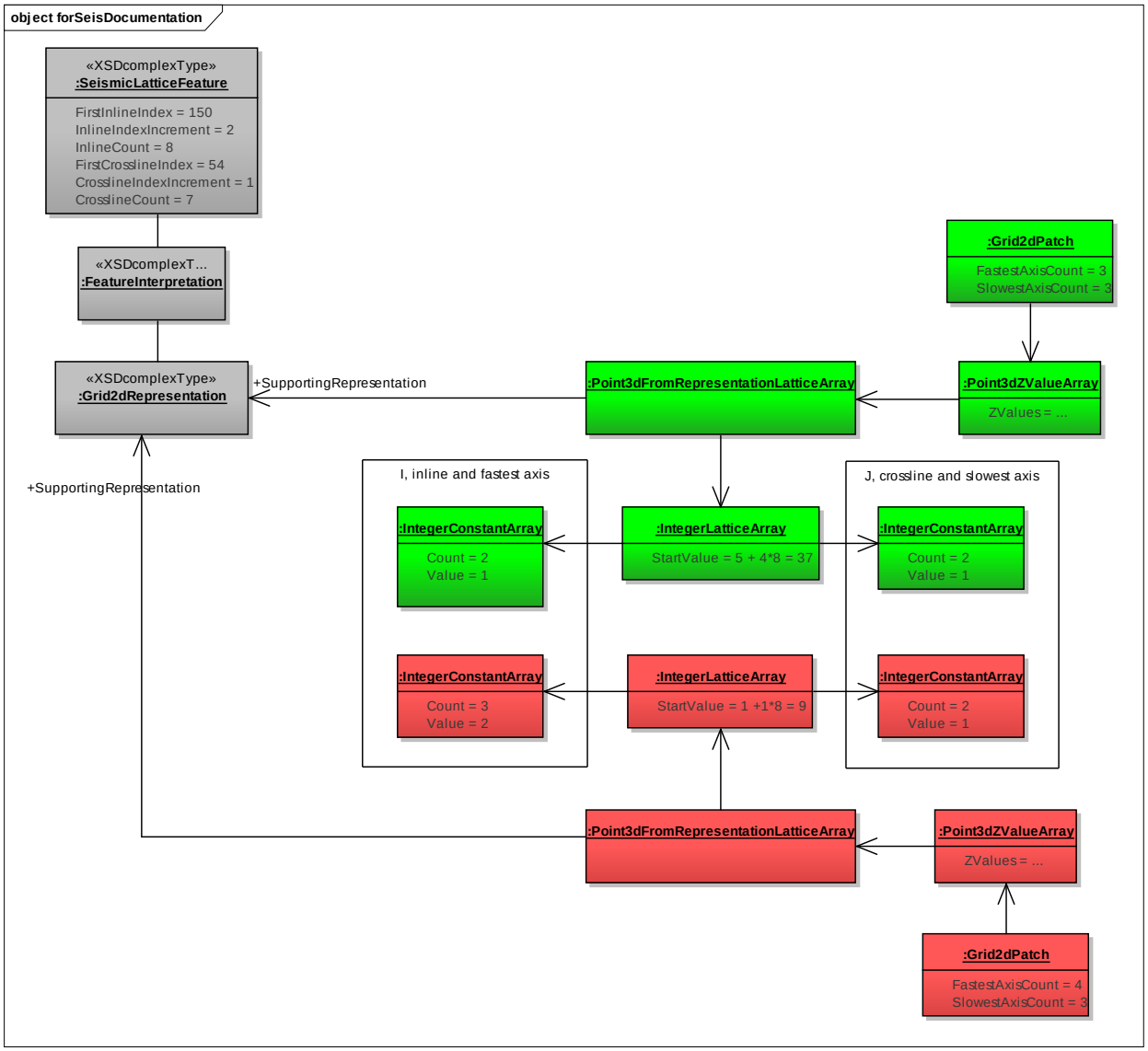


Figure 13-9—The green grid 2D patch and the red grid 2D patch both have a geometry, which is supported by the representation of the seismic lattice.

13.5 Seismic Survey as Extra Information on the Geometry of a Representation

Any representation based on point geometry may have seismic coordinates associated with the points. **(Figure 13-10)**. (For more information on point geometry, see Section 8.3 (page 80).)

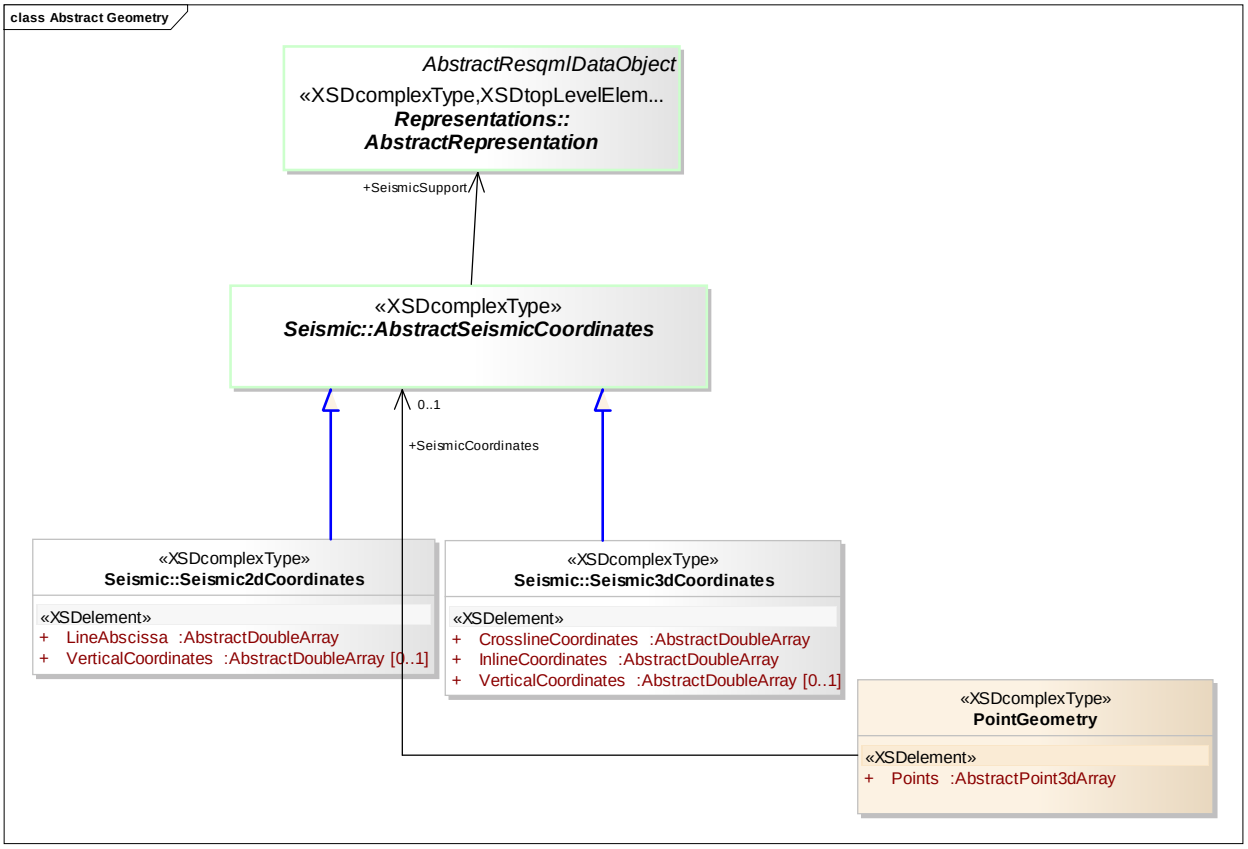


Figure 13-10— Seismic coordinates may be associated with the point geometry of any representation.

Seismic coordinates are based on a supporting representation, which must be a representation of a seismic survey.

