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Ontology of fractures

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ABSTRACT

Fractures are fundamental structures in the Earth's crust and they can impact many societal and industrial activities including oil and gas exploration and production, aquifer management, CO_2 sequestration, waste isolation, the stabilization of engineering structures, and assessing natural hazards (earthquakes, volcanoes, and landslides). Therefore, an ontology which organizes the concepts of fractures could help facilitate a sound education within, and communication among, the highly diverse professional and academic community interested in the problems cited above. We developed a process-based ontology that makes explicit specifications about fractures, their properties, and the deformation mechanisms which lead to their formation and evolution. Our ontology emphasizes the relationships among concepts such as the factors that influence the mechanism(s) responsible for the formation and evolution of specific fracture types. Our ontology is a valuable resource with a potential to applications in a number of fields utilizing recent advances in Information Technology, specifically for digital data and information in computers, grids, and Web services.

1. Introduction

An ontology is an explicit conceptualization of human knowledge in a computer-readable format (Gruber, 1993). It is about structuring information for computer systems for a better human/computer interaction. An ontology establishes concepts (or classes in an ontological term), defines their attributes, constrains, relationships (all called ontological properties), and establishes the constraints on these relationships (Noy and McGuinness, 2001). Ontologies provide a vocabulary that represents and communicates knowledge about a topic (or domain in an ontological term), and define relationships between the terms in the vocabulary. For example, geological structures, deformation mechanisms, stylolites, and pressure solution are "concepts" in the Structural Geology domain. Each of them is a class in our ontology. Stylolites are a type of geological structure and so, are a subclass of geological structures. The subclass relationship forms the class hierarchy. Furthermore, stylolites 'are formed by' pressure solution process, which represents a relationship between a structure and its deformation mechanism.

One of the goals of developing an ontology is to share knowledge about a domain among people and between people and computers by defining a common vocabulary. This definition process is required for an efficient handling of different data sources organized differently by different people and employing different terms for the same concept (Musen, 1992; McGuinness, 2003). Data sources may be database containing journal articles supporting a web search (information retrieval in Information Technology term) or databases containing data about numerous structures. In each data source, it is likely that different terms are used. For example, splay fractures, wing cracks, kink cracks, horse tails, pinnate joints, and feather fractures are terms commonly used for more-or-less the same feature in structural geology (Pollard and Aydin, 1988; Engelder, 1987). For a human to look for articles or data in multiple data sources, it is, then, necessary to know about the specific terminology each database uses and try each possible term against each data source. This may be manageable for a few data sources, but if hundreds of databases exist, computers using ontology are able to extract and aggregate information from these different data sources in an efficient manner. This approach is referred to as mediation services: instead of users searching for each of these terms in each data sources, computers with the help of an ontology that specify those equivalent terms can readily do it in a fraction of a time.

Another common usage of ontology is to outline the relationships between concepts. For example, strike-slip faults have two subclasses based on the sense of slip: sinistral (left-lateral) and dextral (right-lateral). Looking for words 'strike-slip fault' in a data source would not return results about sinistral fault or dextral fault

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if these terms are used. Similar to the previous example, trying all possible terms is not only time-consuming and tedious for humans, but also it becomes impossible as the number of data source increases. This technique is referred to as query expansion in Information Technology.

Several applications of ontology within the broader Earth sciences already exist; the most notable of these are the Geosciences Network (GEON, 2008) and the Virtual Solar Terrestrial Observatory (VSTO, 2008). Both GEON and VSTO provide services supporting mediation, query expansion, data analysis and visualization for a repository of multiple data sources with ontology-enabled tools (McGuinness et al., 2006; Nambiar et al., 2006; Fox et al., 2006; Kerschberg et al., 2006).

Ontologies can be broadly split into two categories based on the type of terms they describe: upper ontology and domain ontology (Russell and Norvig, 1994). An upper ontology covers common objects that are generally applicable across a wide range of subjects. A domain ontology, on the other hand, concentrates on a specific field and represents some particular meanings of terms as they apply to that field.

In the Earth Sciences, several upper ontologies have been developed. The North American Geologic-map Ontology is an upper ontology and provides a data-model standard for the description, classification, and interpretation of geological features in digital geologic-map databases (North American Geologic Map Data Model Steering Committee, 2004). It has a layout for common concepts like Geologic Unit, Geologic Structure, Earth Materials, Geologic Process, and Geologic Property. Another example for upper ontology in Earth Science is the Semantic Web for Earth and Environmental Terminology (SWEET) (Raskin, 2004). Its ontology has broad yet very coarse coverage in Earth System Science, including concepts, like space, time, Earth realms, physical quantities, phenomena and events.

There are several domain ontologies in the Earth Sciences. One of these deals specifically with rock classification (Struik et al., 2002). It aims to provide data mediation on diverse geological datasets and maps. Another domain ontology is for geologic age (GeologicAge, 2005). There was an attempt to develop a domain ontology specifically for Structural Geology (Babaie et al., 2006; Richard et al., 2006). However, the published paper and abstract deal with the design but the final product has not been published.

We present in this paper an ontology for fractures, which is within the specific domain of Structural Geology. The term, fracture, in the context of our ontology is used for structures with all kinds of displacement discontinuities at all scales (Lacazette, 2008; Schultz and Fossen, 2008), including crustal scale (Chester and Chester, 1998).

The ontology presented in this paper is the first of its kind covering an important domain in Structural Geology. Therefore, it is likely not complete or perfect but it provides a starting point. In addition, other views are present in the community that our ontology does not address to. Instead of attempting to cover all, our ontology focuses on areas of the authors' strengths. However, others are welcome to expand and modify this ontology and use it for their own purpose and preference. Our ontology merely provides a platform to structural geologists to discuss and search for better ways of organizing knowledge about rock fractures in the age of Information Technology.

