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Review

# Knowledge engineering in volcanology: Practical claims and general approach

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ABSTRACT

Knowledge engineering, being a branch of artificial intelligence, offers a variety of methods for elicitation and structuring of knowledge in a given domain. Only a few of them (ontologies and semantic nets, event/probability trees, Bayesian belief networks and event bushes) are known to volcanologists. Meanwhile, the tasks faced by volcanology and the solutions found so far favor a much wider application of knowledge engineering, especially tools for handling dynamic knowledge. This raises some fundamental logical and mathematical problems and requires an organizational effort, but may strongly improve panel discussions, enhance decision support, optimize physical modeling and support scientific collaboration.

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## 1. Introduction

The task of volcanic hazard and risk assessment, being the main practical purpose of volcanology, simultaneously poses a theoretical claim to rethink the whole body of volcanological knowledge, i.e., untangle the threads of inference, accurately select arguments to support or refute hypotheses, compare models, evaluate expert judgments and comprehend the field of knowledge in its entirety (e.g., reconstruct a full group of scenarios of unrest for a specific volcano). For a descriptive and language-dependent field like volcanology, this is a real challenge that suggests the need, first of all, to structure the knowledge and, wherever possible, semantically constrain it. This is why volcanologists make wide use of various graphic conceptualizations, along with verbal descriptions and quantitative data.

In the early days of volcanology, this was also strongly stimulated by the limited development of photographic techniques. Now, however, even the photographs in research papers are commonly supplied with notes, pointers, inscriptions and comments. In fact, every scientific drawing, including those based on a photograph, of a volcano or volcanic rock communicates a researcher's vision of its formation and

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dynamics and is an attempt to visualize (and sometimes also organize) scientific knowledge. At the same time, drawings in modern research papers (see, e.g., Fisher and Heiken, 1982; Branney and Kokelaar, 2002, and many others), supplied with terms and pointers, often resemble formalized graphic notations known from graph theory (Tutte, 1998), such as labeled graphs or hypergraphs (Gallo et al., 1993). Therefore, by representing and organizing the volcanological knowledge, the drawings become more and more formal and at some point can be readily substituted by simple boxes and arrows (nodes and arcs, in terms of graph theory) convertible into formalisms tractable by computer (Figs. 1a, b, c, 2a, b).

Looking at the above examples, some important observations can be made on how the knowledge is being represented and structured by conventional volcanological drawing. Indeed, these examples usually refer either (i) to a case when researchers aim to represent one scenario in one plot as shown in Fig. 1 (or even one scenario in several plots stage by stage), or (ii) show no scenario at all but merely the structure of a volcanic object (volcano, eruptive sequence and so forth) — this is exemplified by Fig. 2. Nevertheless, in historical reconstruction and especially in forecasting, it may be necessary to put several scenarios in one plot, methodologically speaking, to bring several alternative scenarios into one mental and intellectual framework.

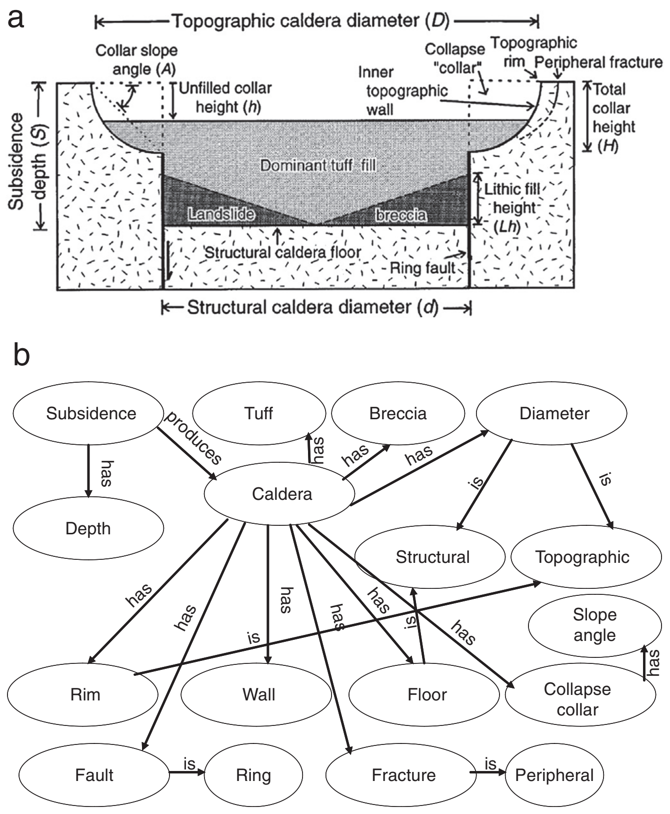


**Fig. 2.** Conceptual drawing of a caldera structure, after Lipman, 1997 (a) and formalized graphic notation showing the same (b). This notation can be converted into semantic network (Sowa, 2006).

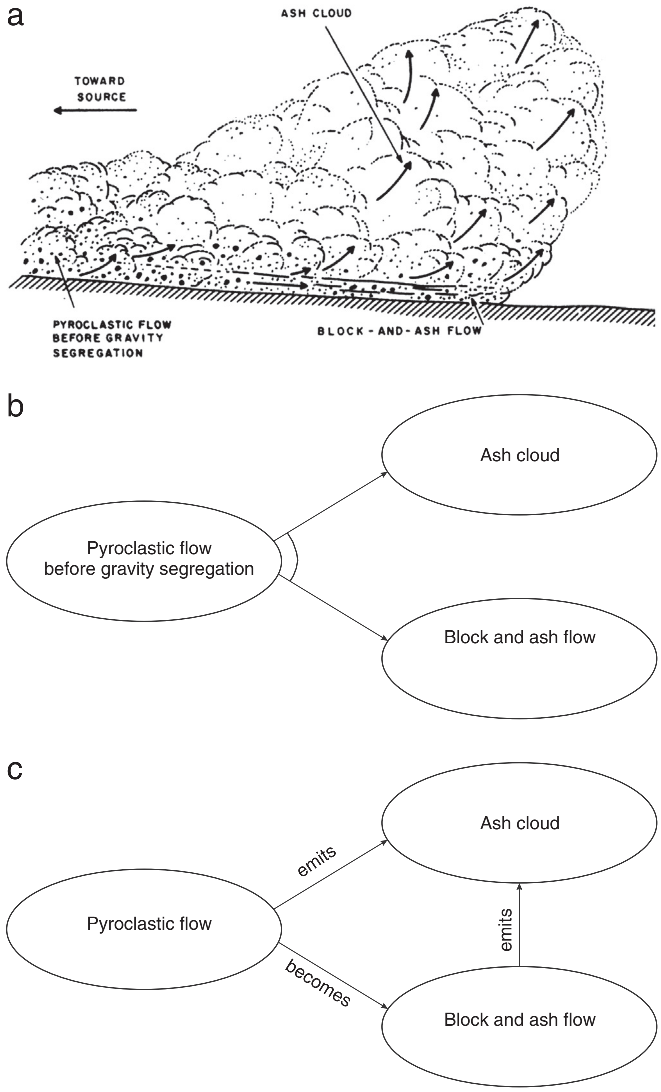


**Fig. 1.** Conceptual drawing of a pyroclastic flow behavior by Fisher and Heiken, 1982 (a) and formalized graphic notations showing the same (b). The notation at (b) can be represented as an AND–OR tree with the only "AND" node, by Giarratano and Riley (1998), and at (c), as a semantic network sensu Sowa (2006). This dual formalization illustrates that notation may better (c) or worse (b) match the modeled environment.

To achieve this, volcanologists depart from conventional drawing and apply purely formal graphic conceptualizations, such as event trees (Newhall and Hoblitt, 2002; Fig. 3), Bayesian belief networks (Aspinall et al., 2003; Fig. 4) and trees (Marzocchi et al., 2008; Fig. 5), UML class diagrams (Gehl et al., 2013; Fig. 6), flowcharts (Gehl et al., 2013; Fig. 7) and others. Definitions of these and other methods mentioned in the text are given in Appendix A.

As is seen from the above, the study of volcanology for decades has been inclined to use what is now called *artificial intelligence* (Giarratano and Riley, 1998). In fact, it appears to have extensively intruded itself into such fields of artificial intelligence as knowledge representation, knowledge management and knowledge engineering, which are tightly interrelated. Knowledge engineering, extending from acquisition of knowledge from experts to its representation in an expert system (Giarratano and Riley, 1998) – or, broadly speaking, in any kind of information system – is understood as a selection of methods of various origins (from statistics to psychology, from linguistics to physiology) to look at how qualitative (commonly, though not necessarily, verbal) expressions are treated by humans (Feigenbaum, 1984), and thus try to minimize the human subjectivity in information modeling (Pshenichny and Kanzheleva, 2011).