- If the seismic survey is a seismic line, then you must give seismic coordinates using the seismic 2D coordinates.
- If the seismic survey is a seismic lattice, then you must give seismic coordinates using the seismic 3D coordinates.

The seismic coordinates must be ordered exactly as the points are ordered in the representation of the business object. The 3D seismic coordinates consist of three arrays of (InlineCoordinate, CrosslineCoordinate, VerticalCoordinate) values. The 2D seismic coordinates consist of two arrays of (LineAbscissa, VerticalCoordinates) values. These coordinates are not constrained to be integers and so can represent positions between the nodes of a seismic survey.

13.6 Seismic Survey Representations on a Grid

There is a reservoir modeling practice in which an IJK grid used for geologic modeling or flow simulation is aligned with the inline/crossline lattice of a seismic survey. There are two natural ways to express this relationship in RESQML, both using subrepresentations.

- If the intent is to align the lattice with the edges of the cells, then the indexable element kind is “pillars” and the NIL x NJL indexing would correspond to inline and crossline, respectively.

- Similarly, if the intent is to align the lattice with the cells themselves, then the indexable element kind is “columns” and the NI x NJ indexing corresponds to inline and crossline, respectively.

The explicit choice of indexable element in the subrepresentation removes the ambiguity in alignment (column or pillars) that often makes this workflow confusing.

Appendix A. Standards Used in RESQML

The following table lists the standards used by RESQML and their respective sponsoring organizations.

Standards / Organization	Description of Use
XML Schema 1.1 XML Schema Part 1: Structures Second Edition http://www.w3.org/TR/2004/REC-xmlschema-1-20041028/ W3C- World Wide Web Consortium 28 October 2004	Used to define the schema that constrains the content of a RESQML XML document.
XML Schema Part 2: Datatypes Second Edition http://www.w3.org/TR/2004/REC-xmlschema-2-20041028/ W3C-World Wide Web Consortium	Used to define the schema that constrains the content of a RESQML XML document.
Hierarchical Data Format 5 (HDF5) The HDF Group http://www.hdfgroup.org/	Open file formats and libraries used with the RESQML schemas. Designed to store and organize large amounts of array data, and improve speed and efficiency of data processing.
Geographic Markup Language (GML) Open Geospatial Consortium (OGC) http://www.opengeospatial.org/	The OpenGIS® Geography Markup Language Encoding Standard (GML). The Geography Markup Language (GML) is an XML grammar for expressing geographical features.
EPSG Codes International Association of Oil & Gas Producers (OGP) http://www.epsg.org/	The European Petroleum Survey Group (EPSG), the globally recognized experts on geodetic issues, has been absorbed into the Surveying and Position Committee of the International Association of Oil & Gas Producers (OGP), which is now the owner of the EPSG database of Geodetic Parameters and assigned codes. RESQML implementations can use EPSG codes to define a coordinate reference system.
IETF RFC 4122 Internet Engineering Task Force https://tools.ietf.org/html/rfc4122	IETF RFC 4122 is a standard for defining universally unique identifiers (UUID). According to the abstract of the specification: "This specification defines a Uniform Resource Name namespace for UUIDs (Universally Unique IDentifier), also known as GUIDs (Globally Unique IDentifier). A UUID is 128 bits long, and can guarantee uniqueness across space and time."
Open Packaging Conventions *Standard ECMA-376* *Office Open XML File Formats* http://www.ecma-international.org/publications/standards/Ecma-376.htm *ISO/IEC 29500-2:2012* *Information technology -- Document description and processing languages -- Office Open XML File Formats -- Part 2: Open Packaging Conventions* *http://standards.iso.org/ittf/PubliclyAvailableStandards/i*	To address the challenges of the multi-file data sets used in upstream oil and gas, Energistics and its members have developed file packaging conventions based on the Open Packaging Conventions (OPC), a widely used container-file technology that allows multiple types of files to be bundled together into a single package. The Energistics Packaging Convention (EPC) is intended for use with all Energistics standards. OPC is supported by the two organizations listed in the left column.

Standards / Organization	Description of Use
ndex.html	
Unified Modeling Language™ (UML®) Object Management Group http://www.uml.org/	UML is a general purpose modeling language, which was designed to provide a standard way to visualize system design. Originally intended for software architecture design, its use has expanded.
Energy Industry Profile of ISO/FDIS 19115-1 Energistics To download the EIP: http://www.energistics.org/asset-data-management/energy-industry-profile-standard Use of EIP replaces the Dublin Core Metadata Elements used in the previous version of RESQML.	The Energy Industry Profile of ISO 19115-1 (EIP) is an open, non-proprietary data exchange standard for data and information with associated spatial coordinates, e.g., geospatial datasets and web services, physical resources with associated location, or mapping, interpretation, and modeling datasets.
RESCUE RESQML predecessor standard.	RESQML Version 1 replaced RESCUE functionality and addresses some of the key user issues with RESCUE. An E&P industry data exchange used since the 1990s for 3D gridded reservoir models, horizons, faults and structural models, and associated well data.

Appendix B. Release Notes

This appendix contains summary descriptions of changes per published version of the standard (schema changes).

Documentation clarifications and corrections have also have been made that do not change (only clarify) how the schema is intended to work. For a list of those changes, see the document Amendment History on page 3.

B.1 Version 2.0.1

New data objects added in v2.01 have been designed to work with the previously published v2.0 RESQML model. Nothing has changed in the v2.0 model. As such, new v2.0.1 data objects are documented in Appendix C (page 224); they include:

- **Activity model** (see Section C.1 (page 224)). Its purpose is to capture:
  - Tasks or actions that occurred to create and edit a subsurface model
  - How the activities relate to the data being exchanged.
- **Property Series** (Section C.2 (page 228)). Makes it possible in RESQML to capture the evolution of property values through time and/or for multiple realizations of values during stochastic processes.
- **Streamlines** (Section C.3 (page 230)). In a reservoir engineering context, streamlines are a way to visualize and represent fluid flow. They have many applications; for example, they have been used as a basis for fluid flow simulation, sweep management, well rate optimization, and infill well placement.

Appendix C. New Data Objects for v2.0.1

The data objects listed here have been designed to work with the existing RESQML v2.0 data model. Because the v2.0 model has not changed since it was published, these new objects are documented in an appendix.

C.1 Activity Model

The purpose of the activity model is to capture:

- The activities (tasks or actions) that occurred to create and edit a subsurface model.
- How the activities relate to the data being exchanged.

Each data object in RESQML has always had metadata about its own history, for example, the date that it was created and last edited and by whom or what software. The purpose of the activity model is to provide additional context about "why" and "how" objects were created and changed, and the dependencies between the different elements of a model.

RESQML currently includes basic mechanisms for defining activities and referencing affected data object(s).

C.1.1 Use Cases

Currently the main focus of the additional activity information is the software user: the goal is to capture human-readable information to provide users with more context to help them make better decisions. (If developers can use the new information for software automation, that use is an added benefit, not the main purpose of the current version.)

Some examples of what the activity model can capture:

- Information indicating that a horizon surface is the result of an interpretation and then a "fit to well marker" process involving a limited set of wells. It can describe the two activities and the parameters used in this process, including the seismic volume on which the interpretation occurred for the interpretation and wells, and markers used in the "fit".
- Information indicating that a reservoir grid property is the result of a geo-statistical simulation involving a limited set of well logs. It can describe the simulation and its input/output, including the well log properties, the simulation type, and numerical parameter values.

C.1.2 How it Works

To describe an activity requires two parts; you must specify:

- **An activity template,** which is a general descriptions of possible activity types. A template is a semantic description of what the activity is about and the types of parameters that could be involved in the activity.

  For example, we can specify a template to describe the creation of any data object (see the example in Section C.1.4 (page 226)). The mandatory output for the template is one or more new data objects. The possible inputs are unlimited so that the template can accommodate the needs (potential complexity) of any data object in an earth model.

