Static and Dynamic Knowledge Modeling in Geotectonics

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Abstract. Geotectonics, being one of the main geological disciplines, encounters conceptual difficulties that likely can be resolved by application of methods of knowledge engineering. However, a strategy of their application is needed. The role of ontologies in the knowledge-engineering process is to facilitate the construction of a domain model. This model can be either static, i.e., address only the observed geological structures and landforms, or dynamic, accounting for processes that operate in and below the earthcrust. Both types of model are required to overcome the conceptual problems of geotectonics, but while the former is more or less present in the literature, the latter represents complete terra incognita. Meanwhile, exactly the dynamic knowledge modeling is the most important for a field like geotectonics.

Keywords: Plate tectonics, structural geology, knowledge engineering, ontology

1 Introduction

The term “tectonics” originates from a Greek word, “tekton”, which literally means builder. Later this word acquired a wider meaning that included the whole process of creation of something, including such connotations as techniques of construction, properties of the material and principle of creation, or architecture (Laugier’s (1753), Botticher (1852), Semper (1951) and Liu and Lim (2009)). In the Earth sciences, this word is known at least since 1894, when it was said at the 6th International Geological Congress, Switzerland, to describe the mammoth architecture of the Alps and Jura Mountains (Franks and Trumpy, 2005). Since that, the tectonics began to form as a subdiscipline of geology and was defined as the branch of geology that deals with the architecture, or structure, of the outer part of the solid Earth. The same time, the account for regional structural or deformation features and the study of their interrelationship, origin and evolution was referred to another subdiscipline called structural geology. The distinction between the two is often blurred, especially at regional and local scales, as both describe the principles and mechanisms of rock dislocation and deformation. To handle the ambiguities, a few terminologies were added, e.g., geotectonics for the study of tectonic features in regional scale, global tectonics, for research of tectonic processes related to very large-scale movement of material within the Earth, megatectonics, a tectonics of very large structural features of the world with respect to time (now rarely used).

It is accepted in knowledge engineering that a model in particular domain is built in process of human-computer (or expert – knowledge engineer) interaction and thus largely reflects the way of thinking of the expert. Relying on multiple experts decreases the "human component" but still keeps the record of personal experiences. Here the emphasis is somewhat different; it is not intended to create a cognitive model, i.e. to simulate the cognitive process of expert. Instead, the challenge is to create a model that represents "bare knowledge" and, as such, offers as much bias-free results as possible. While the expert may consciously articulate some parts of his or her knowledge, he or she will not be aware of a significant part of this knowledge since it is hidden in his or her skills. This knowledge is not directly accessible, but has to be built up and structured during the knowledge-acquisition phase. Therefore, at some point (known to or felt by knowledge engineer) the acquisition of knowledge from particular experts (or texts) should be replaced by building a model, desirably as bias-free as possible. Certainly, any model is only an approximation of the reality. Apparently as well, the modeling process is infinite. However, in every knowledge engineering process the stages of knowledge acquisition and model construction should be, from one side, clearly divided, and from the other, tightly interrelated. In our opinion, the best connection between them could be ontology of considered domain of tectonic knowledge. Creation of ontology or relation of extracted knowledge to some pre-existing ontology should be the result of knowledge acquisition and starting point for knowledge modeling.

Ontology provides vocabulary of terms and relations to a model. The closer it is to the domain of interest, the better the model will be. For instance, if ontology perfectly suits the domain, then a domain model in some cases can be obtained just by filling the ontology classes with instances. However, this rarely happens, first, because the nature of ontology is to be generic, while domains of interest usually occur at intersection or as particular cases of such generic domains, and then, because only static model, assuming that modeled environment does not change, can be obtained right from ontology (see below). Also, ontology helps avoid mixture and overlap of meanings and figure out groundless meanings. For example, geologists often use 'subsidence' and 'uplift' to indicate crustal movements against sea level, however, ignoring the fact that the concept "sea level" is related to other concepts which indicate "exterior" phenomena (e.g., river flow discharge or precipitation from atmosphere) that may change simultaneously with crustal movements (i.e., there will be nodes in ontology denoting these exterior phenomena and nodes denoting blocks of the earth crust, and both types of nodes will be bound with the third type, indicating the periods of time, by similar relation, say, "change" or "vary within").

One can evidently see a two-tier division in modeling of tectonics and related disciplines, (i) modeling of the morphologic features, or "anatomy", of the lithosphere, its interior and surface, and (ii) modeling of the processes that govern the anatomy, i.e., the "physiology" of the lithosphere.

The case (i) implies static entities, like the shape and size of landforms studied by the morphological subdiscipline of geomorphology (when mathematically formalized, this subdiscipline is known as morphometry) or anatomy of geological structures (studied by structural geology that performs description of form, arrangement, representation and analysis of structures that are seen in rocks). It is noteworthy that the "anatomy" of the surface and that of the interior need not to be corresponding each other. Thus, hills may well correspond to synclines and vice versa. Sometimes, if the data are accurately presented, a detailed description may bring an illusion that the static part of scientific research gives full explanation to the phenomenon under study. Still it lacks understanding of the same phenomenon across time and under different parameters.