This raises a few questions, only some of which seem to have a straightforward answer. One issue that can be resolved relatively easily is the distinction between the volcanological knowledge per se and the knowledge of related human activities (from investigation to evacuation). Indeed, the examples presented in Figs. 6 and 7 clearly represent a

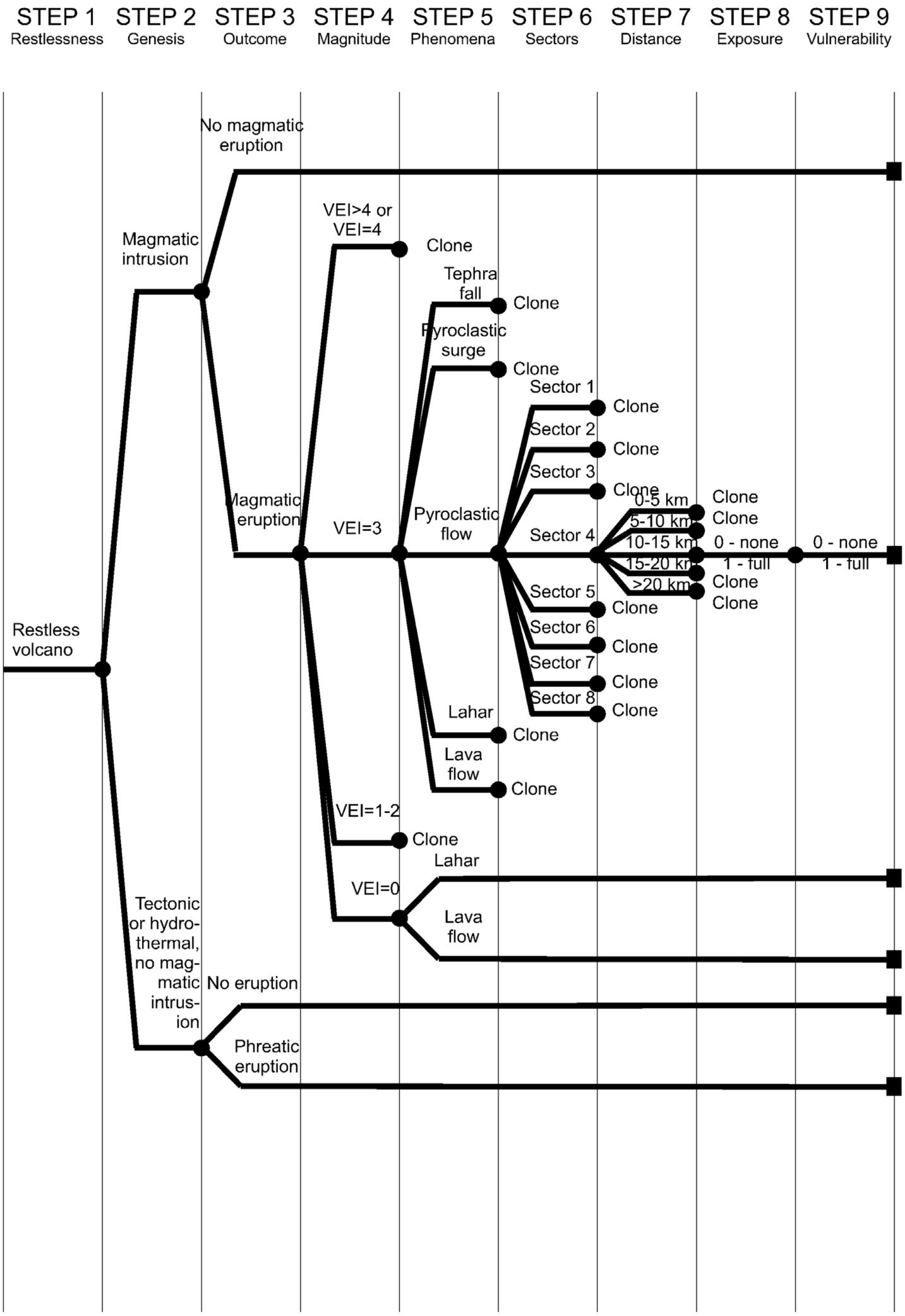


**Fig. 3.** A generic event tree for volcanic hazard and risk estimation (redrawn from Newhall and Hoblitt, 2002, with simplification). VEI stands for volcanic explosivity index. “Clone” means that branching at the node is the same as at the other nodes at the given step. For particular examples of event tree application, refer to Neri et al. (2008), Sobradelo and Martí (2010), Meloy (2006).

different kind of conceptualizations, representing not exactly the volcanic processes and scenarios of eruptions (environmental crises) but human response to them (i.e., research, assessment and mitigation activities). Strictly speaking, these conceptualizations fall into a generic field of administering human activities, but are specific to the domain under consideration (volcanology). This specificity is to be captured by the graphic conceptualizations addressing volcanism per se. It is exactly this kind of conceptualization that will be covered in the present paper.

One method, which can be used for both purposes simultaneously (modeling of natural processes and human response), was developed specially to address volcanic processes and scenarios. This is the event bush shown in Fig. 8. (Pshenichny et al., 2008, 2009; Pshenichny and Kanzheleva, 2011; Pshenichny and Mouromtsev, 2013).

However, there are many other problems of application of knowledge engineering in volcanology, which seem to have no obvious solution. These include, first of all,

(1) What is, or should be, the main scope of application of knowledge engineering in volcanology?
(2) What particular types of tasks and types of methods can be recognized?
(3) What is the role of graphic conceptualizations in knowledge engineering in volcanology?
(4) Whether there are, or can be suggested, rules for composition of graphic conceptualizations (placing of nodes, direction of arcs and so forth) that make them best suited for particular tasks of volcanology?

(5) What terminology should be preferred for use in the nodes?
(6) Is there a relation between knowledge engineering and systems for support of collaborative studies?
(7) What practical action should be taken to bring knowledge engineering to the practice of volcanological research?

Answering these questions, one would formulate the strategy of application of knowledge engineering in volcanology at the current state of knowledge and research. To do this is the purpose of the present paper.

## 2. Specificity of knowledge engineering in volcanology in relation to traditional fields

### *2.1. Knowledge engineering in traditional fields*

Having appeared in the 1970s to operationalize knowledge-based systems and help to create large systems for industrial and commercial use, knowledge engineering aimed to turn the process of constructing such systems from an art into an engineering discipline (Studer et al., 1998). It was traditionally focused on medicine, economics, technical writing and technical design, some fields of chemistry and biology and such particular fields of the geoscience as mineral exploration or hydrology. Knowledge engineering quickly evolved from transferring expert knowledge to a knowledge-based system to its present state, which is the modeling of the field of knowledge (or, broadly speaking, information domain) by a knowledge-based system. Later this process was termed information modeling by Pshenichny and Kanzheleva (2011) who suppose that the architecture of a successful model (i.e., knowledge-based system) may indicate something not only about the modeler's background but also about the modeled environment or phenomenon (e.g., a volcanic object). Hence, information modeling, like any other modeling, is a way of studying the material world.

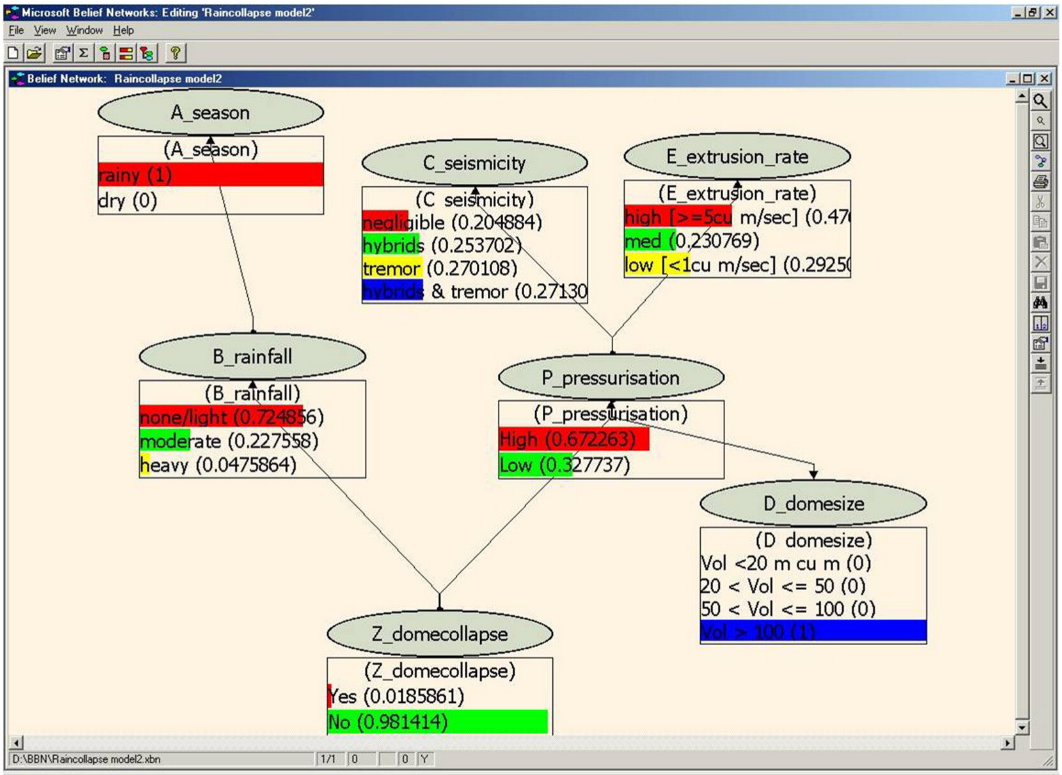
Giarratano and Riley (1998) stress that artificial intelligence, the discipline that includes knowledge engineering, is not just part of computer science and represents an independent field. Meanwhile, a knowledge-based system is commonly understood as a computer program for extending and/or querying a knowledge base. Such systems in volcanology are unknown to the author so far. Still, obviously, a program is just a form in which the algorithm is embedded, while the latter reflects an approach to organization of the knowledge base, which, again, may be more or less adequate to the field of knowledge, while this field mirrors the modeled object or environment. In this sense, a knowledge-based system does not need to be a computer program but is an information model of a studied phenomenon that organizes human knowledge about it.

Assuming this, it becomes possible to reason about the specificity of the process of knowledge engineering performed, even intuitively, by many scientists working in the field of volcanology.

### *2.2. Specificities of knowledge engineering in volcanology*

At this conceptual level, as is evident from the literature on information and semantic science, a common way of representing the knowledge base structure is a labeled graph, which is a mathematical object. Similarly, as shown in Figs. 1b, 2b and 3–7, intuitive volcanological conceptualizations are, or almost always can be, represented as labeled graphs (see, e.g., Pshenichny and Mouromtsev, 2013). Therefore, transition from natural-scientific intuition to mathematical formalism through a graphic conceptualization seems to be the mainstream of knowledge engineering in volcanology for the present day.

Then, at least the first steps of knowledge engineering procedure that precede computer implementation – assessment of the problem, development of a knowledge-based system structure and acquisition and structuring of the related information – are well seen in the practice of volcanologic research and hazard assessment and are very often performed keeping graphic conceptualization in hand or in mind.