One of the motivations for our ontology for fractures is that information for fractures is becoming a highly sought after commodity due to its application to the fields of hydrogeology, petroleum geosciences, contaminant remediation and CO_2 containment. Considering that, in most applications, many of fractures and their components cannot be remotely detectable by current seismic technologies due to their poor resolutions (Yilmaz and Doherty, 1987), it is essential to maximize the knowledge about the formation mechanisms of fractures and their geometric and petrophysical properties. Of course, needless to say, this knowledge should be made available for and easily accessible by the users. In this regard, our ontology should also be helpful for dissemination of the knowledge related to rock fractures.

2. Methods

We chose the Web Ontology Language description logic (OWL-DL) as our ontology language. OWL (Smith et al., 2004) is XML-based and is compatible with and extends Resource Description Framework (RDF) and RDF Schema (RDFS) (Brickley and Guha, 1999). OWL, current a World Wide Web Consortium (www.w3c.org) recommendation, is intended to be used over the World Wide Web and by applications that need to process the content of information. OWL-DL is a species of OWL. This species had the goal of maximal expressiveness that warrants logic inference, so that the software is able to infer logical consequences (Clark and Parsia, 2008; Hollet, 2008).

In this paper, standard ontological notations are used for class and property names. First, the first letter of class names is capitalized and the first letter of property names uses lower case. For example 'Joint' is the class name for joints and 'form' is the property name for the relationship of mechanisms form structures. Second, if a class or property name contains multiple words, all words run together and delimitated by capitalized first letter. For example, the class name for pressure solution seams is 'PressureSolutionSeam'; and the property name for the relationship of structures having structural components is 'hasComponent'. Property name may contain an underscore (_), indicating a relationship between two concepts connected by the underscore symbol. An example is juxtaposition_faultPermeability, meaning the relationship between juxtaposition and fault permeability. Third, all class names are in singular form. To further distinguish class and property names from normal parts of a sentence, typographical *Italic* style is used for the former.

When one concept is described by multiple terms, such as splay fractures, wing cracks, kink cracks, horse tails, pinnate joints, and feather fractures, each synonym is a class. Each of these classes has a property referring to each other that they are of equivalent meaning.

3. Classes and properties

At this stage, our ontology has about 300 classes and 50 properties. These classes and properties reference about 180 articles or textbooks. Due to size limitation, only selected classes and properties are presented here and not all references are listed.

3.1. Class

The core of the knowledgebase is divided into three major classes, *GeologicalStructure*, *DeformationMechanism*, *PropertyFactor*. Fig. 1 summaries how these major top classes are interrelated: structures are formed by some mechanisms controlled by many factors; structures have some properties; and their presence changes some petrophysical properties of the host rocks and effects the subsequent deformation.

3.1.1. Geological structure class

Geological structures comprise the fundamental structures observed in the upper crust, including joints (veins, dikes), pressure solution seams, deformation bands, and faults (Suppe, 1984; Twiss and Moore, 1992; Davis and Reynolds, 1996; Pollard and Fletcher, 2005). Fig. 2 shows the class hierarchy under the *GeologicalStructure* class. Other structures, such as folds, lineation, and

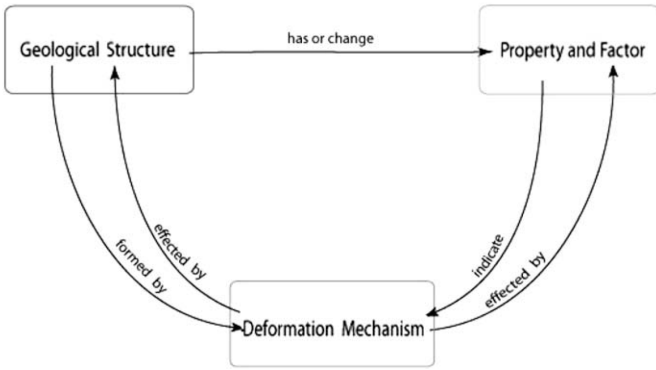

Fig. 1. Diagram showing the relationship between three core classes of the Ontology. Interrelationships between the core classes are also pointed out.

foliations, are included as subclasses of structure element (*Element*) as place holders with no further information.

The first hierarchy of *GeologicalStructure* proceeds based on common associations into structure component, element, zone, set, multiple sets, domain, and assemblage, which are common to all types of structures (Committee on Fracture Characterization and Fluid Flow, National Research Council, 1996). Structure element (*Element*) is the smallest unit that forms as a whole under a certain deformation. Sometimes, one structure element, such as fault, can consist of several components. Structure elements can occur in a set or zone. A set (*Set*) is a collection of parallel or sub-parallel structure elements of the same nature with corresponding length and spacing properties. Structure zone (*Zone*) is similar to a set in the sense that it consists of a collection of parallel or sub-parallel elements of the same type, but they are rather closely spaced. Multiple sets (*MultipleSet*) refer to multiple structure sets with different orientation, thus intersecting each other. Structure domain (*Domain*) refers to a particular pattern of structure set or multiple sets with varying orientation and geometric parameters across a given region. Sometimes that region is also referred to as domain. Structure assemblage (*Assemblage*) describes the common association of related geological structures, structure sets or multiple sets. The difference between structure assemblage and multiple sets is that structure assemblage implies the different structure elements or sets commonly occurring together while multiple sets are used for the same structure element.

The *GeologicalStructure* class is further categorized first, based on the nature of the structures and then, based on their geometrical, kinematical, and petrophysical characters (Fig. 2).

3.1.2. Deformation mechanism class

Deformation mechanisms include macro- and micro-mechanisms involved in the formation of geological structures. Fig. 3 shows the class hierarchy under *DeformationMechanism*.

In our ontology, macro-deformation mechanisms have four major subclasses, jointing (*Jointing*), pressure solution and cleavage (*PressureSolution*), strain localization in the form of bands (*DeformationBanding*), and faulting (*Faulting*) (Fig. 3). Jointing is characterized by opening displacement discontinuity, pressure solution is defined as closing displacement discontinuity, and faulting is associated with shear displacement discontinuity. Deformation bands can occur with a whole range of displacement discontinuities across a narrow band with end members of volumetric dilation, volumetric compaction, and isochoric shear. Shear strain localization is also a subclass of faulting that may have either minor dilation or compaction components (Aydin et al., 2006; Schultz and Fossen, 2008).

