NGMDB Geologic Map Feature Class Model

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BACKGROUND

This document describes the spatial data feature classes in the prototype design for the National Geologic Map Database project (NGMDB; http://ngmdb.usgs.gov). The implementation of thematic data table in the NGMDB prototype is described in a separate document (Richard et al., 2004). The design presented here has been submitted as an ESRI geology data model, and is available from the ESRI support web site (see http://support.esri.com/index.cfm? fa=downloads.dataModels.filteredGateway&dmid=30, and find the NGMDB database design documents link).

Geoscience entities of interest

As a precursor to defining feature datasets and feature classes in an ESRI geodatabase, this section enumerates the geologic entities of interest and the spatial relationships between them. The term "entity" is used here to denote phenomena of interest observed in the 'real world', as opposed to features, which are the database objects implemented to represent our understanding of those phenomena. A feature in ESRI geodatabase usage is explicitly required to have a geometry property that specifies a location and shape. This discussion uses terminology and basic definitions from the NADM C1 model (NADMSC, 2004).

Geologists are concerned with the three dimensional arrangement of material within the Earth. The entities of interest are bodies of material (geologic units) and surfaces that bound or cut them (geologic surfaces). The 2-D map view that is the framework for a GIS represents the geometry of the intersection of these entities with some map horizon—typically the Earth's surface, but possibly some abstract surface like a mine-level, cross section surface, or some buried surface (e.g. top of Precambrian rock). The basic features that may be implemented in a 2 (or 2.5)-D GIS are points, lines, and polygons (and composite features aggregated from these simple features). Points represent the intersection of a line with the map horizon (e.g. a borehole collar), or an observation location on the map horizon (a station). Lines represent the intersection of a surface with the map horizon (surface trace), the projection of some buried line beneath the map horizon (e.g. the cutoff of a contact at a fault, an inclined borehole, a channel axis), or a line defined within the map horizon (e.g. sand dune crest, geomorphic escarpment). Polygons represent one of several situations, including the intersection of bodies with the map horizon (i.e. the outcrop of geologic units), patches defined on the map horizon, the projection of patches on a surface other than the map horizon into the map plane, or the projection of 3-D bodies that do not intersect the map horizon into the map plane.

The following discussion elaborates on this basic framework to define the entities of interest that need to be mapped into feature classes, feature datasets, and topology rules in an ESRI geodatabase implementation.

- **Genetic boundary surface**. Boundaries of geologic units related to the genesis of the unit. Includes depositional contacts, facies changes (in igneous, sedimentary or metamorphic rocks…), and intrusive contacts. Genetic boundaries are surfaces that are either truncated by other younger genetic boundary surfaces, by faults, or by the Earth surface. The identity of a genetic boundary surface is associated with the identity of one of the geologic units juxtaposed at the surface, for example 'base of Escabrosa Limestone', 'boundary of fine-grained facies of Oracle granite', 'top of Cambrian strata'.
- **Fault**. A surface across which there has been shear displacement significant at the scale of observation. Fault surfaces are truncated by younger genetic boundary surfaces, other faults, or by the Earth surface. Fault surfaces may also end because fault displacement may decrease to the point that the fault is no longer identifiable/mappable. Identity of a fault surface is defined by physical continuity at the time the fault is active. Inactive faults that are truncated by younger faults may have segments defined by continuity between truncating faults; these are correlated with other segments based on interpretation of movement history (timing, direction, and magnitude of displacement). Active faults may have discrete segments, separated by recognizable boundaries, which tend to rupture independently. Groups of faults may be interpreted to operate together as a fault system considered to be a single tectonic entity.
- **Fold hinge surface**. A surface defined as the locus of points that occupy the hinge of a single fold structure; the surface itself does not necessarily have a material manifestation, but is locatable. Fold hinge surfaces are truncated at younger genetic boundary surfaces, faults, or the Earth surface, or may terminate where a fold loses definition. Identity is defined by physical continuity of the hinge surface at the time of fold formation.
- **Geologic unit**. An identifiable part of the earth based on some geologic criteria. Typically, a body of material (rock or nonconsolidated). Identity criteria are variable; ideally defined by lithologic properties, but may be defined by identity of bounding surfaces, or interpreted properties like age, depositional environment, alteration history, or P-T conditions. Geologic units are bounded by genetic boundary surfaces, by faults, or by the Earth surface. They are grouped in various part-hierarchies used at different levels of generalization (e.g. member, formation, group, supergroup).
- **Dike**. A geologic unit of igneous origin that is very thin relative to its lateral extent. This generalized definition does not consider relationship to layering of host rock or orientation of body because dikes and sills are depicted the same way on maps. In detail, a dike has two genetic boundary surfaces (one on each side) but, in general, dikes are considered as a surface-like entity. Identity of an individual dike is defined by physical continuity at time of formation, but groups of dikes are typically classified as a unit based on lithology and interpretation of a single magmatic source. Dikes are truncated at genetic boundaries, faults, or the Earth surface, or may simply end where the intruded crack ends.
- **Vein**. Similar to dike, but groups of veins are classified into units based on lithology and interpreted relationship to hydrothermal events.
- **Escarpment**. Abrupt change of slope (from more gentle to very steep) on the Earth surface (exposed or buried), related to erosional or tectonic processes. Fault scarps are coincident with a fault. Identity based on physical continuity. Scarps are classified based on interpreted history.
- **Fissure**. A crack in the earth's surface, generally with dilatational deformation. Fissures may be: 1) intrabasinal in active sedimentary basins, related to desiccation, ground water withdrawal, or compaction, 2) surface collapse due to subsurface dissolution (evaporite or karst), or 3) related to slope failure.
- **Borehole**. A human-engineered hole drilled into the earth to obtain subsurface resources or information. Has an associated point (collar) from which the hole was drilled, typically the Earth surface, but may be a subsurface point from an underground mine or other working. Multiple boreholes may be associated with a single collar location. Identity of a bore hole is defined by a single 'drilling event'. Boreholes may be reentered to drill deeper or to produce a new borehole (sidetrack).
- **Station**. A point location at which data or samples were acquired. Identity defined by observer who locates the station. Stations are not necessarily associated with any particular identifying phenomenon. It is simply where the geologist stopped to measure bedding, record some observations, or perhaps take a picture. A station has a 3-D location that may be inherent in its association with a map horizon (e.g. X,Y coordinated on Earth surface), or borehole (location reported by depth below collar), or explicitly recorded as an XYZ coordinate (a location in an underground mine).

GEODATABASE FEATURE CLASSES

Table 1 summarizes ESRI geodatabase feature classes used to specify location in the NGMDB implementation. All spatial data tables include fields to specify a default text label and symbol to use in map displays if no other symbolization is specified. This is to simplify the rapid display of spatial data. OutcropBoundaryTrace and GeologicUnitOutcrop are line and polygon feature classes whose locations represent observable geologic phenomena in or on the Earth. Station is a point feature class that specifies a location at which observations were made, and does not (inherently) represent the location of some phenomena. The term observation is used in the

Table 1. Location specification tables.

Table	Description
OutcropBoundaryTrace	Line features that represent the intersection of geologic surface that bounds mapped rock bodies with the depicted map horizon. Subtypes include fault and geneticBoundary. These traces may bound GeologicUnitOutcrop polygons.
DikeVeinMarkerTrace	Line features that represent the intersection of a dike, vein, or marker bed with the depicted map horizon; subtypes differentiate these cases.
HingeSurfaceTrace	Line features that represent the intersection of the hinge surface of a fold with the depicted map horizon.
EarthFissureTrace	Line feature that represents a fissure in the depicted map horizon.
ConcealedBoundaryTrace	Line feature that represents the trace of a geologic surface in a map horizon different from the depicted map horizon. Subtypes include concealed faults and genetic boundaries, and structure contours.
GeologicUnitOutcrop	Polygons representing the intersection of a geologic unit with the map horizon.
Station	Point location at which one or more observations are made, or samples are collected.
BoreholeCollar	Point location at which a borehole section intersects a map horizon (typically the Earth surface).

sense of GML Observation and Measurement (Cox et al., 2004). These feature classes are organized according to their semantics, associated properties, and implementation issues for using topology rules in the ESRI geodatabase environment.