(A_season)
rainy (1)
dry (0)

(C seismicity)
negligible (0.204884)
hybrids (0.253702)
tremor (0.270108)
hybrids & tremor (0.27130

(E_extrusion_rate)
high [>=5cu m/sec] (0.47
med (0.230769)
low [<1cu m/sec] (0.2925

(B_rainfall)
none/light (0.724856)
moderate (0.227558)
heavy (0.0475864)

(P_pressurisation)
High (0.672263)
Low (0.327737)

(D domesize)
Vol <20 m cu m (0)
20 < Vol <= 50 (0)
50 < Vol <= 100 (0)
Vol > 100 (1)

(Z_domecollapse)
Yes (0.0185861)
No (0.981414)

**Fig. 4.** A Bayesian belief network modeling possible behavior of Soufriere Hills lava dome, Montserrat.
Aspinall et al. (2003).

Also, such features of knowledge engineering as choosing different approaches for different types of knowledge, elicitation of expert knowledge (Martí et al., 2008) and calibration of expert judgments (Woo, 1999) are used in volcanology. So far, decision support and decision-making in volcanology are largely based either (1) on the subjective-probabilistic computation using the Bayesian belief networks or probability trees (Martí et al., 2008; Marzocchi et al., 2008; Neri et al., 2008), possibly with involvement of physical models for argumentation (Aspinall et al., 2003) or, alternatively, (2) on physical models in the framework of geographical information systems (Renschler, 2005). Then it may seem hard to explain why volcanologists have not advanced toward tight cooperation with knowledge engineers and creation of computer-based knowledge-based systems at least for decision-making and decision support.

Perhaps the reason for this rests in a different approach to modeling traditionally followed in the natural sciences. Modeling in knowledge engineering, though not necessarily pretending to reconstruct the way of reasoning of an expert, still more or less follows the "backward" order in relation to the phenomenon/environment in question, that is, from effects to causes, from symptoms to diagnosis and from assumed causes (or diagnosis) to recommendations. This determines the choice of problem-solving methods, such as heuristic classification (Studer et al., 1998). Though such an approach is appropriate in volcanology in some local tasks and/or at the beginning of research, the general pathway of reasoning is opposite, from supposed causes to possible effects, including unobserved ones. This is very well illustrated, e.g., by Bayesian belief networks, which may have dual use, from child nodes to parents ("normal way" in most knowledge engineering campaigns) and from parents to children (see, e.g., a network for the volcanic crisis in Montserrat by Aspinall et al., 2003). Exactly this "forward" way is shown in Figs. 1–7 illustrating the use of graphic conceptualizations in volcanology. Hence, there is a plain reason to think about formalized graphic conceptualizations used in volcanology as candidates for a new type of modeling frameworks and at the same time, importantly, a new type of structure of the knowledge bases, concordant with the behavior of natural environments and reasoning of researchers (experts).

An issue that needs to be discussed herewith is involvement of different types (formats) of knowledge in volcanological studies and assessments. Verbal descriptions and considerations, mathematical and physical models, drawings, photos and video footages illustrating the scientists' ideas all constitute the body of volcanological knowledge and complement, rather than replace, each other. Interrelation between verbal knowledge and physical (mathematical) models in the event bush framework was more or less set by Carniel et al. (2011) by the example of a basic physical law and a geophysical task. Each variable in their study was related to a subject or predicate used in the event bush, and every assumption and step of computation, to a connective (arc) of the event bush. The same can fully refer to the physical and other strict models used in volcanology — and perhaps not only to the event bush but also to other graphic notations provided that they are formalized enough.

Graphic or, generally speaking, visual information is extensively used in volcanological conceptualizations (see Figs. 1a and 2a) and may serve as a "tag" for terms in different natural languages (e.g., nuee

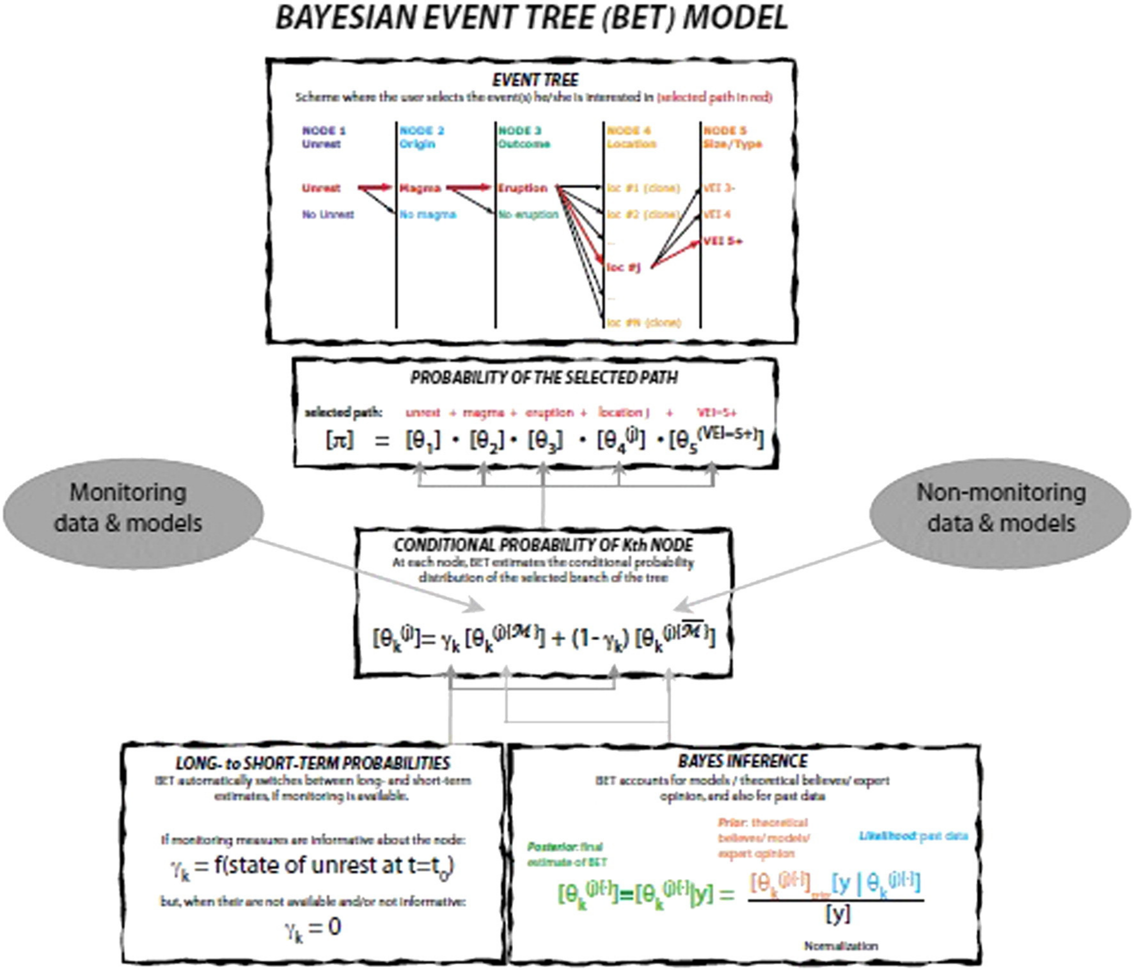


**Fig. 5.** Principal scheme of Bayesian event tree approach used to support decision-making in volcanology. Marzocchi et al. (2008).

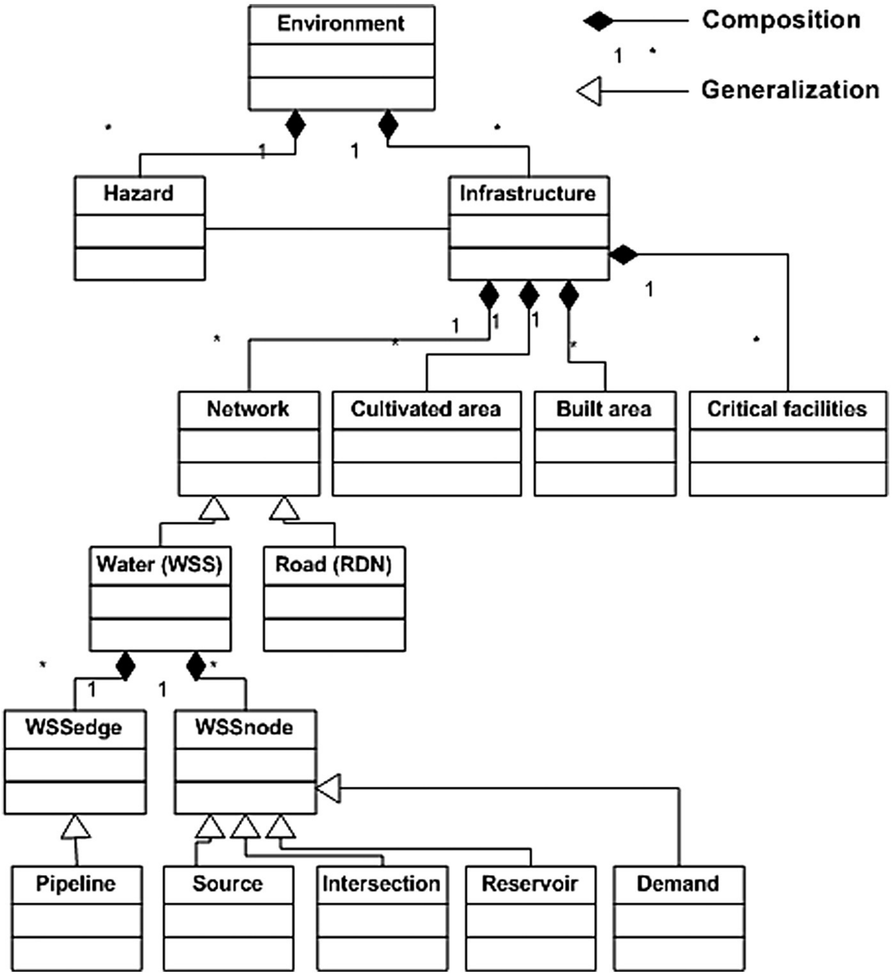


**Fig. 6.** UML class diagram of the infrastructure in vulnerable territory.
Gehl et al. (2013).

ardente, pyroclastic density current, flujo piroclastico, пирокластический поток). This property of graphic information works well in the collaborative studies support systems, e.g., COLLA (Diviacco, 2012) and may lead to very efficient online interlingual dictionaries in various subject areas.