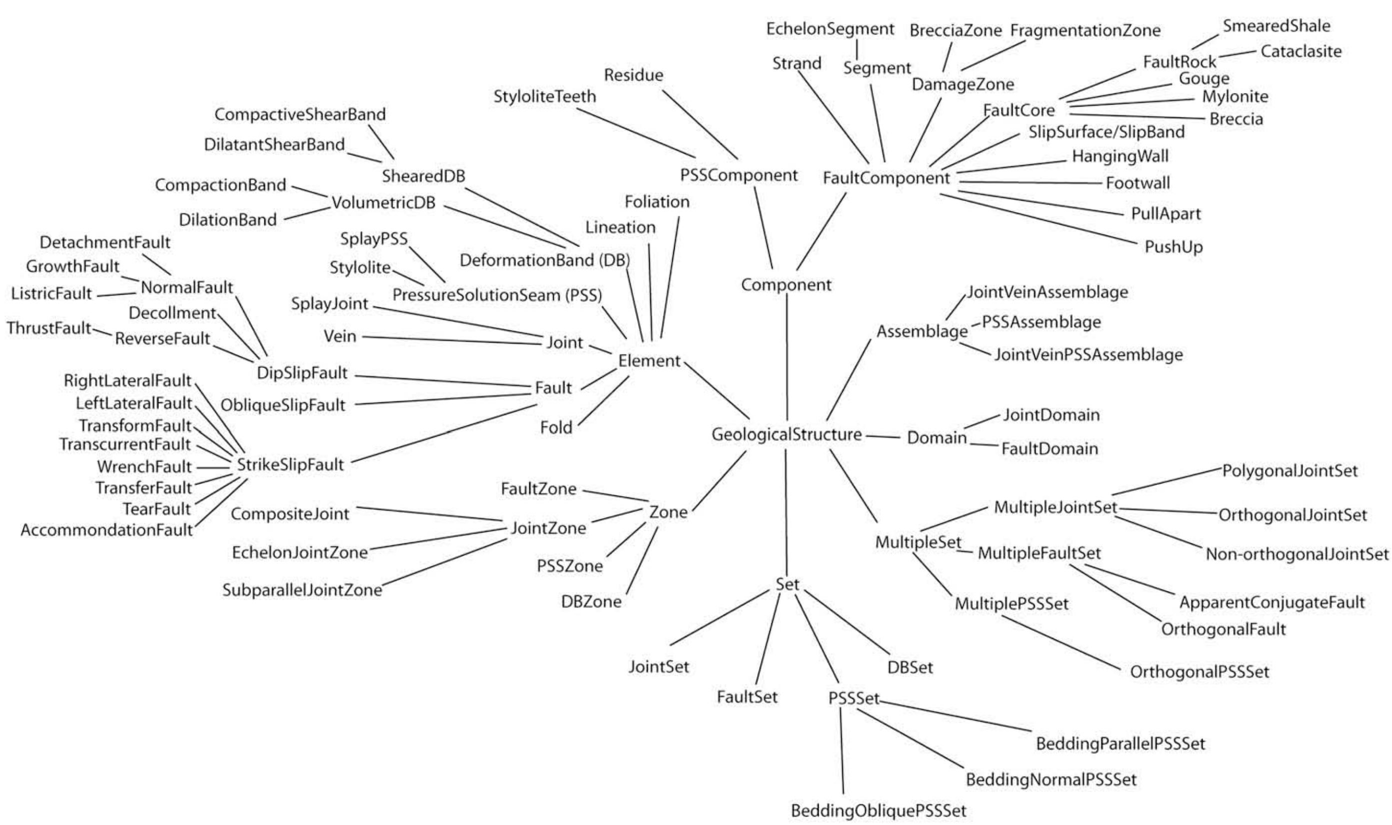

Fig. 2. Class hierarchy of *GeologicalStructure*. PSS is short for pressure solution seam and DB is short for deformation band. The convention for the expression of terms in Figs. 2–6 is described in text under 'Methods'.