  A template may be very generic (for example, if the exporting software does not capture detailed descriptions of activities). Or the templates may be very detailed and precise in providing semantic information about the parameters involved in the activity.

- **An instance of an activity**. The instance describes an activity that has actually occurred. Each instance is associated with a template, which provides its semantics.

As part of a RESQML transfer, a "writer" (software creating data for transfer) must include the most current templates along with the activity instances for the data objects contained in the data transfer. A "reader" uses the templates to understand the activity instances.

To specify relationships between data objects—for example, to attach an activity to the data object(s) it impacts or to attach a template to an activity—use a data object reference. For more information on how data object references work, see Section 5.4 (page 56).

C.1.3 Data Object Organization

Figure 13-11 is a UML model of the activity model class; the model elements are described below. These data objects can be found in the Activities package of the UML model.

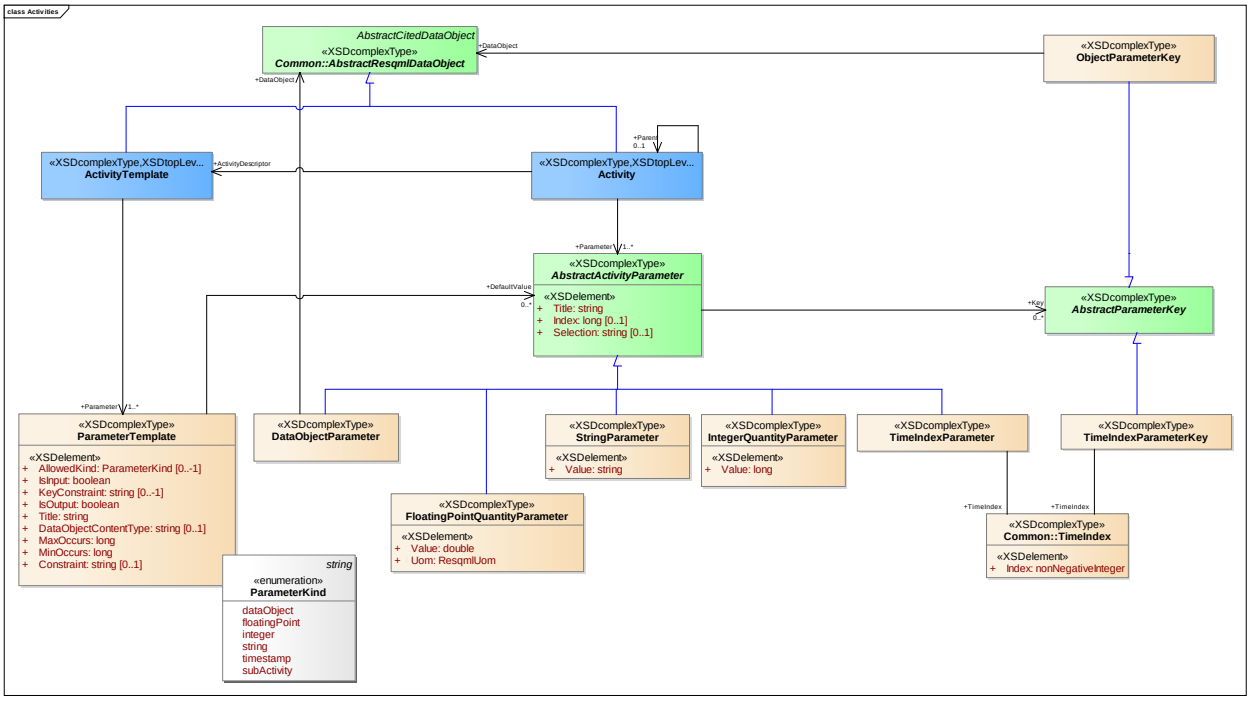


Figure 13-11—UML diagram of activity model data objects, which are described below.

C.1.3.1 Activity Template

An activity template provides the semantics of the activity. The *Title* (or name) provides the type of activity, for example, “GenericCreationActivity” (see Figure 13-12). It also contains a list of parameter templates, which describe each potential parameter along with its role in the activity.

Parameter Template

For each parameter in the activity, describe its:

- Role provided by the parameter *Title.*
- Types associated with this parameter.
  - *AllowedKind* (optional) indicates the possible kinds for this parameter. See SubActivity below.
  - *DataObjectContentType* is used when the kind is limited to data objects and can also restrict the allowed object types.
- Use as input and/or output, based on *IsInput* and *IsOutput* information.
- Cardinality based on *MinOccurs* and *MaxOccurs* information (which are mandatory (1..-1) where -1 means infinite).
- Default value of the parameter.
- Additional constraint provided in free text form and targeted to be human readable.

SubActivity

When inside an activity, a parameter type is itself an activity and is a sub-activity of the main activity. This nested approach means we can create trees of activities, where complex process can be captured as an aggregation of smaller activities. In this case, the *AllowedKind* for the parameter is *subActivity*.

C.1.3.2 Activity

The activity object describes an activity that has actually occurred, which provides actual values to the parameters. An activity is a single implementation of the template it is associated to.

An activity contains:

- A link to the template it is instantiating.
- A list of actual parameter values.
- An optional parent activity, when the activity is a sub-activity.

Activity Parameters

Each parameter is represented by different objects according to the type of value it represents: DataObjectParameter, FloatingPointQuantityParameter, StringParameter, IntegerQuantity, TimeIndexParameter.

A parameter either: 1) stores a value or 2) references another object, for example, the DataObjectParameter. Its *Title* must match the *Title* of the corresponding *ParameterTemplate*.

To provide an optional textual description about the way the values have been selected for this parameter, use *Selection*. For example: “All wells” or “Porosity with maximum values greater than 0.05”.

C.1.3.3 Parameters with Multiple Values

When the cardinality of the associated *ParameterTemplate* is greater than one, then you must provide one value for each cardinality. Each value is provided as an individual parameter and each parameter of this collection must be individualized by one of these methods:

- an *Index*, used when the collection is the equivalent of a list.
- a *Key*, used when the collection is the equivalent of a map. The *Key* can also be a time index or a reference to an object.

C.1.4 Example

This example (**Figure 13-12**) shows how to create an activity template named “GenericCreationActivity” which can be used to describe the creation of one or more data objects. The example also shows how to create an instance of the generic creation activity, in this case, a triangulated representation based on a 2D grid representation.

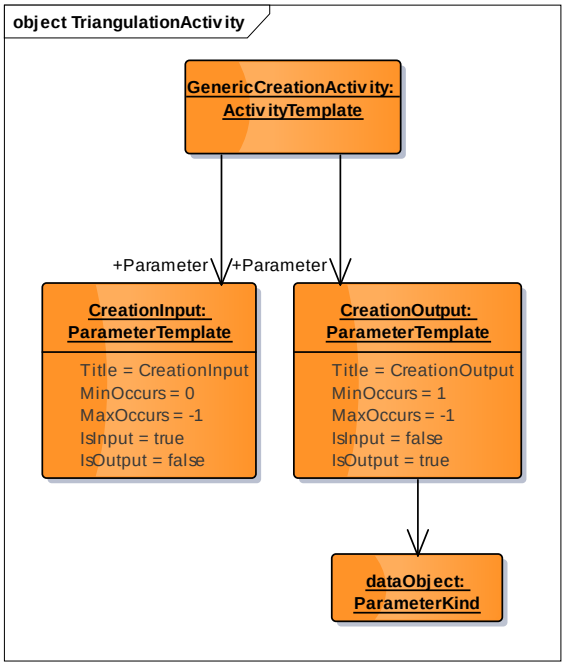


Figure 13-12—Template for a generic "creation activity" which can be used to create any data object.

The left box shows that this creation activity may have zero (see MinOccurs) to unlimited (see MaxOccurs) creation input parameters (see IsInput and IsOutput).