Notes on schema notation and implementation

The schema included in this paper use a UML profile defined by ESRI to build UML models for geodatabase physical implementation using CASE tools. Classes with names in *italics* represent abstract classes, i.e. there is no feature class in the geodatabase with the same name. Attributes of abstract classes are included in all subtype classes. UML subtype links have an open triangle at the parent class end of the link. Attributes in the UML classes represent fields in the geodatabase tables. In the models here, attribute names that end in 'GUID' represent database fields populated by 36-character string GUIDs (Globally Unique IDentifiers). ESRI geodatabase subtypes are linked to their parent class (which represents the physical table implemented in the database) using dashed lines. ESRI subtypes represent subsets of records in a particular relational database table that are differentiated based on an integer value in one of the fields identified as the 'subtype' field. In the NGMDB implementation, ESRI subtype field names always begin with a prefix "ESRI-Subtype". The undecorated solid lines linking classes in the diagrams represent associations implemented as ESRI relationship classes in the geodatabase. These associations are navigable in the ArcMap attribute browser.

Figure 1 shows the top level hierarchy of feature classes in the geodatabase implementation model. The ESRIClasses::Feature and *NGMDBFeature* classes define fields shared by all spatial data classes (see Richard et al., 2004 for discussion of standard NGMDB fields). The feature classes are divided into broad groups represented by abstract classes beneath *NGMDBFeature* in Figure 1. *ObservationLocation* represents features located based on human, observation factors—e.g. where access is possible, what part of a mountain could actually be seen, where the airplane flew. Their location is typically related to geologic phenomena of interest, but their location is not determined by the location of the phenomena. *MappedOccurrence* includes features whose location is determined by phenomena inherent in the earth—contacts between rock bodies, fault zones, fold hinges, etc. *GeologicRoute* features aggregate *MappedOccurrences* that are interpreted to represent the traces of extended geologic surfaces identified based on multiple observations. *AnnotationFeatures* position annotation in map displays. The location of these features is related to a *MappedOccurrence* or *ObservationLocation*, but the actual positioning is determined by cartographic considerations. BoreHoleCollar is in a sense a sort of *MappedOccurrence*, but because the properties of interest are different, they have been implemented as a distinct feature class. The following discussion first treats the subtypes of *MappedOccurrence*, followed by *GeologicRoutes*, *ObservationLocations*, and *AnnotationFeatures.*

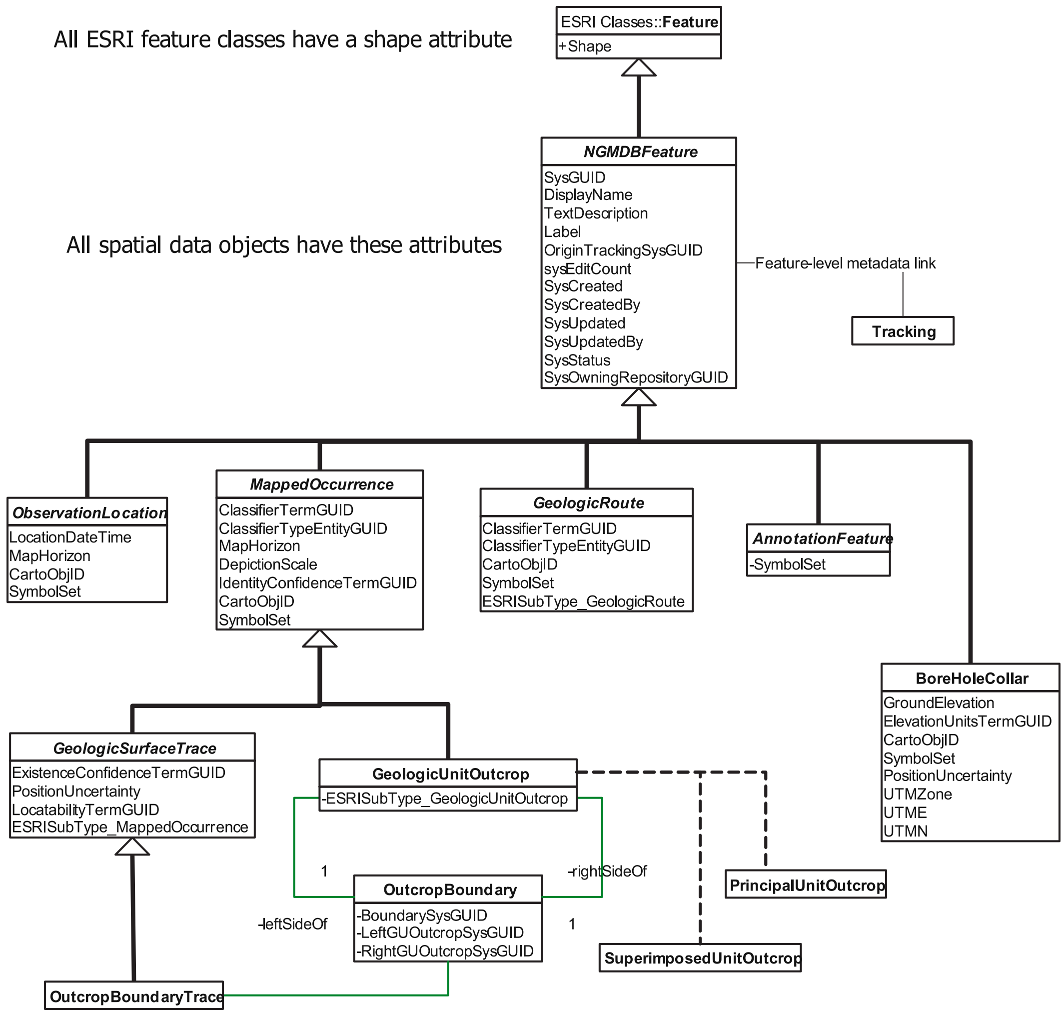

Figure 1. Top level features in the NGMDB implementation. GeologicUnitOutcrop polygons are associated with bounding OutcropBoundaryTrace arcs (LPoly and RPoly of Arc/Info coverages) explicitly through the OutcropBoundary correlation table. PrincipalUnitOutcrop and SuperimposedUnitOutcrop are ESRI subtypes of GeologicUnitOutcrop, discriminated using the ESRISubtype_GeologicUnitOutcrop field. See Figure 3 for some other MappedOccurrence subtypes.

Surface traces

Surface traces are the lines in a GIS that represent intersection of 3-D surfaces with a map horizon. Thus a surface trace always has an explicit or implicit defining map horizon (MapHorizon in *MappedOccurrence*, Figure 1), and a classifier that specifies the kind of surface that intersects the map horizon to form the trace. The surface trace has associated location uncertainty related to how discretely the mapped surface may be located (e.g. sharp or gradational contact), how precisely the location can be determined (good or poor exposure), and how accurately that location can be specified in map coordinates (Figure 2).

Surface traces that are in the depicted map horizon

A geologic map is assumed to portray surface traces and outcrops on some particular map horizon. The depicted map horizon may be different in different parts of the map. For example the current Earth surface may be the map horizon except in the area of a large mine, where the pre-mining surface may be depicted. All of these surface trace types may have elevation values (Z values in geodatabase) associated with vertices along the trace; these elevations represent the elevation of the map horizon.