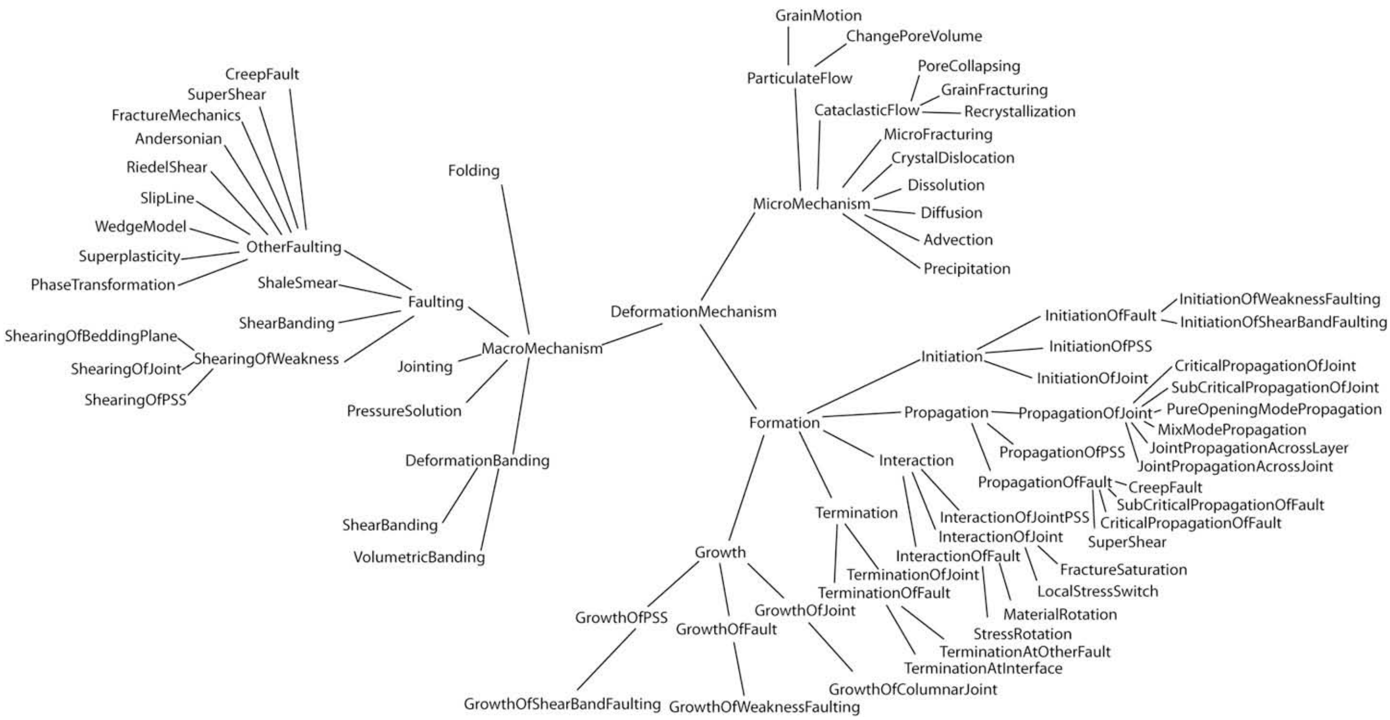

Fig. 3. Class hierarchy of *DeformationMechanism*. *DeformationMechanism* has micro and macro classes and encompasses the formation of structure classes. In turn, it involves in the initiation, propagation, interaction, termination, and growth of structure classes.

The faulting mechanism is further classified. As mentioned in the paragraph above, shear strain localization by bifurcation from a homogeneous deformation field to an inhomogeneous field, for example, is one of the faulting mechanisms, which produces shear bands. Faulting oftentimes exploits pre-existing weaknesses, like bedding or structural weaknesses formed by other mechanisms, which took place prior to faulting. In our ontology, this type of faulting mechanism is called weakness-based faulting. Some other faulting mechanisms, such as Andersonian faulting (Anderson, 1951), Riedel shear (Davis, 1999; Suppe, 1984), slip line model (Cummings, 1976), phase transformation (Green and Burnley, 1989), and shale smearing (Weber et al., 1978) are also included.

Micro-mechanisms, on the other hand, refer to the deformation mechanisms operating at grain or crystal scale. A macro-deformat ion mechanism generally is used for homogenized materials above the crystal scale or grain and intragranular pore scale. Examples of micro-mechanisms are grain translation, grain crushing, dislocation, pore collapse, dissolution, diffusion, and precipitation, whereas macro-mechanism is jointing or faulting producing a corresponding structural entity.

In addition to micro- and macro-mechanisms, each stage of progressive development is organized in the *Formation* class. The stages include initiation, propagation, termination, interaction, and growth. *Initiation* and *Termination* is self-explanatory. *Propagation* and *Growth* are related yet different concepts. *Propagation* refers to the manner by which a single structure element extends its dimension. *Growth*, on the other hand, may describe the formation and evolution of a structure zone, set, or multiple sets; and how they continue to increase in size and number during some period of time. *Interaction* describes how the presence of one structure affects the others nearby.

The *GeologicalStructure* and *DeformationMechanism* classes have totally different classification schemes. *GeologicalStructure* is observation-based, and captures the more traditional aspect of what we see. On the other hand, *DeformationMechanism* is process-based, and is controlled by rock properties and deformation condition. The *GeologicalStructure* and the *DeformationMechanism* classes are cross-linked at *Element* level and *Macro-Mechanism* level, such as *DeformationBand* of *Element* and *DeformationBanding* or *StrainLocation* of *Micro-* or *Macro-Mechanism*.

3.1.3. Property/factor class

Property covers concepts concerning the nature of rocks or structures, like surface morphology, while Factor covers those concepts that determine which deformation mechanism will occur and how they will operate, like loading or stress. Property and Factor are combined into one class because properties are also commonly factors, such as fracture toughness and viscosity. The four subclasses of *PropertyFactor* are *Geometry*, *MaterialProperty*, *Loading*, and *SurfaceMorphology* or *SurfaceRoughness* (Fig. 4). *Lithology* is a space holder for the rock classification ontology (Struik et al., 2002).

The class *Geometry* is further divided into mostly structure-specific subclasses, like the geometry of joint and the geometry of pressure solution seams, etc. The only exception is the Pattern, which describes the common features observed among multiple structure elements or among multiple structure sets. Since these patterns are observed in multiple structures, the leaf classes (those which do not have subclasses) in Pattern mostly have multiple super-classes. For example, *LadderPattern* and *GridPattern* are both subclasses of *OrthogonalPattern*, *OrthorhombicPattern*, and *JointPattern*.