In case (ii), the processes (i.e., dynamic entities) that govern the anatomy are the focus of study. The dynamic entities change in time and space under some external or internal conditions. Nonetheless, unlike structural geology, this sub-discipline of tectonics has no specific term, though may more or less pass under the term geodynamics. Still, geodynamics is commonly meant to deal specifically with the forces and processes of the interior of the Earth. Therefore, to avoid ambiguity, in this paper the following terms are suggested, morphologic tectonics and dynamical tectonics. Such division is natural for many sciences, e.g., anatomy and physiology (of plants, animals and men), planetary science and cosmogony. "Static" (classification) branches are clearly seen in history, while the main body of its knowledge is certainly "dynamic". In general, one may say, on one hand, that "static" subdisciplines address the composition and structure of systems, and "dynamic", the dynamics, function and evolution of the same systems, in terms of Bogdanov (1926) later replicated by Von Bertalanfi (1968). On the other hand, however, this is fully compliant with the division of knowledge in knowledge engineering into static and dynamic suggested by Pshenichny and Mouromtsev (2013) and earlier formulated classification of methods of knowledge engineering into object-based and event-based, correspondingly (Pshenichny and Kanzheleva, 2011).

2 Purpose and Tasks

Geotectonics encounters conceptual difficulties from perceptional conflicts out of variant interpretation of same observation. The dilemma has to be resolved to bring forth unified scientific approach to earth system understanding. This paper considers the applicability and usefulness of knowledge engineering methods in the study of tectonics. For this, it explores the application of knowledge engineering (i) in morphological tectonics (structural geology) and (ii) in dynamical tectonics. Its main mission is to pave the way to future research in bringing a unified ontology which caters dynamic models in geotectonics as well as in other branches of geology.

3 Knowledge engineering in morphological tectonics

Recent studies revealed a variety of perspectives to deal with object based-methods of knowledge engineering in morphological tectonics. Zong et al. (2009) suggested class hierarchy of geological structures (Fig.1). Similar hierarchies and ontologies exist in other earth-scientific domains, on which the dynamical tectonics is based (Ma, 1980; McGuinness et al., 2007; Sinha et al., 2008, and others). These ontologies scrutinize the field of knowledge and make it computer-understandable. The same time, they do not allow to evaluate how trustful regional data are and to what extent their subjectivity is due to the method of study and to what, due to the scientist's preoccupation.

Poole et al. (2008) suggest an approach that marries ontologies and Bayesian probabilistic computation as a possible solution. Here, the structure of probabilistic theories does not necessarily follow the structure of the ontology. For example, an ontology of lung cancer should specify what lung cancer is, but whether someone has lung cancer depends on many factors of the particular case and not just on other parts of ontologies (e.g., whether they have other cancers and their work history that includes when they worked in bars that allowed smoking). As another example, the probability that a room will be used for living depends not just on properties of that room, but on the properties of other rooms in an apartment. Similarly, in geological parlance, it is difficult to bring interpretation directly from the geological data. For instance, in geological mapping, geologist often tends to see what he wants to see, sometimes departing rather far from the facts – e.g., he "sees" faults which unlikely can be seen, finds stress deformations where an evidence of strain exists, traces rock block displacement in an opposite direction and so forth. The decisions made by geologist are often intuitional. It is observed that the instrumental data, geophysical and others, are being treated very broadly, often solely not to undermine the theory that the geoscientist ''believes'' in. Now adding the probability distributions to the classes of ontology, which describes tectonic study, as proposed by Poole et al. (2008) may give a tool to show how probable is the suggested interpretation of given data. However, the result would not solve the remaining puzzle – the evaluation of the theory itself. An attempt to resolve the problem is addressed below, considering all special cases present in tectonics.

4 Knowledge engineering in dynamical tectonics

All existing theories in tectonics are genetic, that is, they not only involve description of products (usually done within the realm of morphological tectonics) but also involve the description and interpretation of processes. For example, the great mountain arc of Himalayas is not described as a static feature; instead, in tectonics it is considered as a product of ongoing phenomenon of uplift, run either by gravity mechanics (principles of heat engine) or by quantum mechanics (principles of stress engine) (Tassos, 1998). It stresses the claim of Pshenichny and Mouromtsev (2013) that tectonic theories entirely lie in the realm of dynamic knowledge.