- **OutcropBoundaryTrace**. This feature class contains

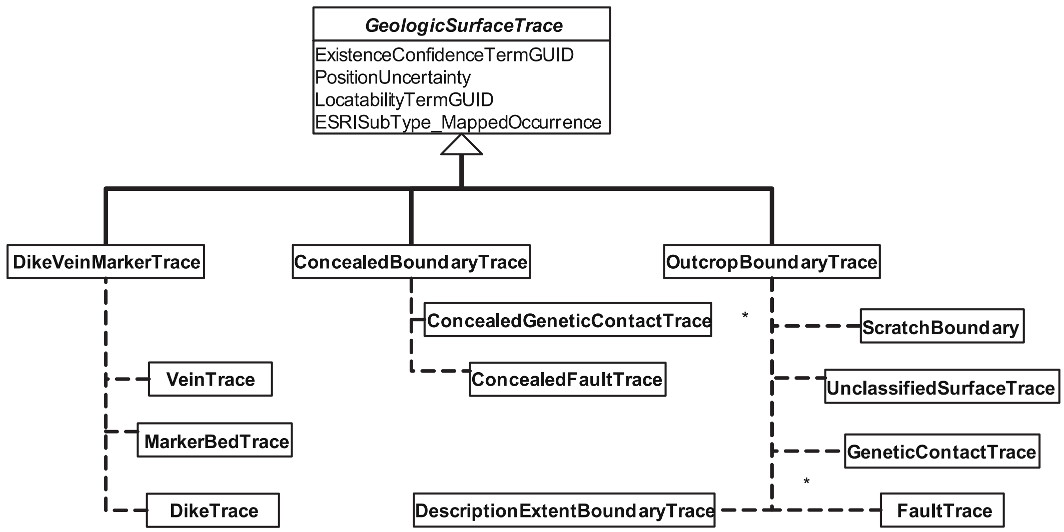

Figure 2. Geologic surface trace feature classes. These feature classes represent the intersection of geologic surfaces with a map horizon. The OutcropBoundaryTrace features participate in polygon topology with the GeologicUnitOutcrop.PrimaryUnitOutcrop features (Figure 1).

surface traces that participate in topologic rules between polygons and the geologic surface traces that bound them. Subtypes identify two broad categories (Figure 2):

- ◦ GeneticSurfaceTrace. Represents intersection of genetic boundary surface with a map horizon. Classifier term property identifies different kinds of geologic body boundaries (intrusive contact, depositional contact, facies boundary, etc.) using terms from a controlled vocabulary (see Vocabulary tables, above). Topologic constraints: no dangles—must connect to other genetic contacts or to faults. No self intersection, may self connect (to form closed loop). GeneticSurfaceTrace may not intersect FaultTrace or GeneticSurfaceTrace (one or the other must be younger, and break the older surface trace). GeneticSurfaceTrace may not intersect VeinTrace or DikeTrace (one or the other must be younger, and break the older surface trace), but may be covered by DikeTrace or VeinTrace where the dike or vein is intruded along the contact. Genetic contacts must be covered by the boundary of a geologic unit polygon.
- ◦ FaultTrace. Represents intersection of a fault surface with a map horizon. Classifier term property identifies different kinds of faults (thrust fault, normal fault, strike slip fault, detachment fault, etc.) using terms from a controlled vocabulary. Topologic constraints: dangles allowed, no self intersection, may self connect (to form closed loop – e.g. window through flat fault). FaultTrace may not intersect FaultTrace or GeneticSurfaceTrace (one or the other must be younger, and break the older surface trace). FaultTrace may not intersect VeinTrace or DikeTrace (one or the other must be younger, and break the older surface trace), but may be covered by DikeTrace or VeinTrace where the dike or vein is intruded along the fault. Has Z—determined by elevations on map horizon. Faults may cover the boundaries of outcrop polygons.

- **DikeVeinMarkerTrace**. Represents intersection of a dike, vein, or marker bed, considered as a surface, with a map horizon. Concealed traces are depicted using the same feature class. Subtypes differentiate dike trace, vein trace, and marker trace. Same rules as FaultTrace.
- **HingeSurfaceTrace** (Figure 3). Represents intersection of a fold hinge surface with a map horizon. Concealed traces are depicted using the same feature class. Topological constraints: dangles allowed, must not self intersect, may self connect (trace of recumbent fold on steep terrain). May intersect GeneticSurfaceTrace, FaultTrace, DikeTrace, VeinTrace (where the surface represented by the trace is folded).
- **EarthFissureTrace** (Figure 3). Represents intersection of a fissure with the map horizon. Must not self intersect.
- **GeomorphicFeatureTrace** (Figure 3). Lines representing the trace of a linear feature defined by the morphology of the map horizon surface. Subtypes identify various kinds with different topology rules and associated classifier/symbol domains.
  - ◦ Escarpment. Line representing the uphill edge of a geomorphic escarpment; line physically resides in a map horizon (e.g. Earth surface, top of bedrock). Topology rules: must not self intersect.
  - ◦ FaultScarp. Line representing the uphill edge of

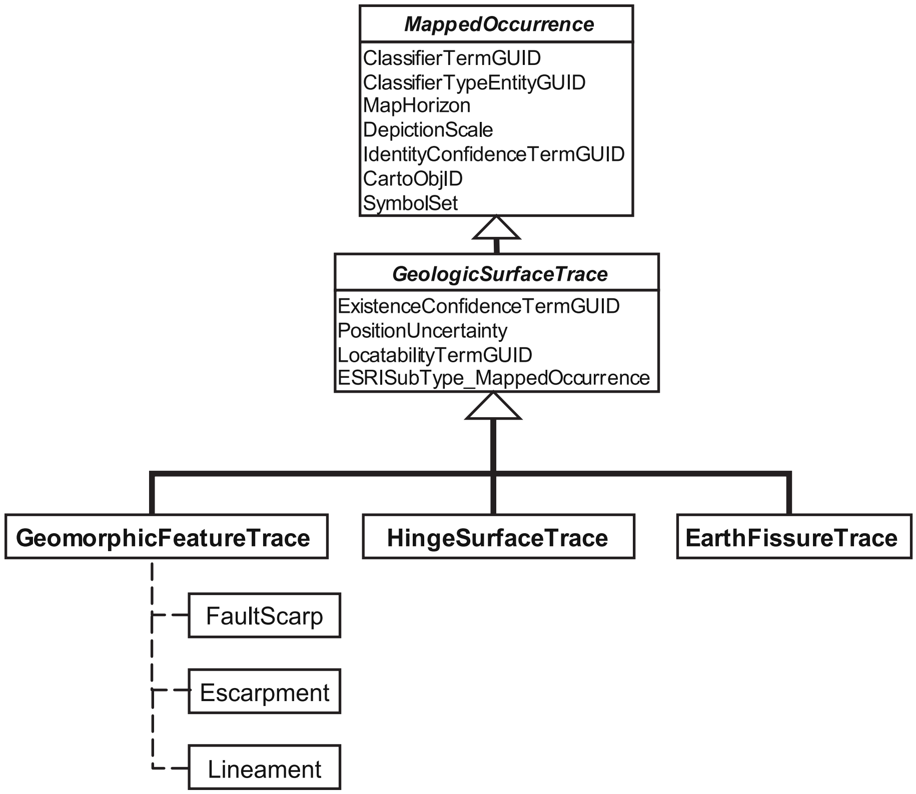

Figure 3. Other mapped occurrence feature classes. These are less frequently encountered mapped occurrences not shown in Figure 1.

a fault scarp. Topology rules: must be covered by FaultTrace or Concealed FaultTrace.
- ◦ Lineament. Line representing a geomorphically expressed lineament of uncertain nature.

Surface traces not in the depicted map horizon

- **ConcealedBoundaryTrace**. This feature class contains mapped features that represent traces that do not participate in topologic rules between polygons and the geologic surface traces that bound them (outcrop boundary traces). Subtypes identify three categories (Figure 2):
  - ◦ Concealed GeneticSurfaceTrace. Dotted contacts on geologic maps are used in different ways:
  - ◦ To represent the trace of a genetic boundary surface on a buried map horizon (e.g. top of bedrock beneath Quaternary cover).
  - ◦ To connect GeneticSurfaceTraces of surfaces that have been intruded by igneous rocks, and thus have no associated map horizon—they are purely to indicate inferred pre-intrusion continuity of some surface.
  - ◦ To show genetic boundaries on a pre-existing but related map horizon, for example the location of an active river channel based on several generations of air photos.