Verbal formulations may represent a serious problem even when only one natural language is used because of the problem of meaning as thoroughly discussed by Diviacco (2012). Following Becher and Trowler (2001), he states that modern research communities resemble "tribes" that evolve separately — and eventually stop understanding each other. The reason for that resides in that a word has meaning only in a context, and exactly the necessity to bring different contexts together when exchanging data and ideas has led to the development of the systems for support of collaborative studies. In fact, these systems represent another tool and simultaneously a result of knowledge engineering. Diviacco et al. (2011) demonstrated that they may be efficiently used in volcanology, and at least some of the graphic conceptualizations used by volcanologists, e.g., the event bush, can successfully serve as a reference in a collaborative research space if brought into the COLLA environment.

Still, to allow not only an exchange of information but also an inference, such systems should be related to the knowledge-based systems. Then, however, we are back to the issue of language, because visual information can be brought into a knowledge-based system as a meaningful object, not just a tag, either if related to an element of a labeled graph as is done in Figs. 1b and 2b, or just formulated verbally. In the former case, however, there should be verbal expressions for the labels of the graph. Pshenichny et al. (2009) suggested that, aiming to best portray the field of knowledge, the terms in the labels should be descriptive, not explanatory. For example, the term "sediment current" looks more appropriate than "gravity-driven current", and the fact that it is driven by gravity should be expressed by (1) another node stating that gravity exists, and (2) a graphic primitive connecting the two nodes and indicating a cause-effect relation between the entities they denote ("Gravity exists → Sediment current originates"). In some cases, however, description can hardly be distinguished from explanation — e.g., washing-out is a description of an observed process and, at the same time, an explanation of changes in soil or rock. Also, wording should be kept as simple as possible because, commonly, the simpler the word, the easier it is to adopt it in a different context or adequately translate it into another natural language. Such simple words and phrases built of them in the nodes of the graph, along with the graphic primitives and their combinations, are potential tags for any number of any complicated terms from any context.

The issue of language and interlinguality is yet more important for another reason not so well-pronounced in most existing practices of knowledge engineering: while engineering volcanological knowledge, not only experts (possibly of different nationalities) are interviewed but also a vast number of publications including those published decades ago. Finally, actual volcanoes are "interviewed" by means of video footages and photographs, and their "answers" are interpreted, preferably in simple descriptive words, to be put into a knowledge-based system — or at least be related to the labeled graph that can be a modeling framework for it. This means, in effect, that it is neither a panel of experts nor texts that are queried, it is the *language* that is queried, and experts and

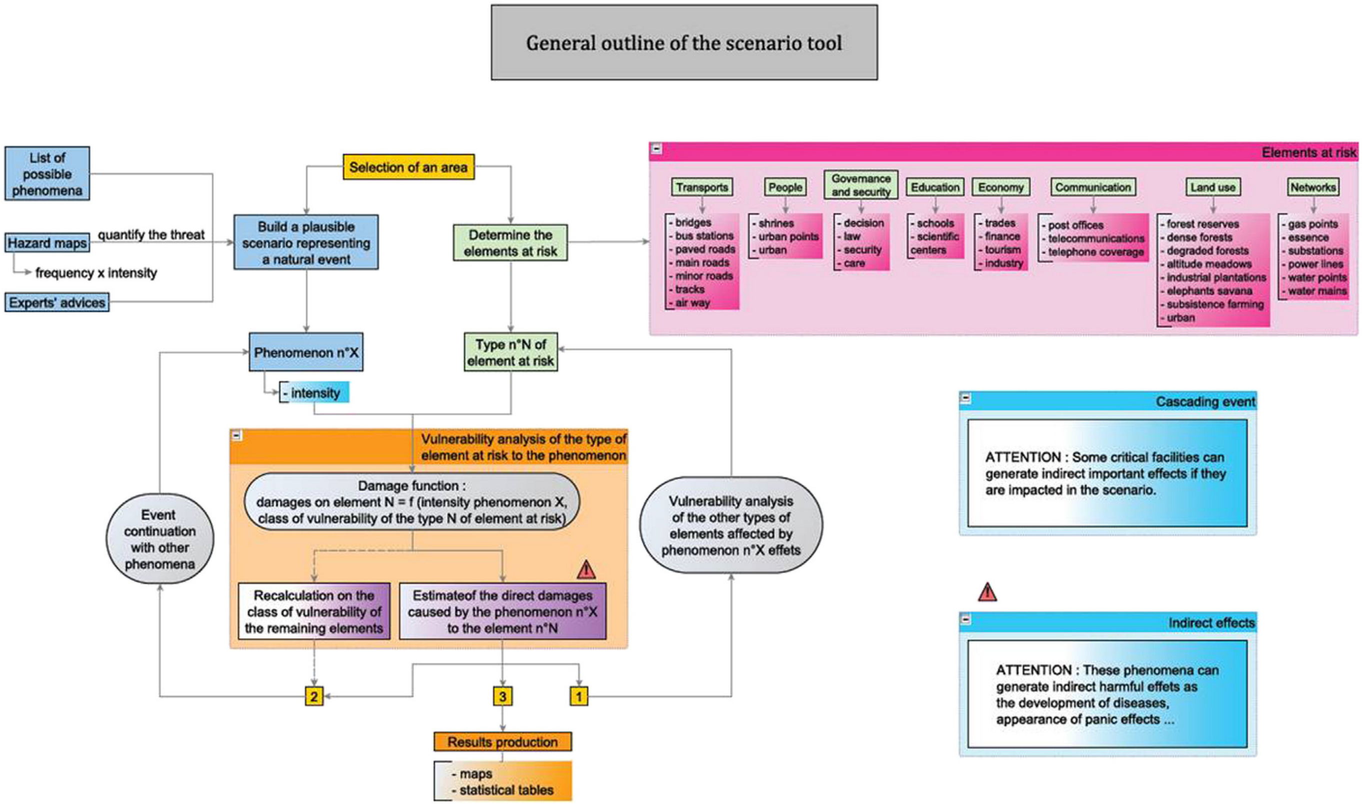


**Fig. 7.** General outline of scenario generator tool in the form of flowchart. From Gehl (personal communication).

texts only help to extract from it what it can offer on the proposed topic (e.g., lava dome collapse, or caldera-forming eruption, or Strombolian activity). The simpler the terms, the closer the "answers" will be in English, Spanish or even Japanese. However, combinations of these simple words and phrases built of them (that directly means complexity of labeled graphs) can be infinitely diverse, like formulae of propositional logic built of a limited number of elementary variables.

Moreover, when put in simple descriptive terms, many queries appear prototypic not only for volcanic environments but also for many others indicating that volcanic processes are often less specific than they seem. It is exactly this that gives a basis to, for example, apply the results of laboratory experiments on granular flows to ground-hugging pyroclastic currents or consider the interaction between the atomic power plant fuel with water and lava flow under the same term of FCI ("fuel–coolant interaction").

Along with construction of knowledge-based systems and computer support of collaborative studies, there are a number of other tasks in which knowledge engineering tools appear highly efficient. First of all, ontologies, being one of the main techniques of knowledge engineering, are similarly widely used for organization of datasets, and this has been already achieved in volcanology (McGuinness et al., 2007; Fig. 9). Then, the event bush has been used to numerically assess similarity/distinction between various eruptions of one volcano (Diviacco et al., in press). Last but not the least, graphic notations help to communicate knowledge to students and interested non-professionals (population, authorities, journalists, volcanophiles) in an easy, friendly and straightforward way.

## 3. Object-based and event-based tasks and methods

One more important specific feature of volcanology for knowledge engineering deserves special consideration and will be addressed in this section. This consideration brings us back to Figs. 1–8.

Geologists rarely have the luxury of observing how their objects are being formed. They commonly deal rather with "anatomy" than "physiology" of the Earth, and the processes in its interior are mostly reconstructed based on models and imagination. A typical example of this is in Fig. 2a.

Volcanologists, on the contrary, are lucky *to see* a lot, which is illustrated by Figs. 1a and 3–8. For volcanologists, a sequence of rocks in an outcrop or an ensemble of landforms or structures (e.g., that in Fig. 2a) are just a "paused narration", and the relations between rocks, structures and landforms seen at any moment are solely the consequences of general rules that govern their self-evolution and interaction with each other through time.

Reasoning about this difference, Pshenichny and Kanzheleva (2011) concluded that there exist two distinct classes of geoenvironment, (1) "no-change environments" that depict only bodies and their properties (i.e., subjects and their predicates) and will be henceforth denoted as static — a geological sequence, tectonic framework, ensemble of landforms and so forth, and (2) changing environments that describe how bodies and properties change with time or under conditions, referred to as event-based (flowing river, erupting volcano, ongoing tectonic movement and others). Similarly, knowledge engineering, depending on the type of environment, is regarded as dealing with static or dynamic knowledge (Pshenichny and Mouromtsev, 2013).