The class *Loading* has two subclasses, *Stress* and *StressChange*. *Stress* is the intensity of causative force and generally is not homogeneous or isotropic within a body subjected to force (Fig. 4). *StressChange* covers some phenomena that change the direction and/or magnitude of the regional stresses or local stresses with respect to the background or initial regional stresses. Regional stress magnitudes and directions can change over geological time. Local stress changes when inhomogeneities induce stress

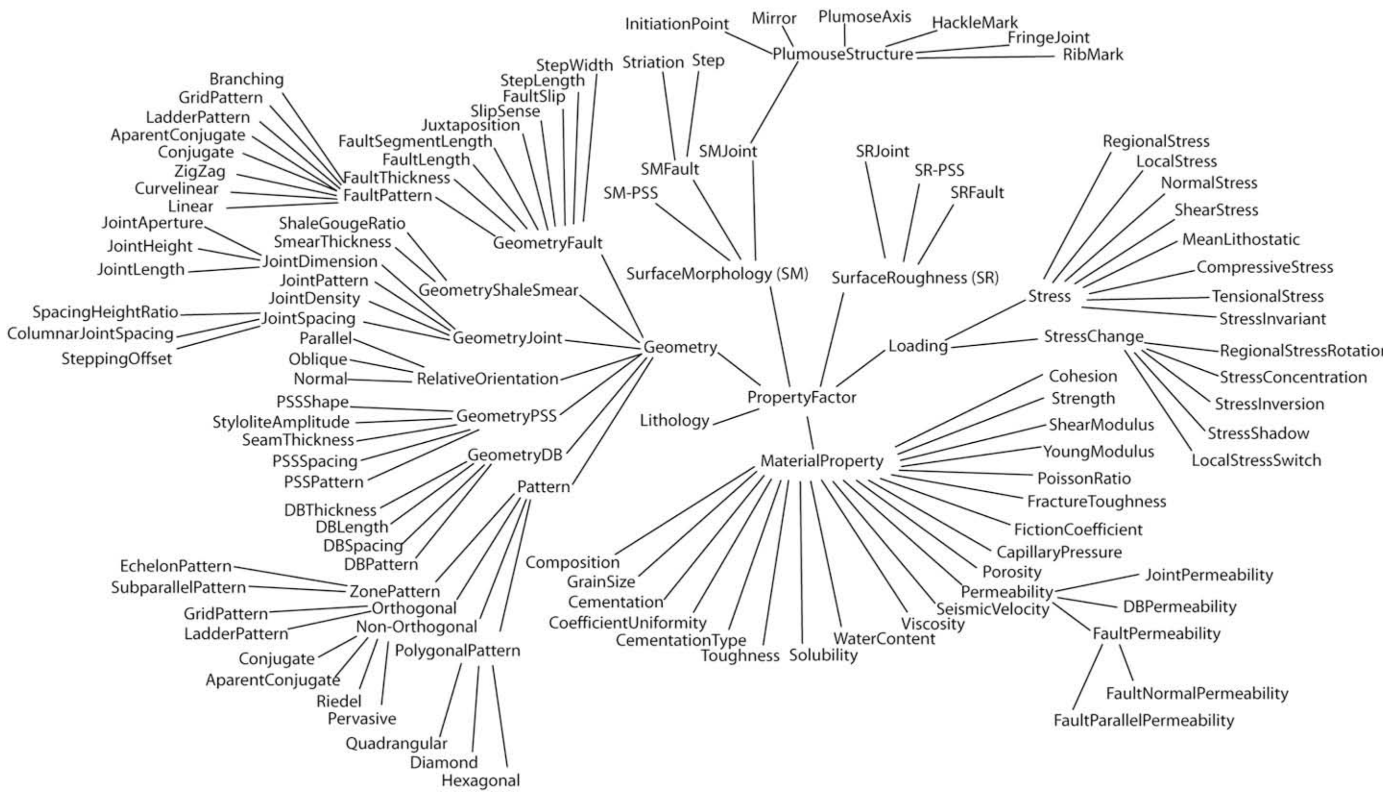

Fig. 4. Class hierarchy of *PropertyFactor*. It covers geometry, morphology, and roughness of geological structures; and material properties of rocks and their changes after forming geological structure; and loading. Material property and loading are common factors effecting what deformation mechanism can occur, so this class has its name as *PropertyFactor*.

perturbation. Micro-inhomogeneities in rocks, like flaws (micro-cracks and dislocations), pores, grains, and inclusions, induce stress concentration and stress shadow. Every structure small or large possesses a particular associated stress field that is different from the background stresses. For example, see Pollard and Fletcher (2005) for stress fields associated with joints or types of faults for certain boundary conditions. Another *StressChange* that is considerably more complex than the cases associated with single *Elements*, is the local stress variation in shear zones (McKinnon and de la Barra, 1998) and stress switch occurring during the development of joint sets in layered rocks (Bai et al., 2002).

The subclasses of *Geometry*, *SurfaceRoughness*, *SurfaceMorphology* classes are commonly correlated to the subclasses of *GeologicalStructure*. The subclasses of *MaterialProperty* and *Loading* are mainly correlated to subclasses of *DeformationMechanism*.

3.2. Property

The property in our ontology covers five major areas (Fig. 5): geometry of structures (*hasGeometry*), components of structures (*hasComponent*/*isComponentOf*), factors effecting deformation mechanisms (*factorMechanism*), factors effecting and relationships among structures' geomety (*factorGeometry*), and fluid flow properties affected by geological structures (*structureProperty*). The properties have value restrictions and are assigned to the most specific classes when possible.

Examples of the first two properties, *hasGeometry* and *hasComponent*, can be seen in Fig. 6 as color-coded arrows. *factorMechanism* has subproperties about the factors determining whether a macro-mechanism can occur. For example, the propagation direction and velocity of a joint is closely related to the stress intensity, or the magnitude and orientation of the local stresses at the joint tip region as well as the medium (layering, for example). Strain localization occurs in rocks with high porosity and weak cementation. Pressure solution involves three micro-mechanisms: dissolution, diffusion, and precipitation (Renard and Dysthe, 2003). Many factors affect either one, or two, or all three steps, such as solubility, pressure, temperature, presence of water, clay content and grain size.

factorGeometry has sub-properties about the factors determining the geometry of joints, pressure solution seams, deformation bands, and faults. Joints commonly occur in a zone and/or set (Pollard and Aydin, 1988). For zones or sets, the spacing is an important parameter affected by many factors, such as strain magnitude, layer thickness (Wu and Pollard, 1995), the sub-critical index of rocks (Olson, 2004), the evolution of the jointing process (Rives et al., 1992), and the cooling rate for thermal joints (Lore et al., 2001).