In either case the topology rules are similar: may not self intersect, no dangles. Concealed GeneticSurfaceTraces are not required to be covered by the boundary of a GeologicUnitOutcrop—they do not participate in geologic unit polygon topology on the map horizon depicted. Concealed GeneticSurfaceTraces may intersect other GeneticSurfaceTraces (e.g. boundaries of mapped covering geologic unit outcrops), but may not intersect FaultTrace, DikeTrace, VeinTrace or Concealed GeneticSurfaceTrace, Concealed FaultTrace, Concealed DikeTrace or Concealed VeinTrace.
  - ◦ Concealed FaultTrace. Trace of a buried fault or connection of intruded fault (see Concealed GeneticSurfaceTrace, above). Rules same as for FaultTrace, except Concealed FaultTrace may intersect GeneticSurfaceTrace.
  - ◦ StructureContour. The trace of a geologic surface on a horizontal surface of some given elevation. This is essentially an abstract map horizon, and the StructureContour is a surface trace on that horizontal map horizon. Thus, structure contours may be modeled as concealed surface traces with the contour elevation identified by the map horizon property of the trace , or using the Z values for the line in the geodatabase feature class. Structure contour maps contrast with other geologic maps in that they do not portray a

single map horizon, but rather display surface traces from a collection of map horizons in a single portrayal. Topology rules: must not self intersect.

Outcrop

Outcrop is used here in the very specific sense of the intersection between a geologic unit and a map horizon, whether or not the geologic unit is exposed on that horizon. The term exposure is used to refer to places where the geologic unit is visible on the map horizon. Outcrops are represented by polygons in the GIS. An outcrop always has an explicit or implicit defining map horizon, and a classifier that specifies the geologic unit that intersects the map horizon to form the outcrop.

- **GeologicUnitOutcrop** (Figure 1). Polygon that represents the outcrop of a geologic unit. Topology rules: boundary must be covered by GeneticSurfaceTrace or by FaultTrace on same map horizon. Must not overlap other GeologicUnitOutcrop on same map horizon. Must not have gaps (map horizon must be covered over the extent of the map). Subtypes:

    - PrincipalUnitOutcrop. Outcrops of units of principal interest.
    - SuperimposedUnitOutcrop. Polygon representing outcrop of a geologic unit superimposed on the principal mapped units, for example alteration zones, zones of crushing, metamorphic zones. These outcrops are on the same map horizon as the associated principalUnitOutcrop. Overlaps between these intersections of contacts must be treated as topology rule exceptions. If there are a sufficient number of superimposed unit outcrop polygons, a new GeologicUnit FeatureDataset should be created with its own lines, polys, and topology rules.

Routes

Collections of surface traces classified to belong to a single 'broader' classification entity. The individual surface trace instances in the SurfaceTrace feature classes are differentiated based on their classification (depositional contact, thrust fault, intrusive contact, facies boundary…), and observation-related properties (classification confidence, location confidence, observer, depiction scale, observation method…). These may be considered together to represent the trace of some geologic entity. These aggregated features are treated separately from the MappedOccurrences because they are fundamentally interpretive, and have different metadata properties.

- **Fault routes** (Figure 4). Fault arcs (individual surface trace instances) may be aggregated to form fault segments or faults, and these may be further aggregated into fault systems of different scales. Fault segments are outcrop traces of fault surfaces bounded by their intersection with other fault surfaces or genetic contact surfaces. Faults are aggregations of fault segments, fault systems are aggregations of faults. Topology rules (using fault as example): segments must be covered by surface trace instances, faults must be covered by fault segments, fault system must be covered by faults. In this context 'covered' means that there must one or more coincident data instances in the covering feature class that together completely match the covered class. Fault segments may not intersect or overlap. No self intersections.
- **Fold routes** (Figure 4). Similar to fault route, individual folds, fold systems (anticlinorium, synclinorium…).
- **Contact route** (Figure 4). Similar to fault route— represents outcrop of a particular geologic boundary surface.

Observation location features

Observation location features have geometry that records the location at which some data or sample was collected. The NGMDB implementation allows structural measurements, text notes, images, and samples to be associated with observation locations. Stations are point features that locate observation sites, SectionLine lines and AreaOfInterest polygons represent extended observation sites. SectionLines may represent traverses, which are observation sites located in the depicted MapHorizon. BoreHoleProjection and FlightlineGroundTracks represent observation sections that do not lie in the depicted map horizon; they are projected into the map plane to depict in a 2-D image. The implementation revolves around the concept of an observation section as a linear analog of a map horizon surface. The observation section is a line in three dimensional space that provides a reference frame in which three dimensional points may be located using a single coordinate, measured along the observation section line from some defined origin (e.g. depth below kelly bushing in a bore hole). In the NGMDB implementation, this reference frame is described informally (as text) in the CoordinateReferenceSystem field (*ObservationSection*, Figure 5).

- **Station**. Point represents an observation location. Has related structural measurements, text notes, images, samples…
- **SectionLine**. Line features that depict 3-D section line in a 2-dimensional (or 2.5-D if they have Z values associated with vertices along their length) view. Each subtype of SectionLine has an associated geodatabase object class that represents the full, three dimensional observation section. FlightlineGoundPath is the vertical projection of a flight line down to the map horizon. TraverseTrace is the trace of a surface traverse in the map horizon. BoreholeProjection is the vertical projection from a borehole to the map horizon.
- **AreaOfInterest**. Polygons that associate observation

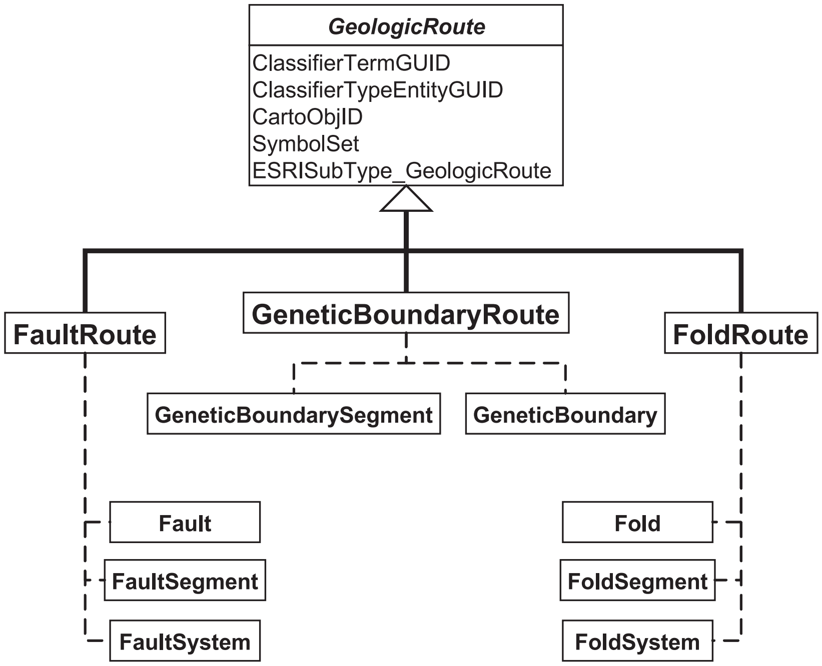

Figure 4. Geologic route feature classes. These feature classes are used to aggregate line segments (arcs) differentiated based on observation-related properties (information source, locatability, location uncertainty) into traces of surfaces that have identity and are bounded by intersection with other surfaces (Fault, Fold). These may then be aggregated into systems that represent compound structures that include multiple faults or folds.