### 3.1. Object-based approach

Static, or "fixed", relations are perfectly captured by the well-known formalisms of ontologies (Figs. 2b, 9) and conceptual graphs (Sowa, 1992, 2000, 2006), as well as by numerous traditional knowledge representation tools: formal concept analysis — FCA (Poelmans et al., 2014), ontology web language — OWL (Web Ontology Language, 2009–2012), knowledge interchange format — KIF (Genesereth and Fikes, 1992), resource description framework — RDF (Resource

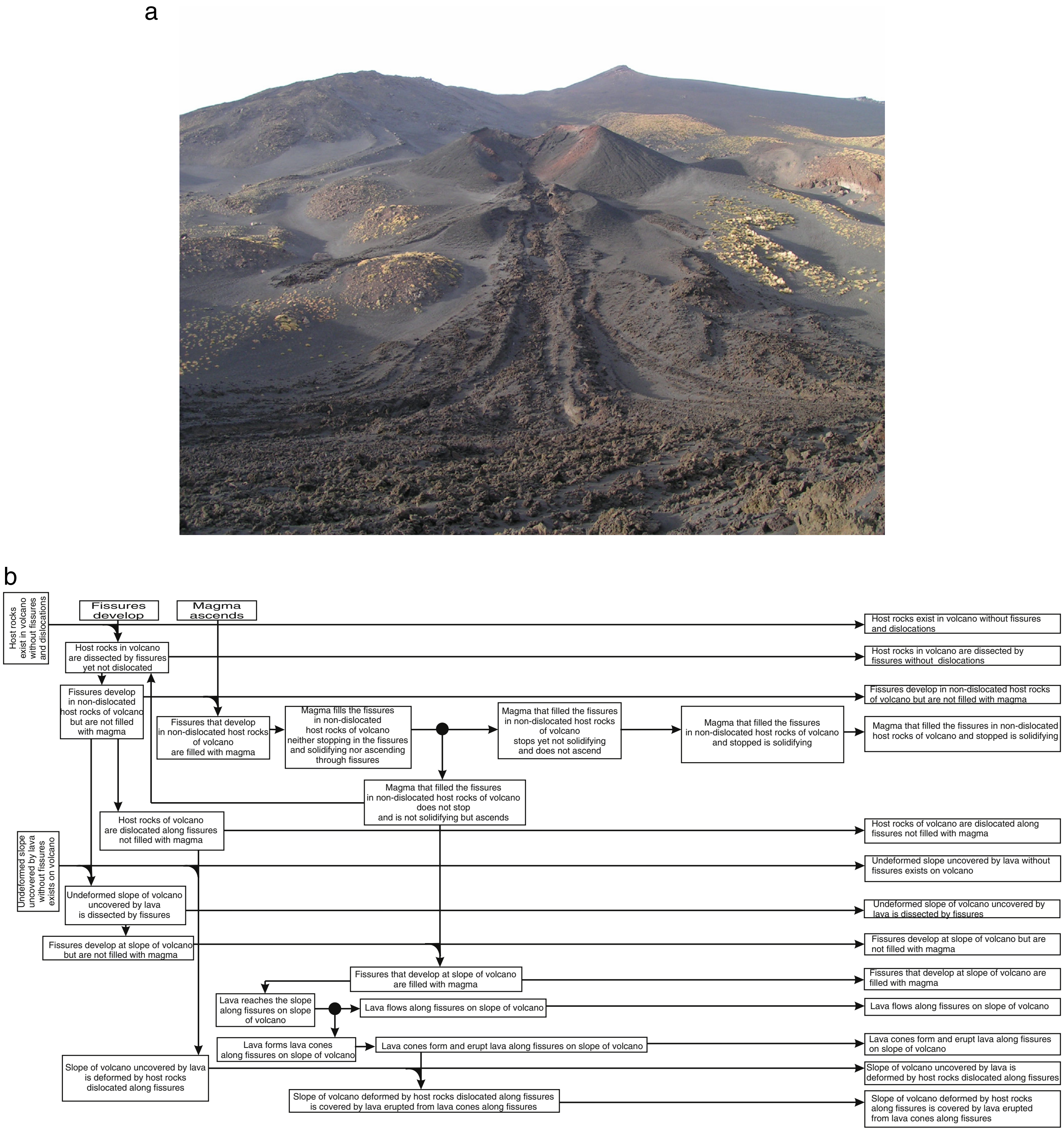


**Fig. 8.** An example of application of the event bush method to model a volcanic environment: (a), the environment proper (Mount Etna, Sicily, near Rifugio Sapienza), (b), the event bush explaining how the observed bodies were formed and what other bodies had to cogenetically form below the surface or could alternatively form on and below the surface.
From Pshenichny and Mouromtsev (2013).

Description Framework, 2004–2014), entity-relationship diagrams — ER (Chen, 1976), and many others, generally convertible into semantic nets sensu Sowa (2000), that operate with objects considered either as classes (i.e., types: concept types or relation types) or as individuals (Martin, 2002). Some of these methods, like OWL (Bonham-Carter et al., 2003; Brodaric and Gahegan, 2010; NADM, 2014) or FCA (Belohlavek, 2003), are well adapted by geoscientists (though still rarely by volcanologists, with few exceptions like McGuinness et al., 2007), and some, like conceptual graphs, still await application in the Earth-science domain.

Names of the objects appear in the boxes of graphic notations — e.g., “Rim”, “Wall”, “Caldera” and so forth in Fig. 2b or “Magma Reservoir”, “Magma Plumbing”, “Volcanic Systems” and others in Fig. 9. This is why they were denoted first subject-based by Pshenichny and Kanzheleva (2011) and then, more correctly, object-based by Pshenichny and Mouromtsev (2013) — see Fig. 10.

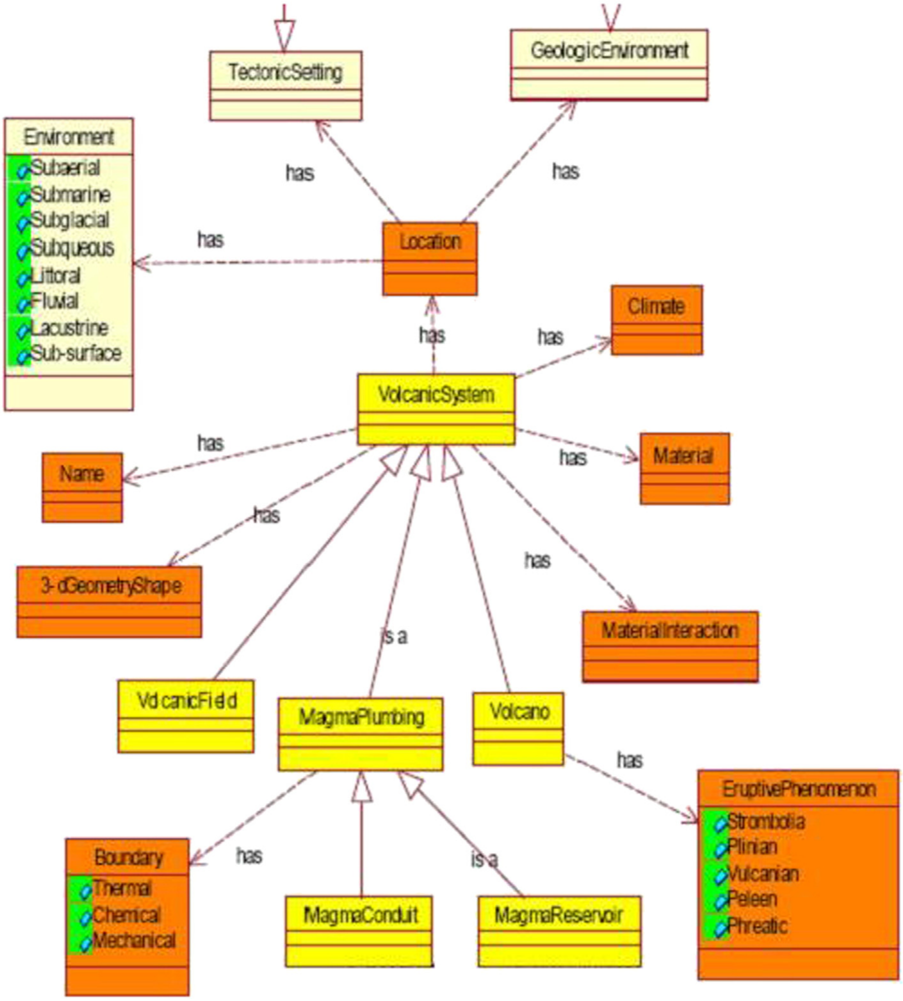
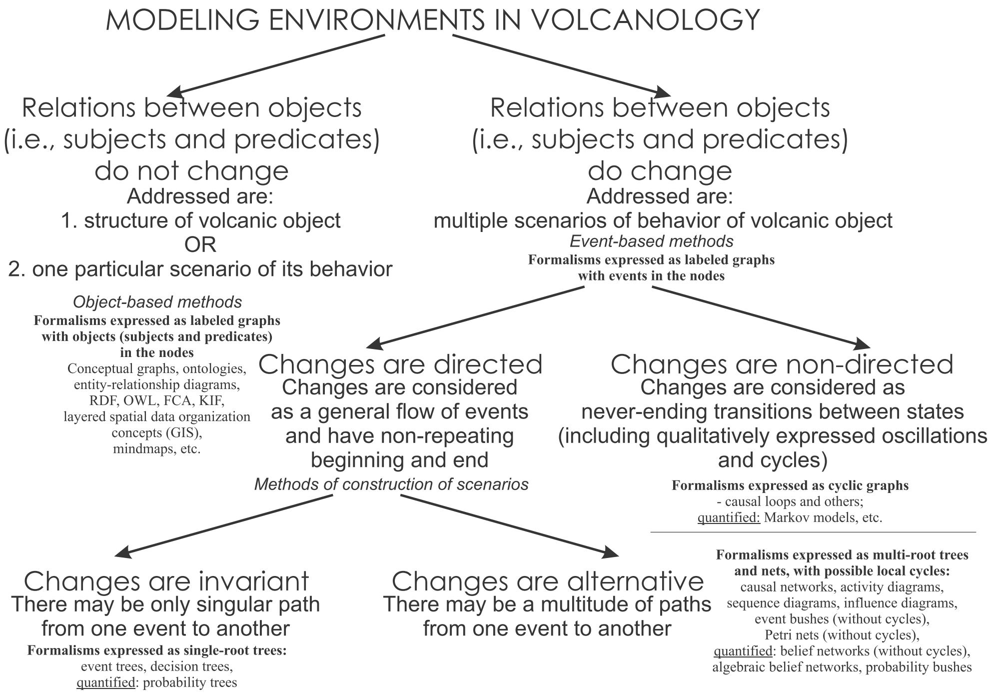


**Fig. 9.** An ontology of volcanic system.
Modified from McGuinness et al. (2007).


MODELING ENVIRONMENTS IN VOLCANOLOGY

Relations between objects
(i.e., subjects and predicates)
do not change
Addressed are:
1. structure of volcanic object
OR
2. one particular scenario of its behavior

*Object-based methods*
**Formalisms expressed as labeled graphs with objects (subjects and predicates) in the nodes**
Conceptual graphs, ontologies,
entity-relationship diagrams,
RDF, OWL, FCA, KIF,
layered spatial data organization
concepts (GIS),
mindmaps, etc.