The right box shows at least one mandatory output (see MinOccurs, MaxOccurs, IsInput and IsOutput) which must be a data object (see the lower right box).

This activity template/description can then be used to describe the specifics of the creation of any data object. For example, in **Figure 13-13**, we created a triangulated representation based on 2D grid representation.

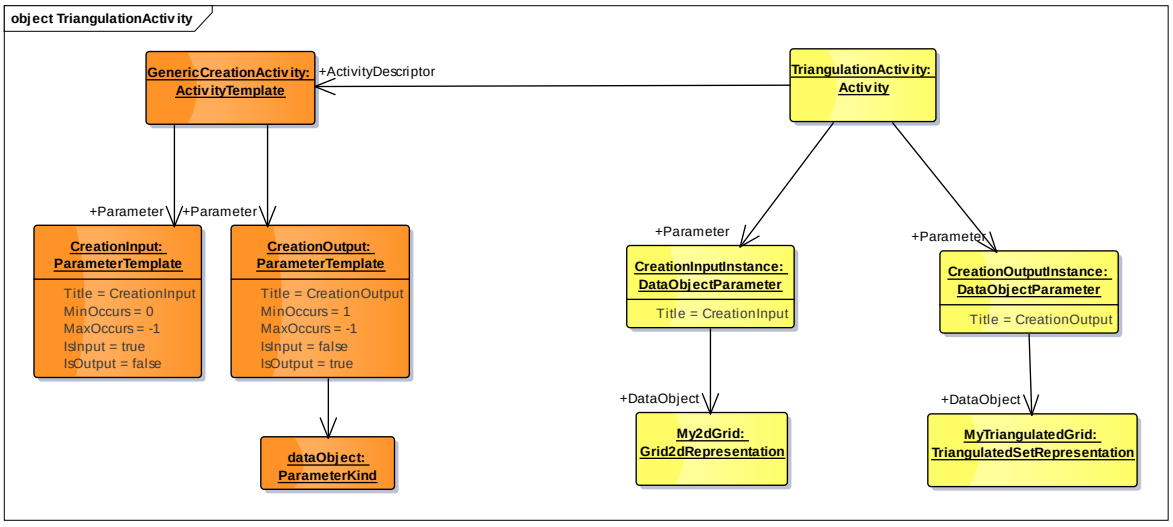


Figure 13-13—Example for a triangulated representation based on a 2D grid.

The triangulation activity (top yellow box) uses the creation activity template/description that we previously defined. This particular triangulation activity indicates that we have created a particular triangulated set representation (called MyTriangulatedGrid) from a particular 2D grid representation (called My2dGrid).

C.2 Property Series

The property series data object makes it possible in RESQML to capture the evolution of property values through time and/or multiple realizations of values during stochastic processes.

C.2.1 Use Cases

RESQML allows us to associate a single scalar value or a vector of values to a location in space. However, some use cases require capturing the evolution of these values through time and/or multiple realizations of these values during stochastic processes.

Examples include:

- Capturing the oil production for a well interval through time.
- Transferring the results of a sequential Gaussian simulation or other geostatistical results.

In these cases, instead of providing a single value or a 1D array for each location, we need to provide one of the following:

- One value for each location and each time.
- One value per location per realization index.
- One value per time per realization, which is the most advanced cases of time-dependent stochastic processes.

In RESQML, this data is added by extending the property model to include property series. The dimensionality of the property series depends on the initial format of the property data:

- If the values were initially represented by an array, time and realization add one or two axis dimensions to this array.
- If the values were scalar values, they each become a 1D or 2D array.

The property series inherits from the abstract values property, which itself inherits from the abstract property. The latter includes optional elements that can be used to associate a single time, a single time step or a single realization index with a property. If the property series is being used to store values for multiple times, multiple time steps, or multiple realizations, then these “single” optional elements should not be used. If provided, then they should be ignored.

C.2.2 Description

Figure 13-14 shows the RESQML properties model with the property series.

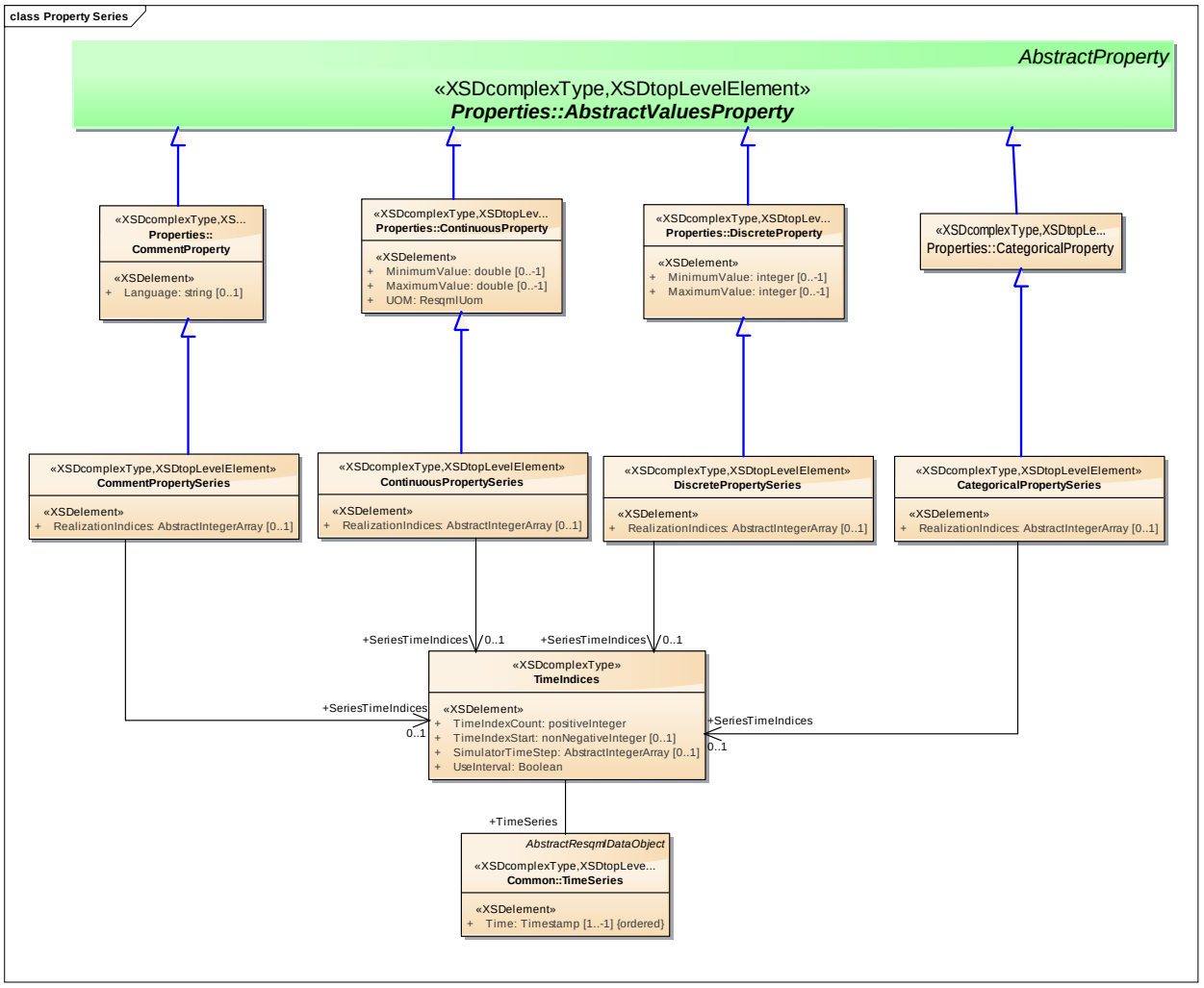


Figure 13-14—UML model of properties with property series.

The property series types are used to capture the two additional dimensions while extending property types. Each property type (continuous, discrete, categorical, comment) has its own property series type.