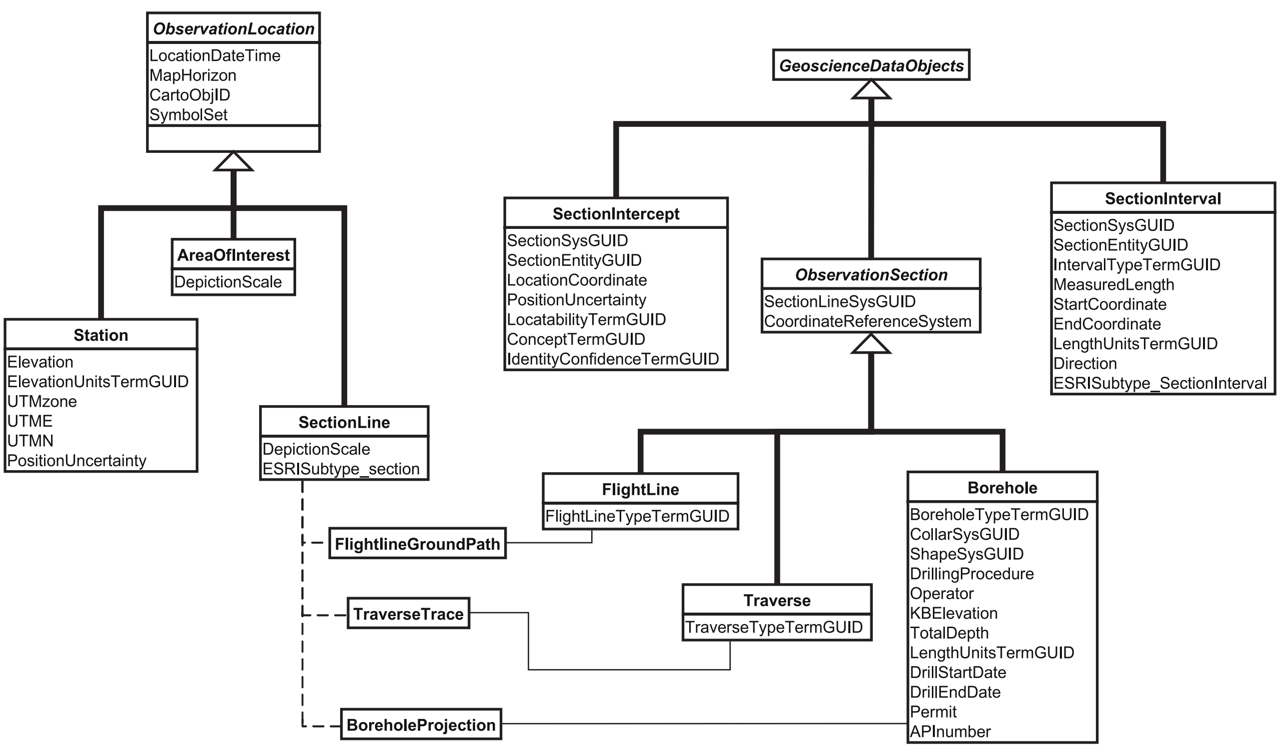

Figure 5. Observation location features. These (the classes on the left side of the diagram) are mapped features that have geometry that records the location at which some data or sample was collected. Stations are point features that locate observation sites. AreaOfInterest polygons represent an extended observation site in some map horizon. SectionLine lines are the projection of 3-D observation sections into a map horizon.

data with some area, for instance to represent that a bedding orientation value or some particular weathering character is consistent over some outcrop area.

Borehole Representation

Figure 6 shows the principal geodatabase object classes associated with BoreHoleCollar points to construct a representation of subsurface geologic information derived from boreholes. This model uses the same pattern to represent data from surface traverses (e.g. measured sections), and flight lines (or ship tracks…), but only the treatment of borehole sections is discussed here.

- **BoreholeCollar**. Point represents collar location from which a borehole was drilled. Generally is intersection of borehole with the Earth surface. Has one or more associated borehole object(s), which are not geodatabase feature classes.

One or more boreholes may be associated with a single BoreHoleCollar point, because a collar may be reentered to drill a splay or side track, which is considered a separate borehole. Individual boreholes (or any observation sections) have collections of associated intervals (SectionInterval table) and intercepts (SectionIntercept table) that may have associated description data. Intervals have a top and bottom, and represent rock volumes, while intercepts have a single coordinate location in the observation section, and represent the intersection of a surface with the section, or a point location in the earth. The NGMDB implementation allows classification of an interval (or an intercept, link not shown in Figure 6) through an ObservationRelationship instance, analogous to mapped occurrence alternative classification (Figure 7). This allows assignment of intervals to geologic units, lithology classes, or any other sort of classification (e.g. aquifer), and association of intercepts with multiple surface classifications. StructureObservation (orientation) data, free text descriptions, and samples may also be associated with intervals or intercepts.

Classification And Descriptions Associated With Features

The NGMDB implementation includes a link to a classifier term in each geodatabase feature class for MappedOccurrences (Figure 1). This primary classification records the original intention with which the mapped feature was delineated, and is thus considered to inhere more strongly with the geometric description than other possible classifications. For GeologicUnitOutcrops, the default or primary classifier will be a GeologicUnit term. Outcrop trace and observation features will typically be classified using terms from a science vocabulary (ScienceLanguage table). Alternative classifications are used for derivative maps or analytical processes, and are produced by grouping the primary classifiers to define a different classification scheme. Such derivative or alternative classifications are represented using classification-typed data instances in the ObservationRelationship correlation table (Figure 7).

Any of the various kinds of descriptions implemented in the NGMDB database may have an associated feature that specifies a geographic extent over which the properties in the description are asserted to hold (Figures 8-10). The feature assigned as the extent for a description may be an ObservationLocation feature or any of the various MappedOccurrences.

Annotation

These are locations in a map view used to position graphical elements for cartographic display. The location of the symbol is related to some geologic feature, but its actual positioning is based on cartographic consideration. In the ArcMap v.9 implementation, annotation that is a text string used to provide supplemental information for spatial objects (point, line, polygon) is best represented using feature-linked annotation feature classes that are built into the Geodatabase. For symbols that are located by points, and identified by a symbol identifier (CartoObjID), the implementation includes a PointAnnotationFeature class. This is subtyped for different kinds of annotation based on relationships to other feature classes.

- **MapAnnotationPointAnno**. Text label indicates dip or plunge value of linked StrikeDip symbol, fault dip symbol, contact dip symbol, or hinge surface orientation symbol. ESRI annotation feature class, related to MapAnnotationPoint features.
- **GeologicUnitOutcropAnno**. Text label annotation. Text string, value is linked to label field in GeologicUnitOutcrop. ESRI annotation feature class.
- **MapAnnotationPoint**
    - StrikeDipPoint. Point feature that positions symbols representing orientation measurements not associated with a surface trace (may cover a Station feature). Has associated structural observation data (not a geodatabase feature class). StructureObservation instances are located by association with a station; this is a one (station) to many (observations) association, and the station may have many other related data objects (samples, images, text notes, physical property measurements). Positioning of the symbol on the map is dictated by cartographic considerations in addition to the actual location at which the measurement was made. Symbol rotates according to value in azimuth field, and has dip or plunge value text label from the label field in the associated structural observation. In the database the symbol information is maintained separately from the location of the station data. Has linked dip (or plunge) label text. See the cluster of three measurements made in the Xp (Pinal Schist)