Relations between objects
(i.e., subjects and predicates)
do change
Addressed are:
multiple scenarios of behavior of volcanic object
*Event-based methods*
**Formalisms expressed as labeled graphs with events in the nodes**

Changes are directed
Changes are considered
as a general flow of events
and have non-repeating
beginning and end
*Methods of construction of scenarios*

Changes are non-directed
Changes are considered as
never-ending transitions between states
(including qualitatively expressed oscillations
and cycles)
**Formalisms expressed as cyclic graphs**
- causal loops and others;
quantified: Markov models, etc.

Changes are invariant
There may be only singular path
from one event to another
**Formalisms expressed as single-root trees:**
event trees, decision trees,
quantified: probability trees

Changes are alternative
There may be a multitude of paths
from one event to another

**Formalisms expressed as multi-root trees and nets, with possible local cycles:**
causal networks, activity diagrams,
sequence diagrams, influence diagrams,
event bushes (without cycles),
Petri nets (without cycles),
quantified: belief networks (without cycles),
algebraic belief networks, probability bushes

**Fig. 10.** Classification of modeling environments in volcanology.

### 3.2. Event-based approach

Conversely, dynamic knowledge engineering methods focus not on relations between the objects but on relations between their combinations in the form of statements. Such relations are defined as *events* by Pshenichny and Mouromtsev (in press), and the methods that focus on them, event-based. *Event* is a set of statements of general form $S$ — $P_1$, $P_2$, …, $P_n$, where $S$ is subject, and $P_1$, $P_2$, …, $P_n$ are predicates, with or without negation, complying the following conditions: (1) subject may be only one in a statement, (2) subject may not be negated, (3) all predicates may not be negated in a statement, at least one must be without negation.

The relations between events are based on relations between the objects but cannot be reduced to these. For instance, considering the notion, "when a lava dome grows, rockfall seismic signal is received", we deal not with relations between the objects "lava dome", "to grow", "rockfall", "seismic signal", "to be received", but between the events "lava dome grows" and "rockfall seismic signal comes (is received)".

Importantly, dynamic knowledge engineering should be understood as engineering of dynamic knowledge, not as dynamic engineering of knowledge. There is quite a research done in the field of the so-called dynamic ontologies and ontology evolution (Stojanovic, 2004; Noy et al., 2006; Zablith, 2008; Murdock et al., 2010, and others), but the approach in this field is quite different and focuses on how to adapt ontology to changing phenomena, not to capture the changes in the phenomena themselves. Speaking about "evolution", "processes", "scenarios" and related issues, the researchers in this field mean the change of ontology proper, not of the world it describes, and look for solutions to keep ontology self-consistent despite the changing world rather than to model the changes of the latter. Thus, dynamic ontologies describe the same static knowledge but assume its incompleteness. So do the dynamic graphs (Demetrescu et al., 2005) and dynamic attributed graphs (Desmier et al., 2013), which perhaps can be applied to represent dynamic knowledge but this is not their virtue denoted as "dynamic". Similarly to ontologies, "dynamic" in this case means "editable" and refers not to the knowledge, but to the model that describes it and to the method to create such model.

Event-based methods include influence diagrams, Petri nets, event/probability trees, event bushes, Bayesian belief networks, causal loops, activity diagrams, sequence diagrams and other approaches. They make it possible to show scenarios of evolution of some domains and relations between the events. A possible application of some of them is shown in Figs. 12–13a, b. (See Fig. 11.)

Abundance and diversity of event-based environments is a feature of volcanology, and the approaches to their information modeling can be considered as a valuable contribution of volcano-informatics to general informatics. Also, this discourse may have an interesting intersection with the discussion of process-based environmental models in volcanology (Renschler, 2005), especially taking into account the existing experience of linking physical models to some of the dynamic knowledge engineering tools (Pshenichny et al., 2013). This type of environment was further classified by Pshenichny and Kanzheleva (2011; Fig. 10), and each subtype of it can be related to favorable graphic notations, used or usable in knowledge engineering. In Fig. 10, however, only the end-members of this classification are shown; there can be imagined, for example, alternative change environments with local cycles — for instance, a pyroclastic flow transforming into a surge and then back into a pyroclastic flow in a mountainous terrain. Pshenichny and Mouromtsev (in press) consider transitional environments in more detail.

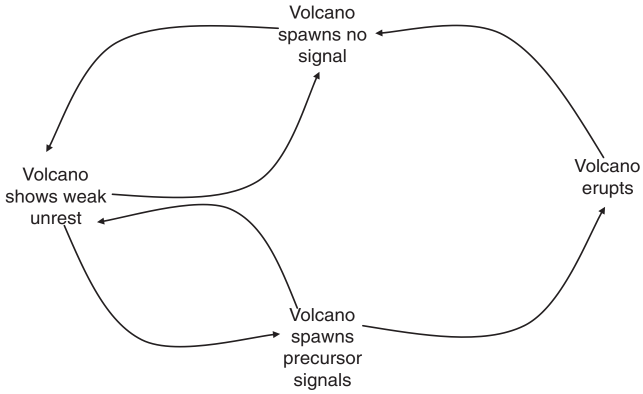


**Fig. 11.** Causal loop conceptualization of a cycle of volcanic activity.

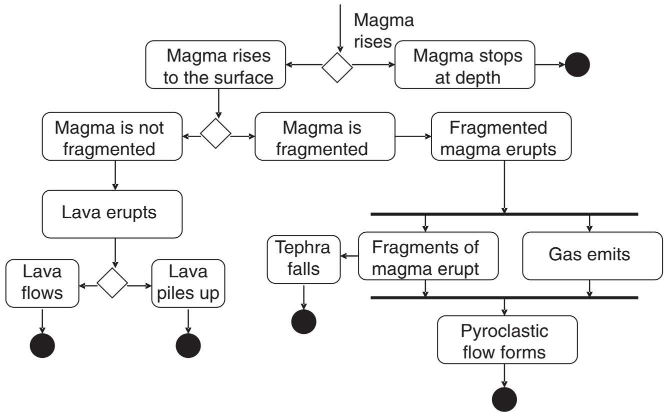


**Fig. 12.** Activity diagram describing main eruptive scenarios.

An important observation must be made here. If, say, a volcano is erupting explosively and the land around is covered with hot bombs and lapilli, intuitively one may suppose that such an environment is event-based where "volcano erupts explosively" and "land is covered with fresh ejecta" are the events linked by the "IF … THEN …" relation. This is well addressed by conceptual graphs. Meanwhile, if asked, *what* is changing, it would be difficult to answer based solely on the events listed above. To answer this question, an addition of two more events is needed, "volcano *was not* erupting" and "land *was not* covered with fresh ejecta". Unless no *change* in eruptive behavior of a volcano is noted, such environment should be considered as "no-change", or "static". Nevertheless, if other events are included with the same subject but a different predicate (or, in some cases, the same predicate but a different subject), this environment cannot be considered object-based anymore. But it is unlikely that notions like "Earth surface is not covered with fresh ejecta → Earth surface is covered with fresh ejecta" can be captured by a conceptual graph.

This can be put as a general rule for distinguishing "change" and "no change" environments: the change of events (i.e., a process) in an environment is meant as a change of existence of subject or predicate. As a result, either the subject of an event *does not exist anymore* and another subject appears in the next event (e.g., block and ash flow instead of pyroclastic flow in Fig. 1a), or a predicate acquires/loses a negation. The latter can be done either explicitly (e.g., "volcano is dormant → volcano is *not* dormant") or implicitly, if some predicates are considered crisp (not fuzzy sensu Zadeh, 1965) and mutually exclusive — e.g., "volcano erupts explosively → volcano is dormant". In the latter case, in fact, it is implied that "volcano erupts explosively and is not dormant → volcano does not erupt explosively and is dormant".

Inapplicability of conceptual graphs to reflect changing environments mirrors a much deeper problem. Being a graphic notation of the classical predicate logic, the conceptual graph has the same scope. The problem is, in fact, that no calculus of classical logic (see, e.g., Gentzen, 1934) allows us to introduce or eliminate singular negation in an inference, proceeding like $A \rightarrow \neg A$ or $\neg A \rightarrow A$. This requires another logical or mathematical formalism to account for changing environments (observed not only in

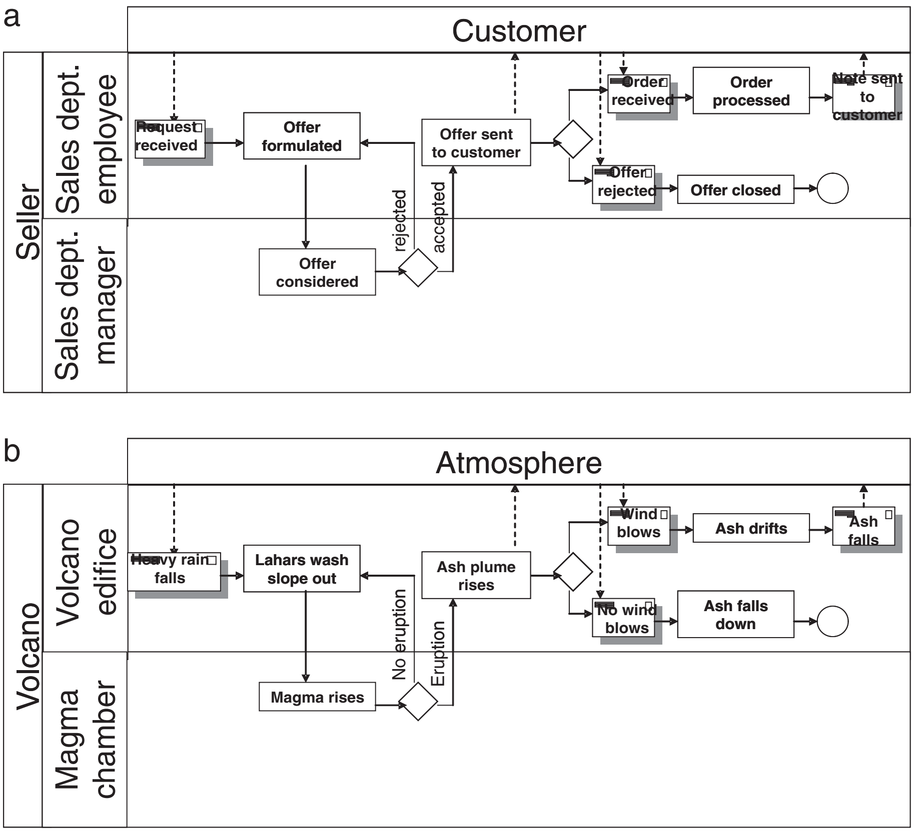


**Fig. 13.** An example of a similar sequence diagram depicting a market task (a) and a volcanic environment (b).

volcanology but also in a variety of fields). However, it should either be interpretable as an existing graph grammar reviewed, e.g., by Verejken (1993), or represent a new type of graph grammar.