All property series types optionally contain:

- An array of realization indices which defines the realization dimension. In stochastic simulations, a realization result or a group of results is often associated with one single index, which often reflects their order in the sequence in which they were created. The realization indices are capturing all the indices used to define the realization's extra axis. In the trivial case—where all results are provided—an integer lattice array can be used.
- A link to time indices defines the time dimension. The first element of the time indices indicates the number of time entries to consider. If the Boolean flag named "use interval" is true, the actual number is this count minus one. The actual time values are provided by a link to a time series and a starting index.

C.2.3 Indexing

Because the values in property series are dependent on some additional axes, it is important to define the influence of the new axes on the value indexing and the place of these new dimensions in the HDF dimension orders.

For property series (and only for property series), values are structured this way in HDF (top is the slowest dimension, bottom is the fastest dimension). The property model results in some attributes that are optional and some that are required in the schema (XSD):

- RealizationCount: Optional, don't provide this dimension if the property series is not related to several realizations (no stochastic simulation).
- TimeCount: Optional, don't provide this dimension if the property series is not related to several time information.
- IndexableElementCount: Required, always provide this dimension even if equal to 1.
- ValueCountPerIndexableElement: Optional, don't provide this dimension if the property values are scalar ones. Provide this dimension if the property values are vectorial ones.

Remarks:

- The time count for property series is only related to the series time indices. It is not related to the inherited time index, which should be ignored if also present.
- The realization count for property series is only related to the realization indices. It is not related to the inherited realization index, which should be ignored if also present.

C.2.3.1 Property Series Example

Here are some dimensionality examples for a property series on 3D IJK grid cells (left is the slowest dimension, right is the fastest dimension):

- **Case A**: The property series is a scalar one and is not related to any time or realization information: [nk][nj][ni]
- **Case B**: The property series is a scalar one and is only related to a time information: [TimeCount][nk][nj][ni]
- **Case C**: The property series is a scalar one and is only related to a realization information: [RealizationCount][nk][nj][ni]
- **Case D**: The property series is a scalar one and is related to a time and realization information: [RealizationCount] [TimeCount][nk][nj][ni]
- **Case E**: The property series is a vectorial one and is related to a time and realization information: [RealizationCount] [TimeCount][nk][nj][ni][ValueCountPerIndexableElement]

C.3 Streamlines

In a reservoir engineering context, streamlines are a way to visualize and represent fluid flow. They are especially useful for understanding the volumetric sweep relationships between wells or within a reservoir. They have many applications and, for example, have been used as a basis for fluid flow simulation, sweep management, well rate optimization, and infill well placement (Datta-Gupta and King 2007).

In a more general sense, streamlines are geometric lines that are everywhere tangential to a vector field, and as a consequence they never cross in space (**Figure 13-15**). Also as a consequence, streamlines are static objects. If the underlying vector field changes with time, then the streamlines must be re-drawn. This is in contrast to a “streakline,” which describes the physical trajectory of a particle in a time-varying velocity field. Streamlines and streaklines are only identical for steady velocity fields.

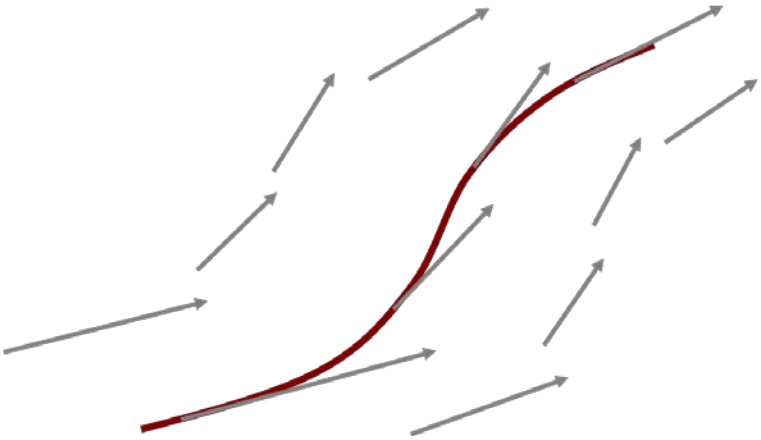


Figure 13-15—Streamlines are the geometric lines that are everywhere tangential to a vector field.

In RESQML, the streamlines data object is used to describe collections of streamlines (**Figure 13-16**).

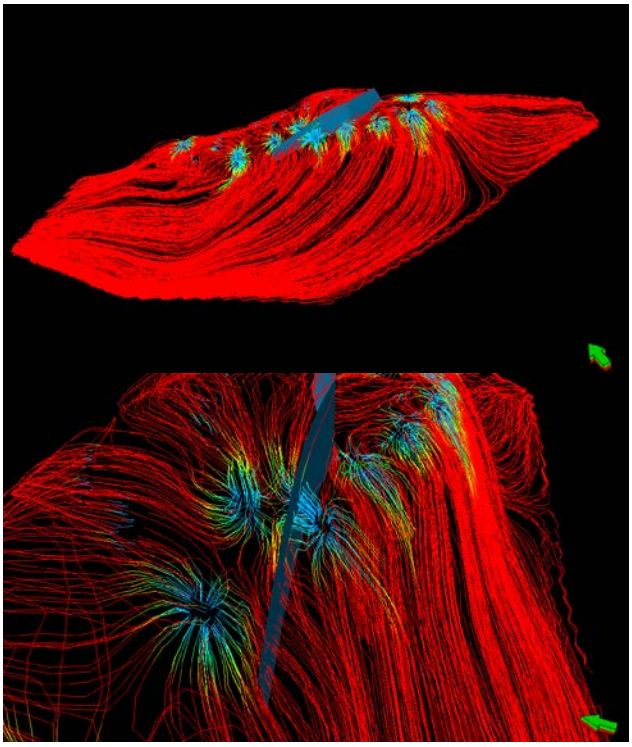


Figure 13-16—Streamlines within a 3D reservoir model (a) Full field, (b) Detailed view near a fault surface.

The streamlines feature describes the nature of the vector field, while the streamlines representation describes the geometry and topology of the lines. All streamlines representations must have both an interpretation and a streamlines feature. As with all other representations in RESQML, properties may be attached to these representations. For example, in Figure 13-16, the streamlines property visualized is the “time of flight to the producer,” which indicates how quickly fluids drain from the reservoir. Although the streamlines appear to cross in the two dimensional field of view, they do not cross in three dimensions.

C.3.1 Streamlines and the RESQML Knowledge Hierarchy

The RESQML description of streamlines is based upon a streamlines feature, the generic feature interpretation, and a streamlines representation. They are related through the abstract feature and the abstract feature interpretation (**Figure 13-17**). Streamlines are an example of a technical feature.