The factors effecting fault geometry are divided into four major areas (Fig. 5): the scaling relationships of faults, including length and other dimensions, factors affecting fault zone geometry, factors affecting the pattern of multiple fault sets, and geometrical distributions of faults.

The *structureProperty* has subproperties covering the shortening (or elongation–extension), porosity, and permeability affected by various structures (Fig. 5). For example, permeability of faults is related to juxtaposition and the architecture of the fault zone. Faults have various components and each component can either reduce, like fault rock, or enhance, like slip surface and splay joints, the fault permeability property by several order of magnitude (Manzocchi et al., 1999; Jourde et al., 2002; Ahmadov et al., 2007).

3.3. Case study I: faults and faulting

The above sections present the core classes and properties. This section relates faulting and faults to explain the rationale behind

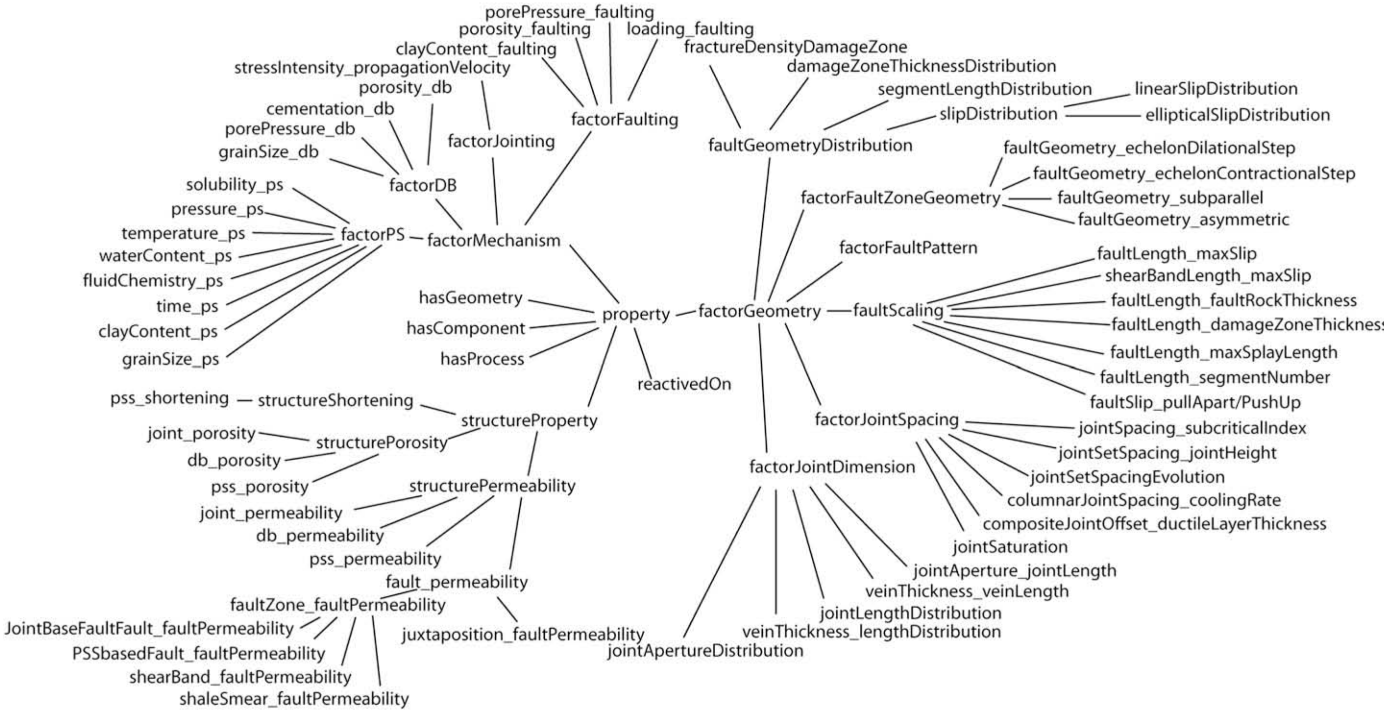

Fig. 5. property hierarchy. ps is short for pressure solution; pss is short for pressure solution seam; and db is short for deformation band.

our ontology. Faults are structures with displacement discontinuities primarily parallel to the plane or zone of the structures. Their equivalent in the engineering literature is shear fractures (Lawn and Wilshaw, 1975; Jaeger and Cook, 1979).

The ontological classes and properties of faulting and faults are illustrated in Figs. 2–5. Several classes and properties are also shown in Fig. 6 to illustrate the linkage of classes by properties.

Faults (*Fault*, Figs. 2 and 6) are a type of structural element formed as a consequence of faulting (*Faulting*, Figs. 3 and 6). Faults form in various tectonic environments and are described by a large number of terms (Fig. 2). For examples, transform fault, transcurrent fault, transfer fault, tear fault, wrench fault, and accommodation fault are all strike-slip faults. Similarly, normal fault, growth fault, listric fault, detachment fault, reverse fault, thrust fault, and decollment are all dip-slip faults (Twiss and Moore, 1992).

Matured faults are commonly made up of several components (*FaultComponent* in Fig. 2 and *hasComponent* in Fig. 6). The fault trace is commonly composed of multiple segments (*Segment*) and/