Moreover, it looks reasonable to expect that this formalism would enable us to deduce ontological or conceptual graph (i.e., classical logical) relations from some generic relations or their changes.

It is exactly this formalism that should become the base for a unified event-based grammar, like classical logic is the base for ontologic, conceptual graph and other types of grammar for object-based environments. Such formalism is being developed now (Pshenichny and Mouromtsev, in press).

Absence of this formalism to the present day is the reason why, while the semantics of object-based methods is well defined, that of event-based ones (except probably the event bush) remains quite loose. Even the statements there are not always put explicitly, and this may make one erroneously take an event-based conceptualization for an object-based. This additionally stresses the need for formalized event-based grammar based on an ad hoc mathematical formalism.

## 4. Discussion: toward a complex strategy of knowledge engineering in volcanology

Even though the fundamental logico-mathematical problem of application of dynamic knowledge engineering tools is still unresolved, the existing framework allows one to speculate about particular strategies of application of knowledge engineering to respond to the practical needs of volcanology. This raises an implementation issue, which is complicated enough to be discussed separately.

Expert judgment elicitation, calibration and weighing take place at panel discussions for risk mitigation at Soufriere Hills, Vesuvius, Teide-Pico Viejo and other volcanoes. Panel discussions usually result in building a graphic conceptualization in the form of a probability tree, Bayesian tree or Bayesian belief network. Still, even in these activities a wider range of conceptualizations could be used, the event bush, sequence diagrams, activity diagrams and Petri nets to be named first of all. For instance, a recent experience of application of Petri nets to political issues (Rogalchuk and Solomin, in press) encourages their application in other largely descriptive fields such as volcanology. The models based on these conceptualizations can be attributed probabilistic or another quantification as discussed, e.g., by Koller and Friedman (2009) and Jensen (1996).

Also, graphic conceptualizations can be used in the research and presentation activities of such projects as Global Volcano Model (2013–2013), Earthcube (2013) and VHub (2008–2013). A conceptual basis for this could be the studies that link physical models to the event bush in seismology (Pshenichny et al., 2013) and systems of support of collaborative studies in volcanology based on the event bush (Diviacco et al., 2011). Especially promising could be the implementation of dynamic knowledge engineering tools in the development of process-based models.

Among these tools, special attention should be paid to a method addressing the most complex type of environment (directed alternative change), the event bush. This method not only structures knowledge in the given domain but also constrains it semantically and allows, inter alia, conversion in Bayesian belief network or direct probabilistic computation (Pshenichny et al. 2005), quantitative assessment of similarity of eruptions and eruptive centers (Diviacco et al., in press), hazard mapping (Anokhin et al., 2012), qualitative “parsing” of physical models (Carniel et al., 2011), building of expert elicitation protocols and online collaborative work (Pshenichny and Diviacco, 2011). However, the development of an entire framework of knowledge engineering methods based on a unified grammar of dynamic knowledge (Pshenichny and Mouromtsev, in press) is essential to best relate the experience and language of researchers, available data, models and knowledge of similar objects and existing computational methods to a particular task of volcanic hazard and risk assessment. The purpose of this framework is to semantically constrain all methods of dynamic knowledge engineering, making them equally rigorous, focused on particular types of task and thus complementary to each other.

Furthermore, keeping in mind that conceptual drawing is immanent in volcanological research, application of graphic conceptualization simultaneously as a means and a result of reconciliation of views, e.g., through systems of support of collaborative studies, could be effected virtually at any scientific discussion — e.g., meetings at the conferences and workshops may result in some kind of "final graph" or graphs summarizing the vision(s) of the problem under discussion, stressing the points of disagreement and lines for future research. Also, discussion sections in research papers may include a reference to such a graph provided as electronic supplementary material, with links to relevant data related to its nodes and arcs. Perhaps graphic abstracts optionally used in some research journals mark the beginning of such implementation of knowledge engineering in scientific publishing. Then, in the case of practical necessity – e.g., during a volcanic crisis, or at debates on waste disposal repositories in volcanic areas like Yucca Mountain, or at geological exploration activities at ore deposits of volcanic origin – such graphic conceptualizations could be easily retrieved, compared, elaborated further by panel of experts or even a team of fieldworkers — and stored again for future reference. This approach would save money and time and ensure involvement of the larger bulk of existing knowledge, making expert decisions more impartial and better grounded. Moreover, the shape of the graph and semantics of labels in its nodes would channel the discussion and, finally, the thinking of researchers. Thus the whole body of volcanology would be eventually rethought on a new basis, materializing the vision of pioneers of application of information technologies in the geosciences, see Loudon (2000), who foresaw that these techniques would transform the very way of thinking in the Earth studies.

At present this perspective encounters practical hindrances, such as

(1) The volcanological community's lack of awareness of many promising methods of knowledge engineering (evidenced by absence of works relating many existing methods to volcanological tasks);
(2) Misunderstanding of those methods being currently used — event/probability trees, Bayesian belief networks, ontologies (pronounced in the skepticism of many volcanologists to the formalized expert judgment elicitation procedures);
(3) Poor fit of the methods to the vision of researchers (as a possible reason for the misunderstanding of these methods);
(4) Poor fit of the methods to the tasks that they are used for (mostly, the use of ontologies to describe environments in which changes are essential).

The first shortcoming can be overcome by publications introducing the armory of knowledge engineering to the volcanologists, this paper being the first to pave the road. However, it should be noted herewith that dynamic knowledge engineering is quite a new field and needs to be organized itself. Hence, the practical claims of volcanology may stipulate the research in knowledge engineering.

The next points have a complex nature. As is evidenced by personal communications of many volcanologists involved in hazard assessment, the experts often do not understand the sense of elicitation procedure and especially the way of quantification of event tree or Bayesian network based on subjective probability values. One important action to be taken is establishment of a new subdiscipline in the field of volcanology, the reasoning research — similar to, or as a part of, a wider initiative that exists, though not too actively, for ten years (Reasoning Research in the Geosciences, 2003–2013). Perhaps a commission in the IAVCEI, specialized sessions at well-recognized international scientific meetings and a regular specialized peer-reviewed publication forum could facilitate this process. It should be stressed that, to avoid the necessity of additional "training of experts" prior to including them into panels has been informally suggested by some volcanologists who were in charge of decision-making or decision support, there should be a special professional specialization within the field of volcanology (or geoscience in general), the knowledge engineer in the given field. The experience shows that mathematicians or computer/information scientists, when operating as knowledge engineers, rarely understand the specificity of knowledge engineering in the field of volcanology, which was considered in two previous sections of this paper. Hence, knowledge engineers should be educated *within the field of the geoscience*, with development of appropriate university curricula.

Notwithstanding this, misunderstanding of methods by the volcanological community is sometimes aggravated by the poor fit of these methods to the task in hand, which may be caused by insufficient semantic accuracy of the method. For instance, experts complain that the Bayesian approach requires an input of numerous conditional probability values which have no meaning in terms of volcanology. This becomes especially painful when Bayesian networks are adapted to time intervals.

The poor fit of the methods to the tasks can be cured by the proposed classification of geoenvironments that allows, inter alia, to relate each research task and each method of knowledge engineering to its particular kind of environment (Pshenichny and Kanzheleva, 2011), thus looking for the best match. However, to fully solve this problem (e.g., to get rid of meaningless probability values) a unified strict event-based grammar and semantics are necessary.

The proposed approach is believed to form a strategy of application of knowledge engineering in a domain of knowledge that would be beneficial not only for volcanology but also for many largely descriptive fields with a wide range of changing environments, from geosciences to medicine, history and other fields.

## 5. Conclusions

The study of volcanology may benefit from knowledge engineering in decision support, clarification of opinions, storing knowledge in knowledge bases, linking strict models to verbal descriptions and education.

In volcanic hazard assessment, in addition, knowledge engineering is or shall be used for assessment of expert quality and weight for decision-making, calibration and elicitation of expert judgment, extraction of knowledge from experts for probabilistic computation of hazardous scenarios, reconciliation of expert judgments in panel discussion and shared decisions, communication of knowledge to nonprofessionals (population, authorities and decision-makers, journalists and other interested parties).

Transition from natural-science intuition to mathematical formalism through a graphic conceptualization and labeled graphs seems to be the mainstream of knowledge engineering in volcanology for the present day.

Unlike many fields of application of knowledge engineering, in volcanology the problem-solving proceeds largely not from effects to causes but vice versa, according to the nature of the studied environment, from causes to effects, and this determines the choice of modeling frameworks for knowledge-based systems.

Systems for support of collaborative studies may be efficiently used in volcanology but, to allow inference, they should be related to the knowledge-based systems.

Wording in the nodes of labeled graphs should be kept descriptive and as simple as possible, but phrases built of these words and combinations of phrases can be infinitely diverse.

In applying knowledge engineering to volcanology, the context should neither be a particular expert or expert panel, nor even a volume of literature but the entire natural language.

Depending on the type of the studied environment, tools of engineering of static or dynamic knowledge may be applied.

Tools for dynamic knowledge, describing the most specific and diverse type of volcanic environment, still lack semantic strictness, and this issue seems to refute the applicability of classical logic and claims for a development of another logical or mathematical formalism.