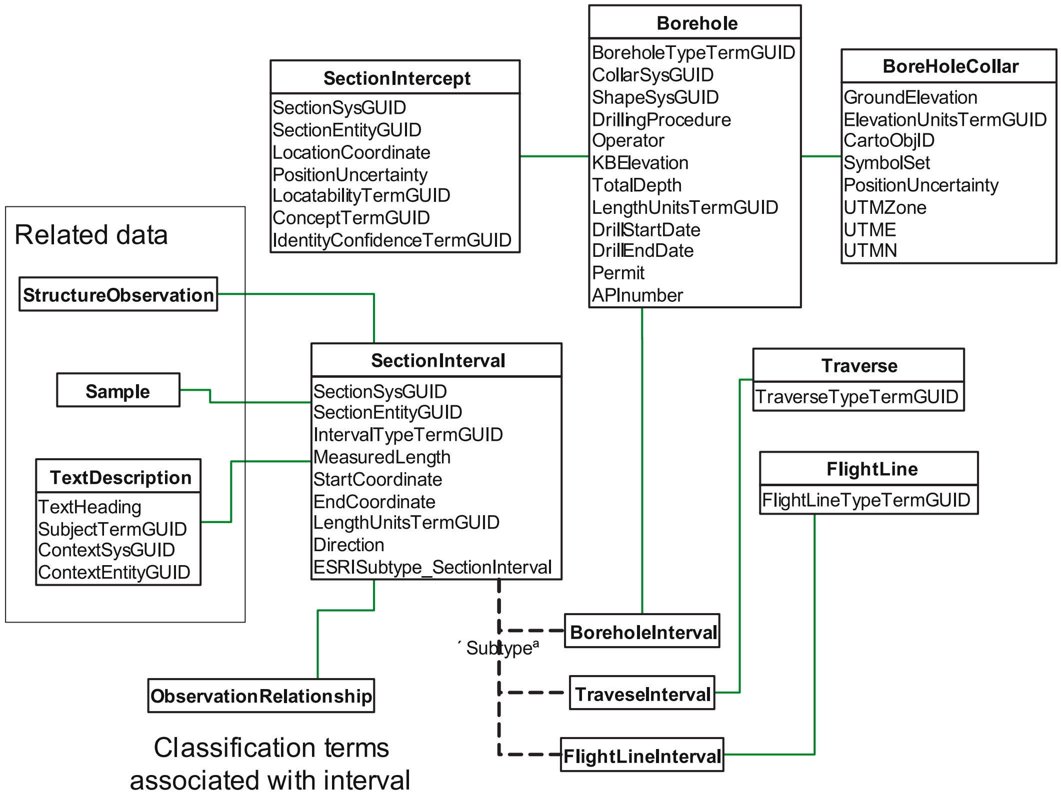

Figure 6. Observation sections: borehole implementation. BoreHoleCollar is a point feature class in the geodatabase that represents the intersection of a borehole with a map horizon. Borehole is a geodatabase object class. The ShapeSysGUID field in Borehole is an NGMDB-defined link to a three dimensional description of the borehole geometry. This is a hook to provide compatibility with three-dimensional models. Borehole is a kind of ObservationSection (Figure 5, see also https://www.seegrid.csiro.au/twiki/bin/view/Xmml/ BoreHole, and discussion in text here).

unit in the demo data map (Figure 11). When the structure data are displayed as an event theme on the StructureObservation table, the symbols are on top of each other. The StructureObservation events were exported to a shape file, then loaded into the MapAnnotationPoint feature class, and the point locations adjusted so that all three symbols are discernible on the map.

- FaultDisplacementPoint. Points that position displacement symbols along a fault trace according to cartographic considerations. Examples of symbols located by these points include bar and ball symbol, right and left arrows, or 'U' and 'D' used to indicate slip or separation on a fault. These should move with fault trace if its geometry is edited, and rotation of symbol is dictated by local trend of fault trace.
- SurfaceOrientationPoint. Points that position orientation symbols along a geologic surface trace, for which symbol is oriented perpendicular to surface trace at the point location. Dip arrows show orientation of a geologic surface, location of point is dictated by observation location and cartographic considerations. Linked to surface trace, should move if geometry of trace is modified. Rotation of symbol is determined by trend of surface trace at point location. Has linked dip label text.
- SurfaceTraceLinkedStrikeDipPoint. Points that position orientation symbols along a geologic surface trace, for which symbol is oriented according to a StructureObservation associated with the surface (not the local trend of the surface trace). The orientation of a gently dipping geologic surface may be annotated by an arrow for which the azimuth of the arrow is determined by strike measurement on the surface (from a structural observation), which may be discordant to the local surface trace trend because of topography. The orientation of the fold hinge for a map-scale fold may vary along a hinge surface trace, and may be discordant to the local trend of the surface trace; thus hinge line measurements linked to a fold hinge surface may be rotate according to structure observation data, not the local trend of the

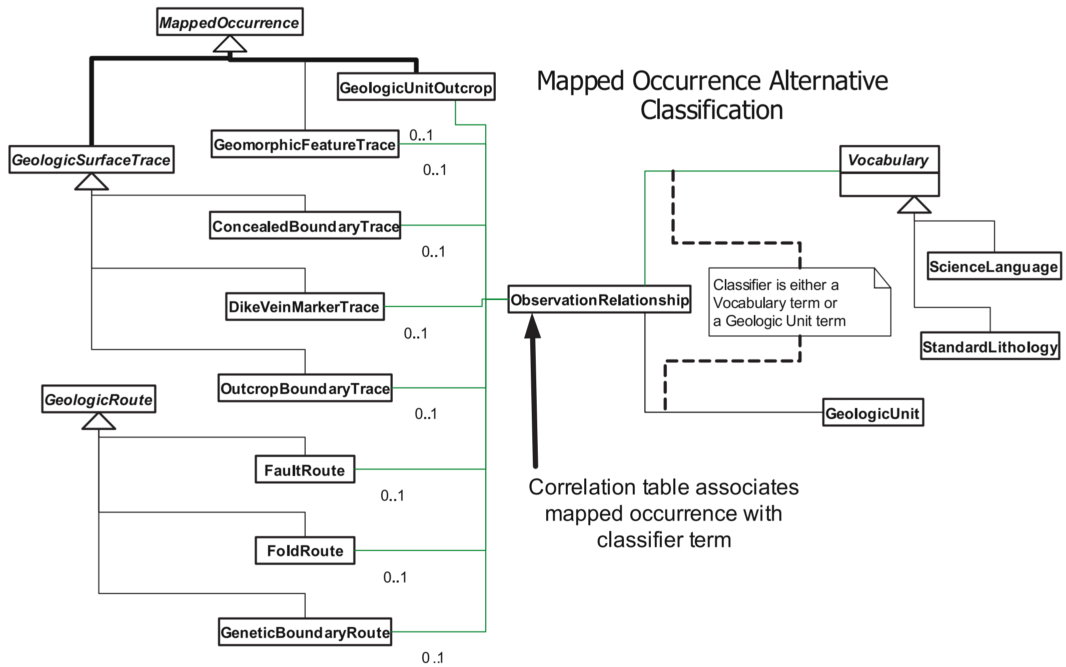

Figure 7. Observation relationship links for alternative classification of mapped features. Default (primary) classification is assigned by ClassifierTermGUID/ClassifierEntityGUID attribute tuple in the feature class table. The primary classification records the original intention with which the mapped feature was delineated. Alternative classifications are used for derivative maps produced by grouping the primary classifiers to define a different classification scheme. The Observation-Relationship correlation table uses sysGUID/entityGUID pairs to identify the type of feature class and actual data instance for the source and the type of classifier and particular classifier term for the target of the relationship. ObservationRelationship also has properties on the relationship (classification) instance to assign a confidence and other metadata information.

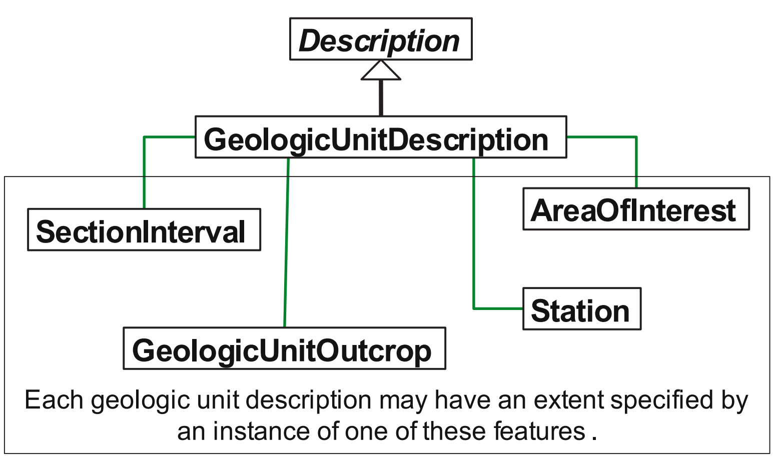

Figure 8. Geographic extents associated with geologic unit description. The extent associated with a description indicates the geographic region within which the description is asserted to be valid. The associations shown are implemented as geodatabase relationship classes, allowing navigation from mapped features (e.g. GeologicUnitOutcrop) to associated descriptions in the ArcMap interface. The foreign key from GeologicUnitDescription to the mapped feature is DescriptionExtentSysGUID, which links to the primary key (SysGUID) in the mapped feature. Details of GeologicUnitDescription are discussed in Richard et al. (2004).