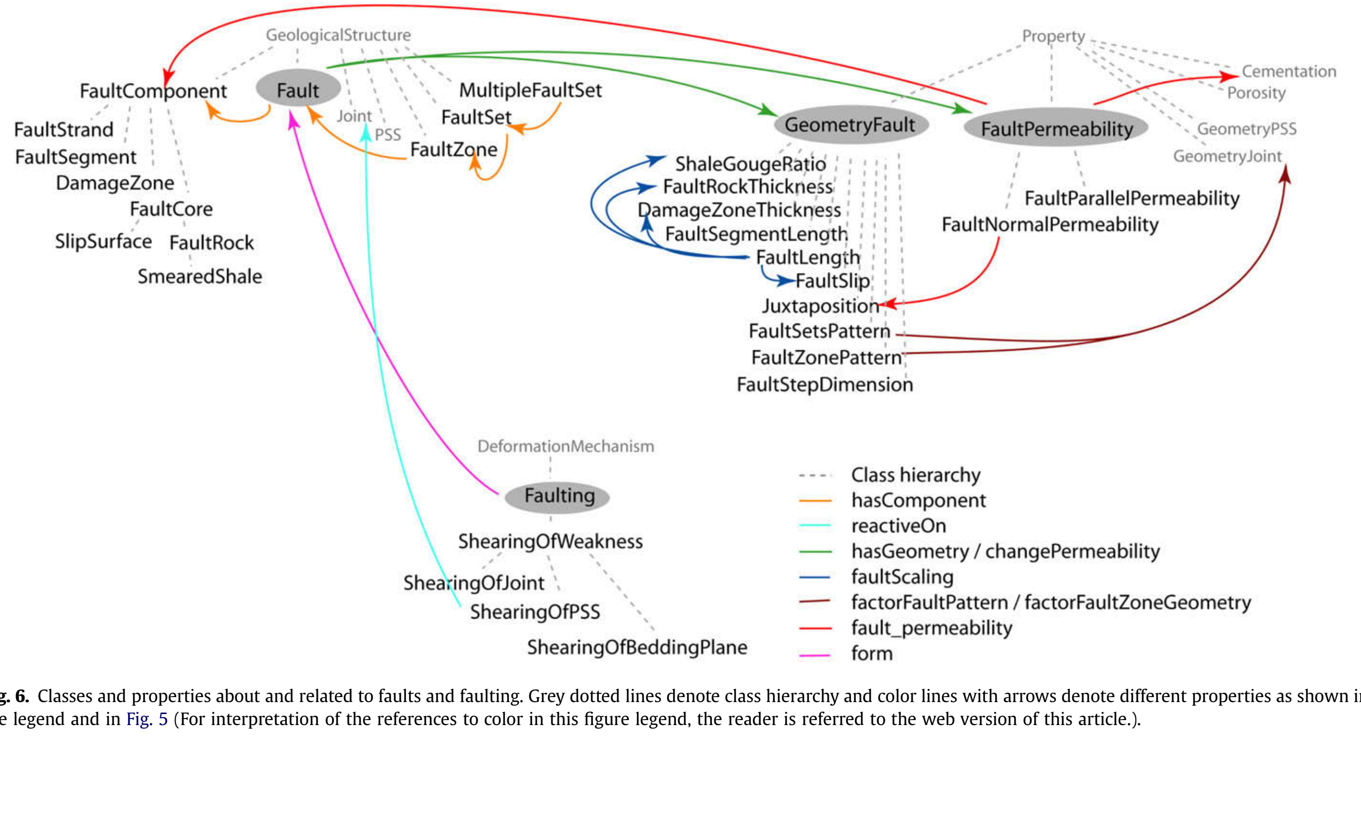

Fig. 6. Classes and properties about and related to faults and faulting. Grey dotted lines denote class hierarchy and color lines with arrows denote different properties as shown in the legend and in Fig. 5 (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

or strands (*Strand*) in all dimensions (Aydin and Nur, 1982; Cartwright et al., 1995; Kim et al., 2004). Normal to the direction of the fault trace, a fault core (*FaultCore*) consisting of fault rock, gouge, mylonite, breccia (Caine et al., 1996; Groshong, 1988), and slip surfaces or fault planes (*SlipSurface*) (Aydin and Johnson, 1978; Shipton and Cowie, 2001) or slip bands (*SlipBand*) (Ahmadov et al., 2007) surrounded by damage zones (*DamageZone*), which are composed of subsidiary faults, deformation bands, pressure solution seams, and joints in the form of splay fractures (Shipton and Cowie, 2001; Kim et al., 2004; Agosta and Aydin, 2006; de Joussineau and Aydin, 2007). Fault rock may be composed of cataclasite, a fine-grained fault rock formed by dominantly brittle fracturing, pore and grain size reduction, and sometimes recrystallization (Groshong, 1988). When shale or ductile rock is attenuated into the fault zone, they are called smeared shale or shale smear (*ShaleSmear*) (Weber et al., 1978; Yielding et al., 1997). Faults commonly occur in narrow zones (*FaultZone*) consisting of multiple strands or segments, in a set (*FaultSet*) consisting of multiple faults, and in multiple sets (*MultipleFaultSet*) consisting of several sets with different orientations (Fig. 2 and *hasComponent* in Fig. 6).

Faulting (*Faulting*, Fig. 3) is a macro-deformation mechanism (*DeformationMechanism*) that forms (*form*) faults. Faulting mechanisms include shear deformation banding (*ShearBanding*, Rudnicki and Rice, 1975), shearing of pre-existing weaknesses (*ShearingOfWeakness*, Segall and Pollard, 1983; Myers and Aydin, 2004), phase transformation or super shear (Green and Burnley, 1989; Burridge, 1973; Andrews, 1976). Based on the type of the weaknesses, there are sheared bedding plane-based faulting (*ShearingOfBeddingPlane*, Ohlmacher and Aydin, 1995; Cooke et al., 2000), sheared joint-based faulting (*ShearingOfJoint*, Segall and Pollard, 1983; Myers and Aydin, 2004), and sheared pressure solution seam-based faulting (*ShearingOfPSS*, Graham et al., 2003). The processes involved in faulting depend on the type of faulting, the type of initial weakness (*reactivedOn Joint*, *PSS*, etc, Fig. 6), and the rheology of rock.

Faults have properties which may be classified under geometric, petrophysical, and mechanical properties. For example, hydraulic properties of faults are important for application to fluid flow problems (Manzocchi et al., 1999; Jourde et al., 2002; Odling et al., 2004). In our ontology, hydraulic properties are considered to be under permeability, which has components with respect to the orientation of faults: fault-perpendicular or cross-fault (*FaultNormalPermeability* in Figs. 4 and 6) and fault-parallel or along-fault (*FaultParallelPermeability* in Figs. 4 and 6).