Appropriate and extensive application of knowledge engineering may transform the entire field of volcanology leading to its thorough rethink. This would bring immediate practical benefits at reducing costs and time and increasing the quality of expert decisions. Nevertheless, a considerable action needs to be taken including the establishment of publication media and educational curricula to make this perspective come true.

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This paper is written in memoriam Boris Grigorievich Fyodorov (1933–1996), the author's first teacher in the geoscience, a pioneer of formal thinking and information studies in geology. His ideas, running well ahead of time, still need to be understood and put to work. They remain largely unknown to the international scientific community by three reasons. First, his independent thinking and readiness to desperately fight for truth in science and in life did not favor abundant publication in the Soviet, science full of ideological and other rigors. Then, his bitterly early and immediate death in 1996, shortly before computers became easily available for Russian scientists, did not allow either him or his students and friends to save his work in an electronic format. And finally, he did not care about the authorship too much. Like Leibnitz, whom he was conversing with all his life, or other great thinkers of the past, he was just shining on everyone who occurred near, disseminating his thoughts and revelations, often in the form of a joke. Some of his thoughts gave the seeds in the minds of others, some did not. Once he said to the author of this text, "Sooner or later we will manage to clearly see, how a river is flowing its information to us". In twenty years, this phrase, rethought manifold, led to the method of event bush and a concept of knowledge engineering framework in the field of volcanology.

## Appendix A. Definitions of the methods and tools of static and dynamic knowledge engineering and representation

Quite a few methods and tools used or usable in knowledge engineering and representation have been mentioned in this paper. To help the reader understand what these methods are (or at least get a general idea), their definitions are given below. It should be stressed that only definitions are presented, not the consideration of application, or pictures with examples. All this can be found in the sources referenced below.

Also, the definitions are given without any attempt to justify their proposed position in the cluster of static or dynamic knowledge engineering tools or interrelation with each other. These issues will be thoroughly debated in forthcoming publications based on the unified grammar of dynamic knowledge (Pshenichny and Mouromtsev, in press). Related terms are often not defined too, but the reader is referred to publications where he/she can find appropriate definitions.

The methods are listed in the order that they appear in the text of the paper.

*Event tree* is a "graphical, tree-like representation of events in which branches are logical steps from a general prior event through increasingly specific subsequent events (intermediate outcomes) to final outcomes" (Newhall and Hoblitt, 2002, p. 3).

*Bayesian belief network* is a "graphical construct in which multiple uncertain variables are represented by separate nodes, and causal or influence links between nodes are represented by arcs (Jensen, 1996). Associated with each node is a set of conditional probability values, expressing the relationships of the states of that node to any others in the network to which it is linked. These relationships can be given in terms of statistical probability distributions, when data are plentiful, as discrete condition states when hard information is available, or as subjective probabilities or expert opinion when evidence is uncertain and sparse. Behind the graphical interface of a BBN lies the numerical means for computing possible Bayes' Rule outcomes, with whatever type of information is input" (Aspinall et al., 2003, p. 280).

*Bayesian event tree* is based on the event tree (Newhall and Hoblitt, 2002) and proposes some significant novelties like the introduction of the fuzzy approach, the inclusion of a node for the vent location, and an improvement of the statistics formalism (Marzocchi et al., 2008).

*UML class diagram* is a UML structural diagram (UML stands for unified modeling language) that includes the following nodes and edges:

(1) Association
(2) Aggregation
(3) Class
(4) Composition
(5) Dependency
(6) Generalization
(7) Interface
(8) Interface
(9) Realization (OMG Unified Modeling Language™, 2011).

*Flowchart* is a broad term to denote a graph-based notation depicting algorithms, workflows or processes based on a standard graphic notation, which uses arrows as arcs and a set of nodes of fixed types of meaning: a start or stop point of a process, an operation or action step, a question or branch in the process and so forth. There exist several sets of nodes suggested by Gilbreth and Gilbreth (1921) for optimization of technical drafting, Goldstine and von Neumann in 1947 (Goldstine, 1972) for programming, and Yourdon and Constantine (1975) for description of workflows and software engineering.

*Event bush* is a method of dynamic knowledge engineering that aims at the construction of scenarios in environments of directed alternative change, is based on the multiflow structure and must include the connectives of flux and influx and may include the connectives of conflux and furcation (Pshenichny and Kanzheleva, 2011; Wolter and Pshenichny, submitted for publication).

*Probability tree* is an event tree with probability values attributed to its nodes or conditional probability values attributed to its arcs.

*Geographic information system* is an integrated collection of computer software and data used to view and manage information about geographic places, analyze spatial relationships, and model spatial processes (ESRI Support, 2014; http://support.esri.com/en/knowledgebase/GISDictionary/search).

*Heuristic classification* is a problem-solving approach that describes reasoning in terms of goals to be achieved, actions necessary to achieve these goals and knowledge needed to perform these actions (Studer et al., 1998).

*Ontology* is a set of representational primitives with which to model a domain of knowledge or discourse. The representational primitives are typically classes (or sets), attributes (or properties), and relationships (or relations among class members) (Gruber, 2009).

*Conceptual graph* is "a variety of propositional semantic networks in which the relations are nested inside the propositional nodes. They evolved as a combination of the linguistic features of Tesnière's dependency graphs and the logical features of Peirce's existential graphs with strong influences from the work in artificial intelligence and computational linguistics" (Sowa, 1987, p. 8).

*Formal concept analysis* (*FCA*) is the part of the theory of concept lattices dealing with applications to analysis of object-attribute data (Belohlavek, 2003).

*Ontology web language* (*OWL*) is a "computational logic-based language such that knowledge expressed in OWL can be exploited by computer programs, e.g., to verify the consistency of that knowledge or to make implicit knowledge explicit. OWL documents are known as ontologies" (Web Ontology Language (OWL), 2009–2012).

*Knowledge interchange format* (*KIF*) is a formal language for the interchange of knowledge among disparate computer programs that allows one to understand the meaning of expressions in the language without appeal to an interpreter for manipulating those expressions. It has declarative semantics, provides for the representation of nonmonotonic reasoning rules and for the definition of objects, functions, and relations (Genesereth and Fikes, 1992).

*Resource description framework* (*RDF*) is a standard model for data interchange on the Web that extends the linking structure of the Web to use URIs to name the relationship between things as well as the two ends of the link (Resource Description Framework (RDF), 2004–2014).

*Entity–relationship* (*ER*) *diagram* is a data modeling technique that creates a graphical representation of the entities, and the relationships between entities, within an information system. Its three main components are:

1. The entity, which is a person, object, place or event for which data is collected;
2. The relationship, being the interaction between the entities;
3. The cardinality that defines the relationship between the entities in terms of numbers (TechTarget, 2000–2014).

*Semantic net* in a broad sense is a graphic notation for representing knowledge in patterns of interconnected nodes and arcs. Computer implementations of semantic networks were first developed for artificial intelligence and machine translation, but earlier versions have long been used in philosophy, psychology, and linguistics (Sowa, 1987).

*Mindmap* is a semantic net with a central node denoting the issue of consideration and radial arcs going out of it to the nodes that specify its meaning in different aspects, possibly with similar continuation after some or all of these second-order nodes. In its present form it was defined and implemented by Anthony Buzan, though many great thinkers of the past had used more or less similar approaches (Mind-mapping, 2006–2014).

The *Markov chain* is a sequence of trials of an experiment such that (1) the outcome of each experiment is one of a set of discrete states and (2) the outcome of an experiment depends only on the present state, and not on any past states (Markov, 1906).

*Causal network* is an acyclic digraph arising from an evolution of a substitution system, and representing its history (Wolfram, 2002).

*Algebraic belief network model* is an additive belief network model that allows multiplicative decompositions of a belief network (Dagum and Galper, 1993).

*Dynamic ontology* is an ontology that can be corrected (or, in other words, can *evolve*) with new input data (Zablith, 2008).

*Dynamic graph* is a graph that is subject to a sequence of updates (Demetrescu et al., 2005).

*Dynamic attributed graph*, combining the above definition of dynamic graph by Demetrescu et al. (2005) and that of attributed graph by de Lara et al. (2007), should be understood as a graph with some algebra attributed to it, which is subject to a sequence of updates.

*Influence diagram* (also called a relevance diagram, decision diagram or a decision network) is a generalization of a Bayesian network, in which not only probabilistic inference problems but also decision making problems can be modeled using the maximum expected utility criterion. This type of diagram was developed by a decision-analysis community to express expert knowledge, uncertainties, objectives and decisions (Morgan and Henrion, 1998). Correspondingly, it has directed arcs and different types of nodes relating to the above issues.

The *Petri net* is a directed labeled bipartite multigraph whose structure is defined by a tuple $\{P, T, I, O\}$, where $P = \{p_1, p_2, \ldots, p_n\}$ is a set of places, denoted as $p_i$, $T = \{t_1, t_2, \ldots, t_m\}$ is a set of transitions, denoted as $t_j$, $I$: $P \times T \rightarrow \mathrm{N}$, an application of precedence, and $O$: $P \times T \rightarrow \mathrm{N}$, an application of incidence, N being the set of natural numbers (Petri, 1977).

*Causal loop* is a cyclic causal diagram that includes nodes representing the variables and edges expressing a relation between the two variables (Sterman, 2000).

*Activity diagram* is a graphical representation of workflows (Glossary of Key Terms at McGraw-hill.com, 2014) whose nodes include

1. rounded rectangles represent actions;
2. diamonds represent decisions;
3. bars represent the start (split) or end (join) of concurrent activities;
4. a black circle represents the start (initial state) of the workflow;
5. an encircled black circle represents the end (final state); and arrows represent the order in which activities happen (OMG Unified Modeling Language™, 2011).

*Sequence diagram* (also known as event diagram or event scenario) is an interaction diagram that shows how processes operate with one another and the order of their interaction. It includes parallel vertical lines (lifelines) representing different processes or objects that live simultaneously, and horizontal arrows meaning the messages exchanged between them, in the order in which they occur (OMG Unified Modeling Language™, 2011).

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