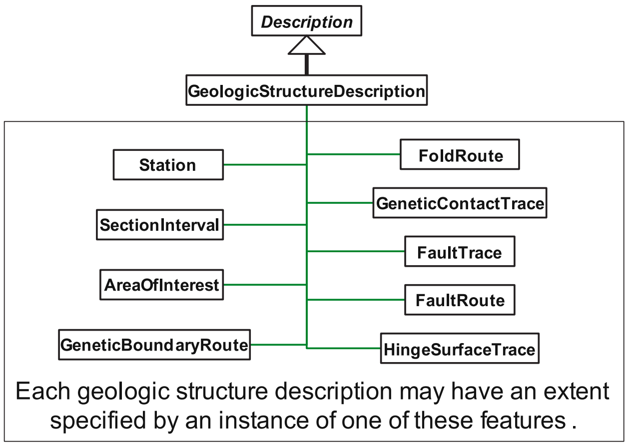

Figure 9. Geographic extents associated with geologic structure description. The extent associated with a description indicates the geographic region within which the description is asserted to be valid. The associations shown are implemented as geodatabase relationship classes, allowing navigation from mapped features (e.g. FaultTrace) to associated descriptions in the ArcMap interface. The foreign key from GeologicStructureDescription to the mapped feature is DescriptionExtentSysGUID, which links to the primary key (SysGUID) in the mapped feature. Details of GeologicStructureDescription are discussed in Richard et al. (2004).

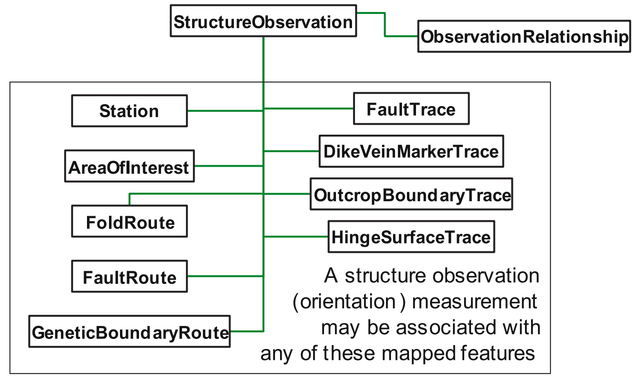

Figure 10. Structure observation description extent. Structure observation is a geodatabase ‘object class’ that is used to record orientation measurements for geologic structures. The extent associated with a structure observation indicates the geographic region within which the orientation measurement is asserted to be valid. The associations shown are implemented as geodatabase relationship classes, allowing navigation from mapped features (e.g. Station) to associated orientation measurements in the ArcMap interface. The foreign key from StructureObservation to the mapped feature is LocationSysGUID, which links to the primary key (SysGUID) in the mapped feature. Details of StructureObservation attributes are discussed in Richard et al. (2004). ObservationRelationship links to StructureObservation are used to correlate related observations (e.g. foliation in lineation, cleavage axial planar to fold).

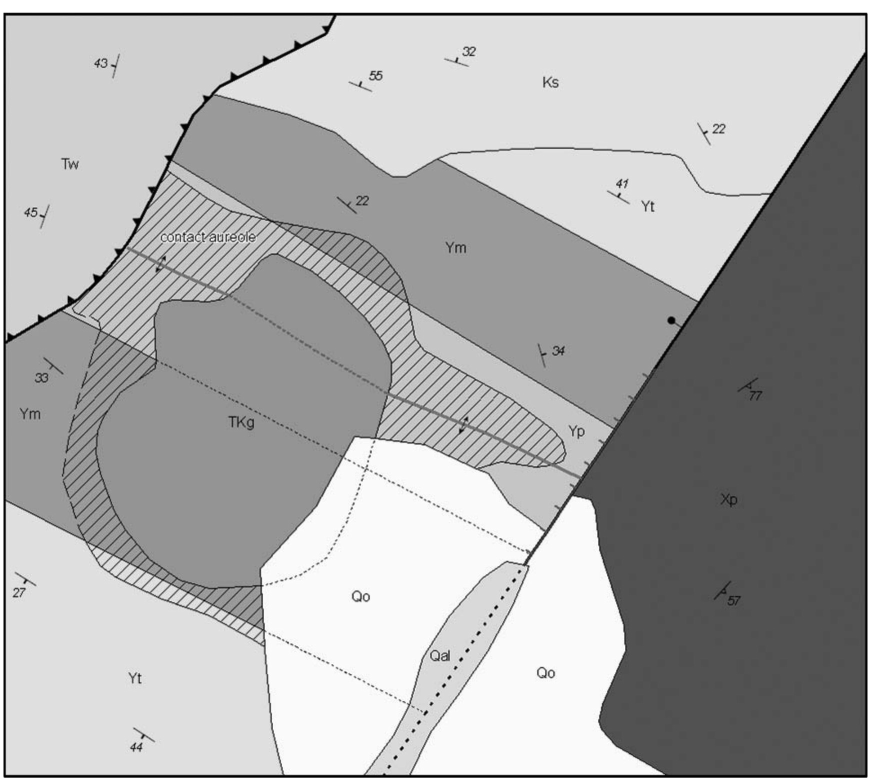

Figure 11. Geoland demonstration map. Original is in color, converted to grayscale for display in print.

hinge surface trace. Has linked dip (or plunge) label text. Location of symbol generally determined by an observation location (station), adjusted according to cartographic considerations, but should move if the associated surface trace is edited.

- FoldGeometryPoint. Points that locate symbols placed along a hinge surface trace to indicate the geometry of the fold—syncline, anticline, overturned syncline, etc. Location determined by cartographic considerations. Should move with the surface trace if it is edited. Topology rule: must be covered by HingeSurfaceTrace.

Orientation data

Structure observation is a geodatabase 'object class' that is used to record orientation measurements for geologic structures. The extent associated with a structure observation indicates the geographic region within which the orientation measurement is asserted to be valid (Figure 10). The most common application is the association of common bedding or foliation measurements with a Station feature. This model makes a clear separation between the observation location—a station, and the data acquired at the location (a structure observation). For cartographic purposes, for example to display a strike and dip symbol, a MapAnnotationPoint is created using the station location and the azimuth value to rotate the symbol and text label for the symbol are determined from the related structure observation data. The symbol can be repositioned for cartographic purposes without losing information about the actual location at which the measurement was made.

EXAMPLE MAP

Figure 11 is a geologic map of an imaginary study area, based on a demonstration geodatabase designed to exercise various capabilities of the NGMDB design. Many of the geologic unit names and general character are based on units found in Arizona, but this is just a convenience to make easier the generation of descriptions. Figure 12 is the ArcMap table of contents for layers displayed in Figure 11; each layer is described below:

- The 'Map boundary' layer in the ArcMap table of contents (Figure 12) is based on OutcropBoundaryTraces, with a definition query for the layer set to '[CartoObjID] = 65' to select the lines in that feature class that are symbolized with the line symbol used for the map boundary line. This layer is just the neat line around the boundary of the map area to provide a reference frame. The map boundary layer is shown in the subsequent figures for reference.
- The MapAnnotationPointAnno layer (Figure 13) displays an ESRI Annotation feature class from the geodatabase that contains the strike and dip numbers for structure data on the map. This layer was generated by using the auto label feature in ArcMap, then converting labels to feature-linked annotation, and adjusting the position of the labels.
- MapAnnotationPoint is a point feature class that is used to position point symbols associated with other features but whose location is not determined by an observation location. In this map view (Figure 13), the two anticline symbols along the fold hinge surface trace and the bar-ball symbol on the fault trace are located by these points.
- Station is a point feature class (turned off in this view) that displays the locations at which observation data were collected. All strike and dip symbols shown in the map view have associated stations.
- The GeologicUnitOutcropAnno layer (Figure 14) displays an ESRI annotation feature class from the geodatabase, generated by the same procedure as MapAnnotationPointAnno.
- In the ArcMap table of contents (Figure 12), geology is a group layer that includes the mapped occurrences displayed in the map view.
- StructuralObservationEvents displays structure measurements from the StructureObservation table (Figure 13), located using the X, Y coordinates stored in that table. In a complex map view composition, these might be exported to the MapAnnotationPoint feature class to allow repositioning of the symbols for cartographic purposes without disrupting the observation location points. The symbols are rotated using the Azimuth field in the StructureObservation table. The symbols are identified by the integer CartoObjID field. This is a default symbolization scheme determined by the data originator.
- GeomorphicFeatureTrace (Figure 15) displays a line feature class with the same name. Only one feature is included—the scarp along a section of the NE trending fault in the east side of the map. This line was drawn coincident with the fault using snapping.
- HingeSurfaceTrace (Figure 15) displays a line feature class with the same name. Three arcs are included along the hinge surface trace of the upright anticline in the central part of the map. Two are solid, one part is dotted through the intruding pluton. A FoldRoute.FoldSegment object could be constructed to represent this entire hinge surface trace segment if there was a need to describe the fold in its entirety.
- The 'Superimposed unit Outcrop' layer (Figure 16) is based on the GeologicUnitOutcrop feature class, with a definition query for the layer set to '[ESRISubType_GeologicUnitOutcrop] = 1', to display only the superimposed geologic unit polygons. In this case, the only polygon in this layer represents the contact aureole mapped around the pluton. It is symbolized with a hatch pattern with transparent background so the underlying primary geologic unit polygons are visible.
- OutcropBoundaryTrace (Figure 17) displays a line