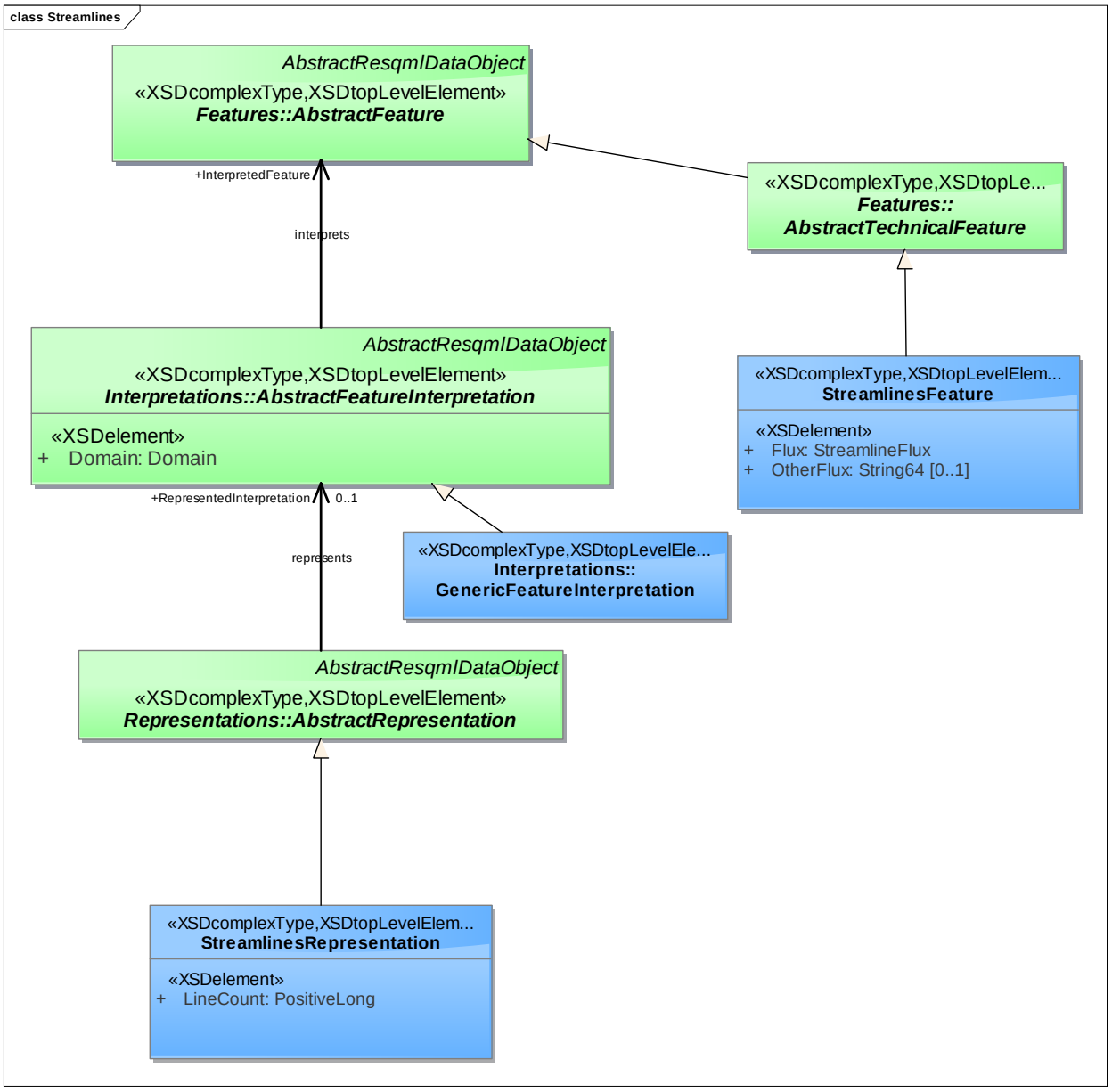


Figure 13-17— Streamlines feature, interpretation, and representation.

Although RESQML allows the relationship between representation and feature interpretation to be optional, for the streamlines representation, all data sets must include a generic feature interpretation and must include the streamlines feature.

C.3.2 Streamlines: Feature

The streamlines feature is used to describe the underlying vector field from which the streamlines are constructed (**Figure 13-18**). In a finite difference calculation, the vector field is projected and integrated onto the cross-sectional area of the grid cell faces to obtain a flux on that face. The streamlines feature describes that flux. In a streamline tracing algorithm, the vector field is reconstructed from the flux and interpolated within the cells of the grid. In most instances, the resulting trajectory geometry may then be obtained by analytic integration within each cell.

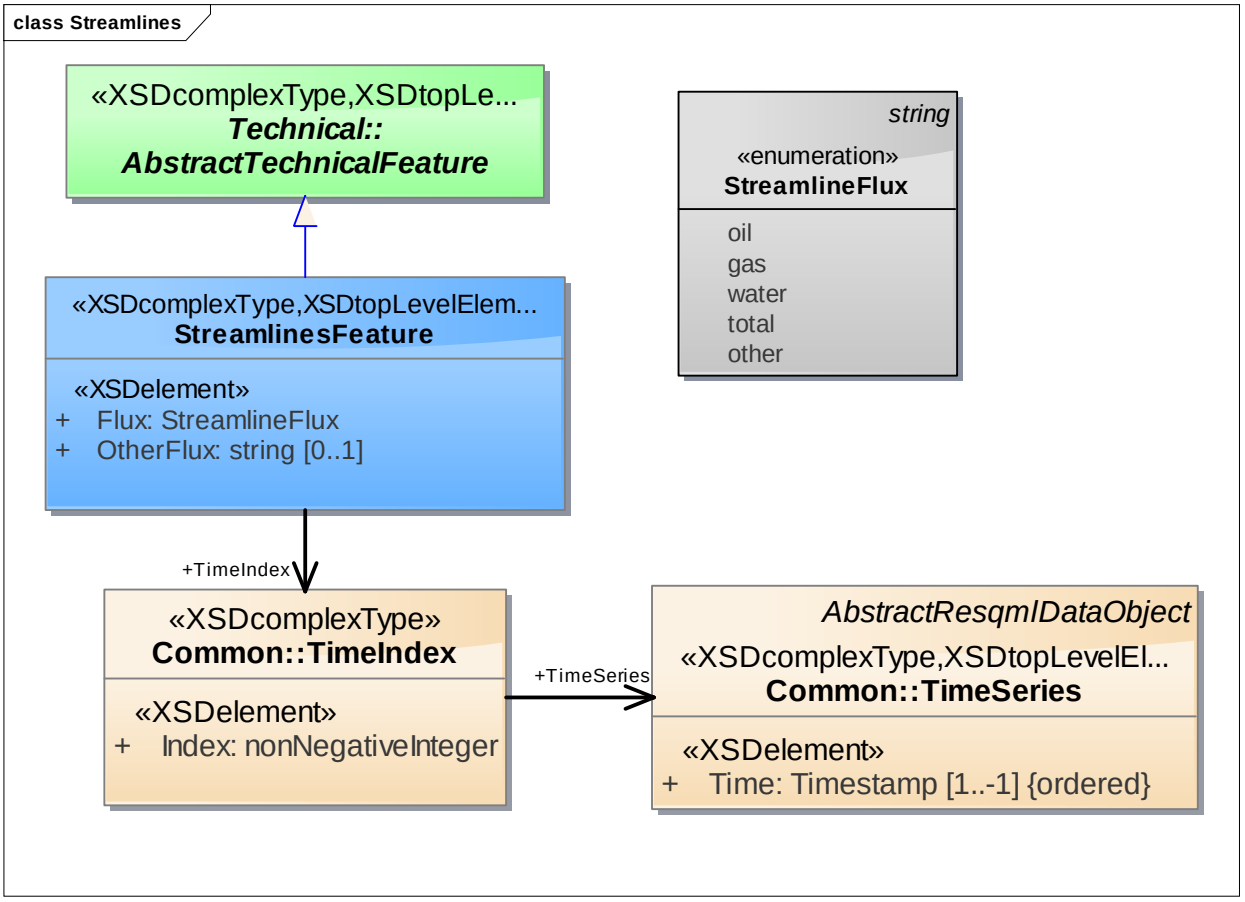


Figure 13-18—Streamlines feature.

C.3.2.1 Flux

The choice of flux type can be quite general. It is most common to sum the volumetric flux for all phases (streamline flux = total). However, we may also choose to generate streamlines for individual phases (streamline flux = oil, gas, or water) to visualize the flow of each phase. We may also choose to visualize the flow of individual components in a compositional simulation, or other fluxes, for instance, thermal. In these cases, the enumerated streamline flux should have the value of “other” and the optional “OtherFlux” element should be used to describe the flux. Other flux must only be used when the streamline flux is other. As the flux is time varying in reservoir simulation, the time index into a time series is mandatory. It is used to specify the time at which the flux is calculated and for which the streamlines are traced.