For the geometry of fault (*GeometryFault* in Fig. 4 and *hasGeometry* in Fig. 6), there are scaling relationships among the fault dimensions (*faultScaling* in Fig. 6). Other than dimensions, faults have several specific geometric and mechanical parameters (Fig. 4), like slip (*FaultSlip*, Scholz, 2002), juxtaposition (*Juxtaposition*, Knipe et al., 1997), segment length (*SegmentLength*, Cartwright et al., 1995) and step geometry (*StepLength* and *StepWidth*, Aydin and Nur, 1982), and shale gouge ratio (*ShaleGougeRatio*, SGR, Yielding et al., 1997) for smeared shale (*ShaleSmear*) in the fault rock. Faults also have patterns (*FaultPattern* in Fig. 4), such as branching pattern, echelon pattern for single faults and conjugate pattern (*Conjugate*) (Anderson, 1951; Davatze and Aydin, 2003; Flodin and Aydin, 2004), orthogonal pattern (*Orthogonal*), and Orthorhombic pattern (Aydin and Reches, 1982; Krantz, 1989) for multiple sets of faults. For weakness-based faults, the geometry of the initial weakness (*GeometryPPS*, *GeometryJoint*, etc…) affects the geometry of the faults, like the architecture of the fault zone (*factorFaultZoneGeometry* in Fig. 6) and the pattern of multiple fault sets (*factorFaultPattern* in Fig. 6).

The permeability of fault (*FaultPermeability*, in Figs. 4 and 6) may be significantly different than that of the host rock and may be an important property of faults. It is affected mainly by three factors (property *fault_permeability* in Fig. 6): the juxtaposition (*Juxtaposition* in Figs. 4 and 6) (Knipe et al., 1997), the geometry (*GeometryFault*) and property of fault components (*FaultComponent*) (Flodin et al., 2005), and the cementation (*Cementation*) and porosity (*Porosity*) due to syn- and post-faulting diagenetic events (Eichhubl and Boles, 1998).

3.4. Case study II: fault query expansion

In coordination with the Fault example in the previous section, an experiment with keywords "fault permeability" is conducted on two popular search engines in order to demonstrate the advantage of using our ontology for retrieving relevant information. From Fig. 6, subclass of *FaultPermeability* has property *isEffectedBy* with value *Juxtaposition* and *FaultComponent*. 'juxtaposition' is chosen as the expanded keyword since it is not in the original keywords. Two queries, 'fault permeability' and 'fault permeability juxtaposition', were thus run on Google and Yahoo!. The first 20 documents are judged for the relevance. A document is regarded as relevant when it gives guidelines or provides methodology about permeability changes related to a fault or faulting process. If a result links to a resource that is not accessible, like journal's archive that requires subscription, it is regarded as irrelevant. The precision for the top 20 ranked results were recorded (Table 1).

In both cases, the results with the expansion using our ontology show that more relevant results are returned (increased precision) compared to the query only paradigm. The expanded keyword provided by our ontology helps filter out irrelevant results. This result is especially valuable to unseasoned users who do not know which keywords to apply, and ironically the people who need to search for information most. Furthermore, being usable by computer programs, our ontology helps to save time by automating the process of expanding keywords for mechanism-related query.

4. Discussion

Our ontology is much more refined and detailed from any other ontology in the Earth Sciences. Specifically, it differs from the previously proposed Structural Geology Ontology (Babaie et al., 2006):

1. Our ontology covers fractures, where fractures include joints, veins, dikes, pressure solution seams, deformation bands, and faults.
2. Our ontology is process-based, covering the deformation mechanisms responsible for various types of fractures and faults and the interactions of these structures with geological, physical and chemical changes.
3. The property hierarchy in our ontology correlates structures, mechanisms, and physical properties together.

An ontology with the content highlighted above can be used by computer programs to better handle diverse data sources to assist human investigations. In addition to factual information about classes, subclasses, and their properties, our ontology is especially

Table 1
Precision for the top 20 hits (P @ 20) of keywords "fault permeability" and those after query expansion to "fault permeability juxtaposition". Data collected on April 03, 2008.

Keywords	Google	Yahoo!
fault permeability	0.20	0.30
fault permeability juxtaposition	0.45	0.50

valuable for mediating rationale types of information, such as "how do faults effect fluid flow?".

The first three core classes in our ontology have corresponding classes in the SWEET ontology (SWEET, 2005), in case other ontologies would need to compare to or merge with our ontology. The *GeologicalStructure* class can be mapped as subclass of *Feature* class in DOLCE (Bottazzi and Ferrario, 2006); or subclass of the *Strain* class in SWEET, which has subclasses *Fault*, *Fold*, and *Fracture*. The subclass *MacroDeformationMechanism* of the *DeformationMechanism* class is a subclass of the *MechanicalProcess* of SWEET. Each subclass of *Formation*, another subclass of the *DeformationMechanism*, including initiation and individual propagation and growth may be analogous to the *Event* referred to by Brodaric and Probst (2007). The *Property* class in our ontology is the same as the *Property* class of the SWEET ontology. There are a few overlapping terms, such as *Pattern*, *Roughness* and *Force*.

5. Conclusion

In this paper, we presented and discussed the architecture of the Ontology of Fractures. Our ontology is process-based emphasizing formation mechanisms of fractures, their geometry and petrophysical properties as well as their interrelationships. This ontology will be helpful for applications related to fractures, especially in defining and recognizing their types, formation mechanisms, properties, and their interrelationships. It improves information retrieval by enhancing search precision. Our ontology should also aid education of advanced students and communication among professionals from different but allied fields, such as structural geology, tectonophysics, geomechanics, rock physics, rock mechanics, engineering mechanics, hydrogeology, and petroleum geosciences dealing with rock fractures and their impact on a number of societal problems.

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