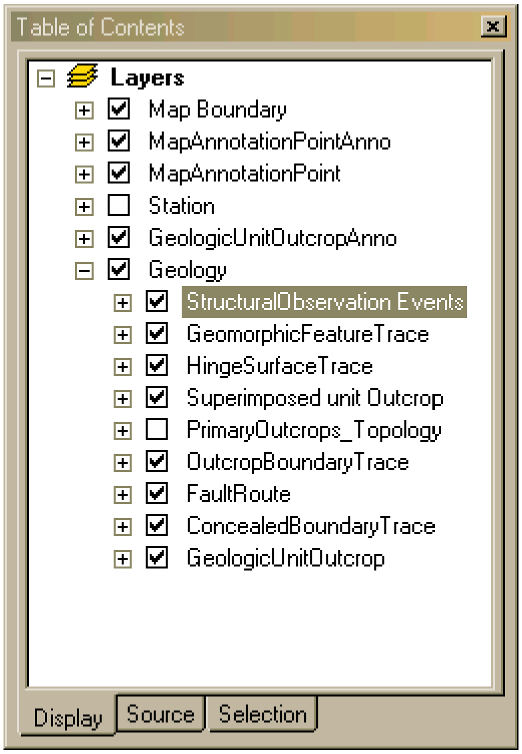

Figure 12. ArcMap table of contents showing layers displayed in map shown in Figure 11.

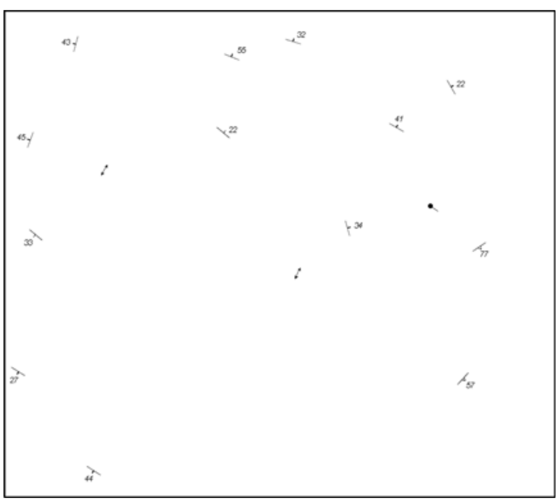

Figure 13. Map annotation points, StructureObservation events, and MapAnnotationPointAnno layers.

Figure 14. GeologicUnitOutcrop and GeologicUnitOutcropAnno layers.

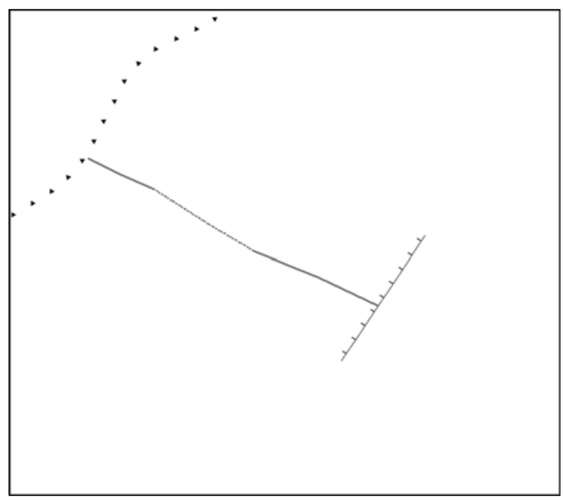

Figure 15. Geomorphic feature trace (fault scarp), hinge surface trace, and fault route layers. The fault route is used to place the triangular decorations along the thrust fault so that the spacing between triangles is regular, because the decorated line has no pseudonodes.

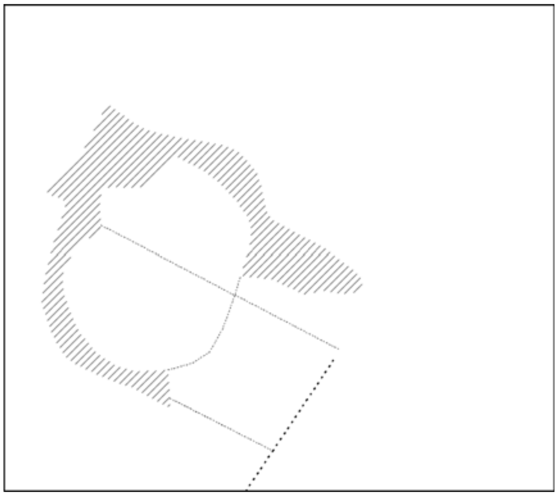

Figure 16. Superimposed geologic unit polygon and concealed boundary trace layers.

Figure 17. Outcrop boundary trace layer.

feature with the same name, symbolized on CartoObjID from a legend file that includes all line CartoObjIDs in the AZGSSymbolSet. These are the outcropping geologic contacts and faults in the map.

- FaultRoute (Figure 15) displays a line feature class with the same name. The features in this feature class aggregate the mapped parts of each fault trace into a single fault trace that may be associated with descriptions of the fault. The route features are also useful for symbolization. Labeling of the fault using the route feature avoids duplicate labels, and decorated faults (e.g. thrust, detachment, low-angle normal) can have the decorations applied using the fault route to obtain a much more cartographically pleasing effect. In this map view, the southeastern, high angle fault route is not symbolized. The thrust fault in the NW part of the map has no line stroke, but has filled triangle ornaments to place the teeth along the fault trace that is drawn by the OutcropBoundaryTrace layer.
- ConcealedBoundaryTrace (Figure 16) displays a line feature class with the same name. This feature class includes concealed faults and outcrop boundary contacts. They are included in a separate feature class because they do not participate in the polygon topology.
- GeologicUnitOutcrop (Figure 14) displays a polygon feature class with the same name that represents the outcrop of primary geologic units. This layer is based on the GeologicUnitOutcrop feature class, with a definition query for the layer set to '[ESRISubType_GeologicUnitOutcrop] = 0'. Colors in this map are assigned based on the Label field in the GeologicUnitOutcrop table. This is an expedient approach to symbolization during initial map compilation, when the final set of geologic units may not be known for sure.

OUTSTANDING ISSUES

Major implementation questions that must be addressed in developing a multiple map database, of the sort envisioned for a geological survey enterprise archive, include:

- how to implement multiple-scale representation. At different levels of generalization, a single geologic entity may be represented by different geometry. Topology rules must be applied to features that represent the same resolution.
- how to account for multiple map horizons (e.g. Earth surface, bedrock surface, top Precambrian…)
- how to account for different geologic perspectives that have related but loosely coupled geometric and topologic relationships. For example, geologic units on an alteration map may overlap some protolith geologic units and faults that cut them, while being cut by post-alteration structures and overlapped by post alteration geologic units that would share geometry with the stratigraphic geologic unit map.

One approach that we are experimenting with would group features into different feature datasets to represent different map horizons or resolution (generalization). Related, but loosely coupled geologic features like alteration map units would be represented using subtypes of the GeologicUnitOutcrop polygons, perhaps with a separate set of topologic rules from the principal unit outcrop boundary traces and outcrop polygons.

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