C.3.3 Streamlines: Interpretation

Streamlines use the RESQML feature/interpretation/representation knowledge hierarchy (**Figure 13-17**). For example, two representations of a specific velocity field that share a feature *and* an interpretation may differ in their spatial resolution, but they are expected to represent the same underlying velocity field. The most common example of this is where we may choose to construct the streamlines for a particular producer, e.g., locally at high density, and then again create a full field view of the streamlines in the reservoir with fairly uniform density. Two representations that share a streamlines feature but not an interpretation may differ in any number of ways. For example, they may have been developed from different realizations of properties in a subsurface model. In this case, they would have different but related velocity fields. Finally, two representations that do not share a streamlines feature object have no specific relationship to each other.

C.3.4 Streamlines: Representation

The streamlines representation is constructed from a number of optional objects which together support a variety of workflows (**Figure 13-19**).

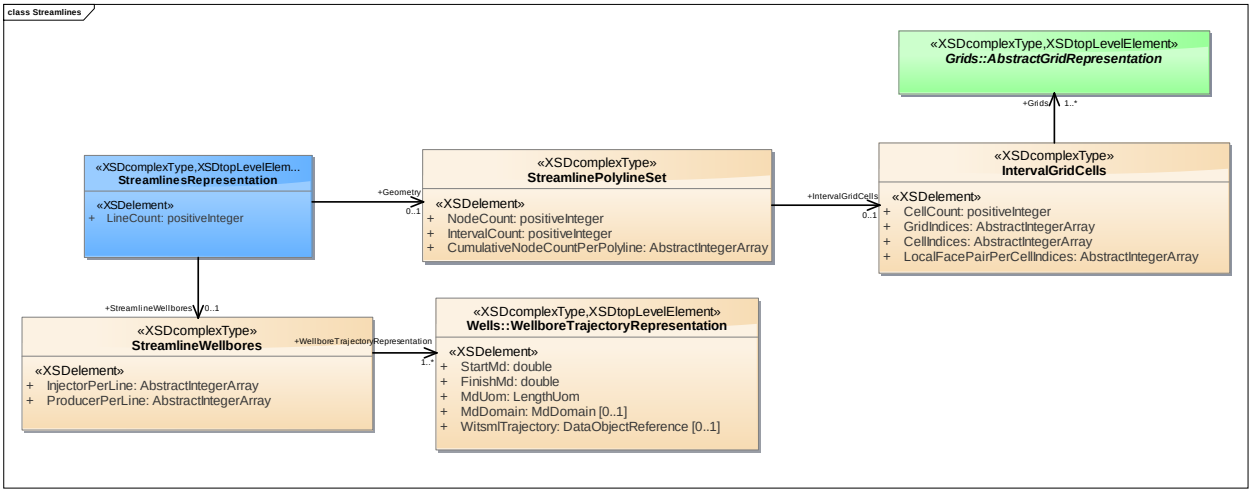


Figure 13-19—Streamlines representation.

C.3.4.1 Lines

The most basic representation has only a single mandatory element, which is simply a count of the number of streamlines. Streamlines use “lines” as their indexable element. The line index may be used to represent properties whose values do not vary along a streamline. For example, in **Figure 13-20**, each streamline takes on a different color based on the producer. These streamline bundles show the drainage volumes of each producer. Other examples of properties represented in this way are the flux injected or produced per streamline or the total time of flight between an injector and a producer.

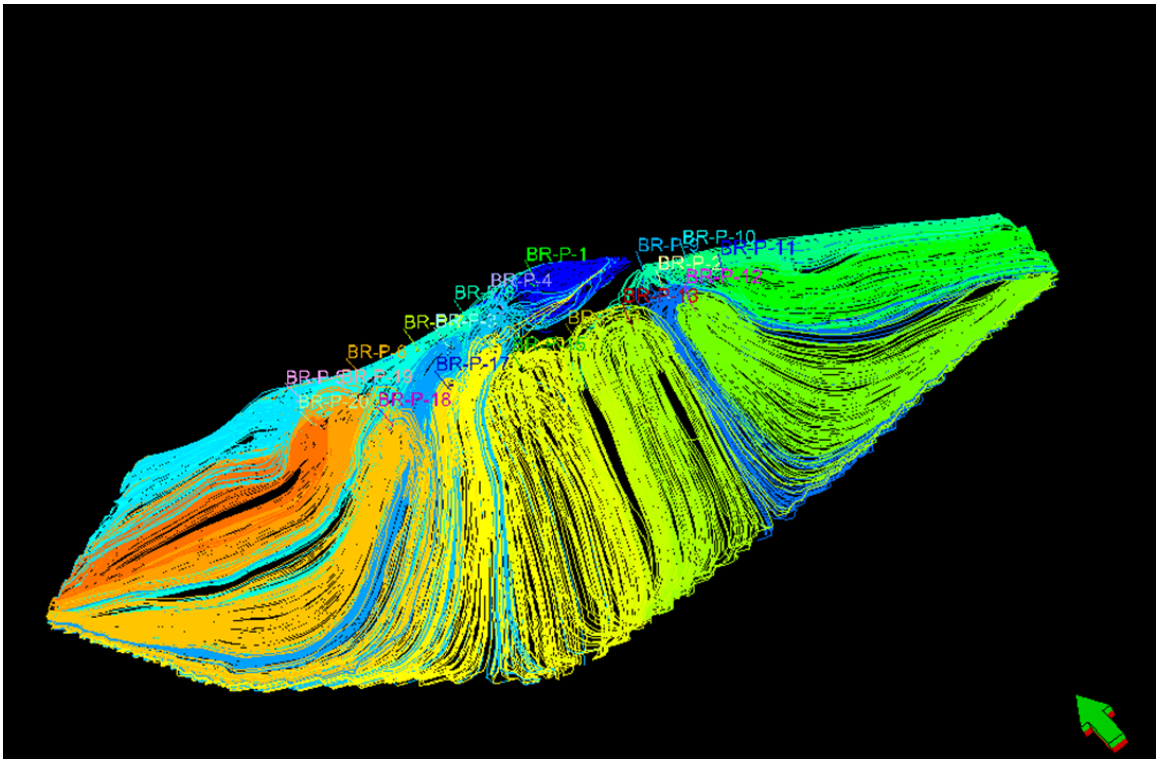


Figure 13-20—Streamline visualization of the drainage volumes of the producing wells in a reservoir.

C.3.4.2 Streamline Sources and Sinks

The streamline wellbores object is used to reference the injectors and producers. Streamlines may originate at an injector, along the boundary of a model, at an aquifer, or within the reservoir due to volume expansion. The injector per line element indicates the injector for each streamline, or takes on the null value. Similarly, the producer per line element indicates whether streamlines terminate at a producer, along the boundary of a model or within the reservoir near a stagnation area. 0-based wellbore indices are defined based upon the order in which a reference to the wellbore trajectory representation appears.

C.3.4.3 Streamline Geometry

The geometry of the streamlines is described using a polyline set. The indexable element type “nodes” is used to attach point geometry to the nodes of the polylines, with an explicit total node count. The polyline set usually consists of multiple polylines, and the node count per polyline array is used to differentiate each polyline within the set. The node indexable elements are used to store properties. As an example, the time of flight to producer displayed in **Figure 13-16.**

The indexable element type “intervals” is used to attach properties or otherwise reference the intervals within the polyline set. If N is the number of nodes on a polyline (N>1), then that line has N-1 intervals. The interval count in the polyline set is the total sum of intervals summed over the polylines.

C.3.4.4 Polyline Interval Grid Cells

The polyline set is used to describe the geometry of lines in space. For streamlines specifically, these lines have been developed based on an underlying computational grid. The relationship from line to grid is described using the interval grid cells object. The grid indices element is the most important, because it indicates which grid, if any, corresponds to each interval of the streamline polyline set. Nulls are used to indicate intervals that do not lie on any grid. Non-null grid values indicate that that interval is a cell.

The indexable element type “cells” is used to attach properties or otherwise reference those intervals with non-null grid indices. The cell count is specified explicitly and must be equal to the total count of intervals

with non-null grid indices. The remaining elements (cell indices array and local face pair per cell indices array) are used to further specify the spatial support of the streamlines on the cells of the grid(s).

C.3.5 References

Datta-Gupta, Akhil and King, Michael J. (2007). *Streamline Simulation: Theory and Practice*. SPE Textbook Series, Vol. 11.

Appendix D. HDF5 Implementation Overview

- For more information on how HDF5 is used with RESQML and the Energistics Packaging Convention, see 3.2.6.1 (page 31).
- For HDF5 conventions used with RESQML, see 6.2.2 (page 61).

The contents of a RESQML HDF5 file may be inspected using tools provided by the HDF Group or other third-party vendors. For example, the H5DUMP application lists the attributes, groups, datasets, and data found in an HDF5 file.

D.1 Adding HDF5 to your Code

HDF5 is provided as dynamic link libraries with a C-like application interface. You may add references to these DLLs directly using the C headers provided with the libraries. You may similarly link to these libraries in a .NET application using P/Invoke, or in a Java application using JNI.

A number of language-specific implementation layers are available on the HDF Group website. These implementations "wrap" the C interface, and they may provide a more intuitive way of accessing HDF5. These implementations vary in terms of the amount of the HDF5 API that is covered, and they may not be appropriate for advanced use of HDF5. However, RESQML requires only a subset of the HDF5 API, so you may find one of these implementations suitable for your development needs.

The rest of this appendix illustrates a number of typical RESQML HDF5 scenarios using the C API.

D.2 HDF5 Handles

The HDF5 API uses a handle-based pattern. This means that the typical programming scenario is as follows:

- Create or open an HDF5 element, such as a file or Dataset. HDF5 returns a handle of type *hid_t*.
- Interact with the HDF5 element using the handle.
- Close the handle using the appropriate "close" method. For example, you can close a file handle using the *H5Fclose* function.

In the examples below, the closing of handles is omitted for clarity.

D.3 Reading from a RESQML HDF5 File

Reading data from a RESQML HDF5 file involves a number of steps. This brief overview shows the key steps in this process, omitting details, such as error handling and handle closing, for clarity.

D.3.1 Reading from a RESQML HDF5 File

Reading data from an HDF5 file involves these steps:

(i) Open the file

(ii) Open the dataset and read the data

(iii) Close the file

- **Open a RESQML HDF5 File**

To open a RESQML HDF5 file, use the *H5Fopen* function from the H5F family of functions. Many options are available, but this example shows how to open a file for reading only.

```
hid_t FileID = H5Fopen(_FileNameH5F_ACC_RDONLY, H5P_DEFAULT);
```

- **Open a Dataset and Read Data**

Reading data from a Dataset involves a number of steps: (i) open the hierarchical groups containing the Dataset, (ii) open the Dataset, (iii) get the Dataspace information to determine the rank and dimensions of the data in the Dataset, (iv) read the data, and (v) close all the handles when done.

The path to the Dataset—including the groups it is contained in—is provided in the XML file. This path may be broken into group components, and each of these groups may be opened in turn. Alternatively, the complete path information may be passed to the dataset-opening function. This sample opens the dataset directly using the complete path information.

```
hid_t DatasetID = H5Dopen2(FileID, DatasetName, H5P_DEFAULT);
```

After the Dataset is open, you may query the Dataspace to get information on the rank and dimensions of the data. This information is usually also contained in the RESQML XML file, but you may still want to read it from the HDF5 file to verify the integrity of the file.

```
hid_t DataspaceID = H5Dget_space(DatasetID);
int ndims = H5Sget_simple_extent_ndims(DataspaceID);
if (ndims == ExpectedDimensionsRank)
  ndims = H5Sget_simple_extent_dims(DataspaceID, Dimensions, NULL);
```

Reading the data may be done all at once or in pieces called *hyperslabs*. Reading using hyperslabs can be more efficient in terms of memory usage, but for clarity the sample below reads all data into a memory buffer at once.

```
herr_t e = H5Dread(DatasetID, TypeID, H5S_ALL, H5S_ALL, H5P_DEFAULT, Buffer);
```

D.4 Writing Data to a RESQML HDF5 File

Writing data to a RESQML HDF5 file is similar to reading data from a file. You must create the appropriate types as before, and all handles must be closed when they are no longer required.

D.4.1 Enabling Compression

RESQML is designed to store large quantities of data, and HDF5 helps with this by compressing the data as it is saved to a file.

HDF5's implementation of compression provides the writer with a trade-off between compression efficiency and access speed for readers. It does this by splitting the data into fixed-sized "chunks" and compressing each chunk individually.

The larger a chunk is, the more efficient the compression will be. However, this efficient compression is at the cost of reading efficiency, because HDF5 needs to read and decompress into memory larger parts of the file to get at a particular part of the data.

Smaller chunks improve the reading efficiency of HDF5, because less data must be read and decompressed into memory to get at a particular part of the data. The downside to this is that the compression is less efficient and resulting file sizes will be larger.

When determining a chunk size to use, consider how the data will be accessed. For example, a likely use case for applications reading explicit grids is to extract only particular layers out of the data using hyperslabbing. A chunking setup that supports this scenario is to make a chunk for each layer. This approach makes accessing the data a layer at a time maximally efficient, while still giving HDF5 a large enough block of data to compress.

Enabling compression involves creating an HDF5 Parameter that is used when creating a Dataset. This parameter contains the size of the chunk and the compression properties.

```
hid_t DatasetParameterID = H5Pcreate(H5P_DATASET_CREATE);
if (DatasetParameterID > 0)
{
  herr_t e = H5Pset_chunk(DatasetParameterID, ChunkRank, ChunkDimensions);
  e = H5Pset_deflate(DatasetParameterID, 1);
}
```

D.4.2 Creating the Groups that Contain the Dataset

Groups are handled slightly differently when writing to a file: HDF5 does not create groups automatically when a Dataset path is supplied. Your application must do one of the following:

- If a group doesn't yet exist, explicitly create each group.
- If a group does exist, open it before creating the dataset.

With the current HDF5 format, only two groups are required:

- The top-level RESQML group.
- A group for the object being stored, which has the object's GUID as its name.

The top-level group is created using the FileID:

```
hid_t RESQMLGroup = H5Gcreate2(FileID, "RESQML", H5P_DEFAULT, H5P_DEFAULT,
H5P_DEFAULT);
```

The object group is created using the RESQMLGroupID:

```
hid_t ObjectGroupID = H5Gcreate2(RESQMLGroup, ObjectGuidString, H5P_DEFAULT,
H5P_DEFAULT, H5P_DEFAULT);
```

Remember to close these IDs when you are finished with them.

D.4.3 Creating the Dataspace

The Dataspace tells HDF5 how much data is to be stored and how it is configured in terms of rank and dimensions.

```
hsize_t Dimensions[Rank];
Dimensions[0] = Length0;
//Etc.
hid_t DataspaceID = H5Screate_simple(Rank, Dimensions, NULL);
```

D.4.4 Creating the Dataset

The Dataset is created using the ObjectGroupID, the DataspaceID, the DatasetCompressionParameter, and the Dataset name.

```
hid_t DatasetID = H5Dcreate2(ObjectGroupID, DatasetName, TypeID, DataspaceID,
H5P_DEFAULT, DatasetParameterID, H5P_DEFAULT);
```

D.4.5 Writing the Data

Writing of the data to the Dataset is done using the DatasetID the TypeID of the data being stored, and a pointer to the data buffer. Hyperslabbing may be used to write the data a portion at a time.

```
herr_t e = H5Dwrite(DatasetID, TypeID, H5S_ALL, H5S_ALL, H5P_DEFAULT, Buffer);
```