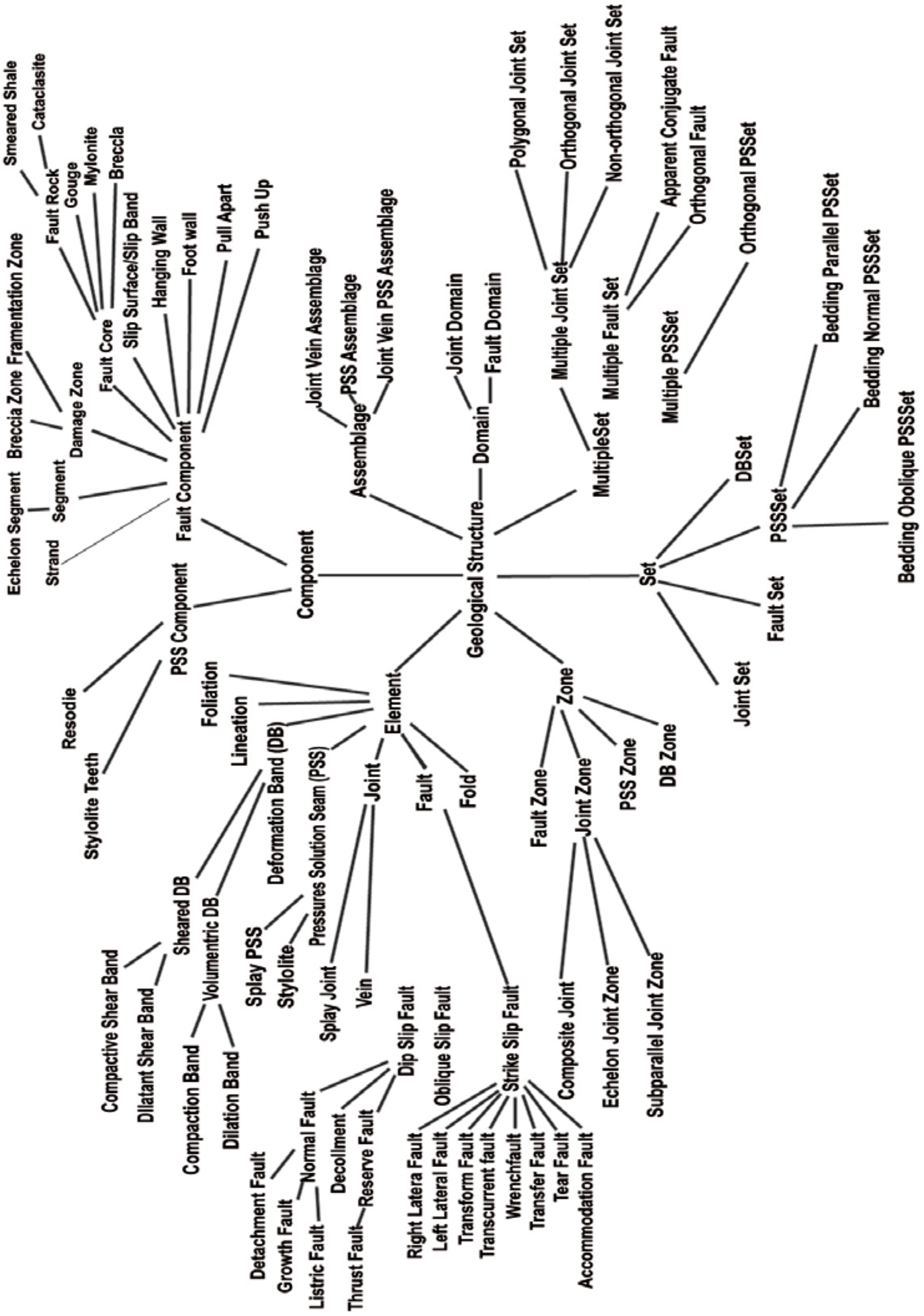


Fig. 1. Class hierarchy of Geological Structure. PSS - pressure solution seam and DB - deformation band (Zhong et al., 2009).

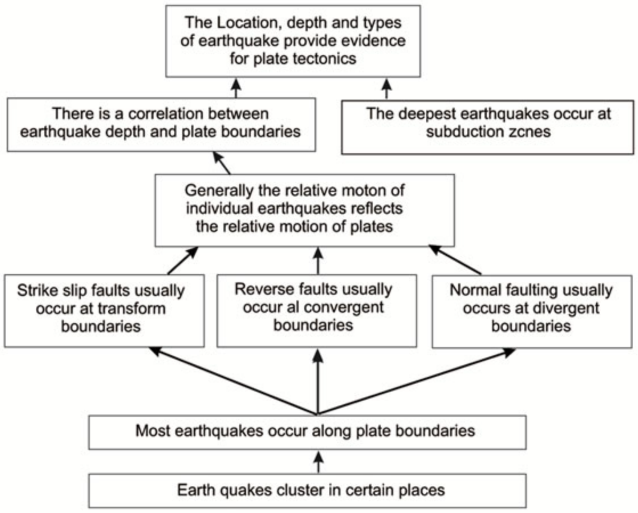
During last two centuries, the Earth science saw the rise and fall of many hypotheses that intended to look into the dynamical tectonism. They all can be considered as modern way of looking into the planet Earth and its evolution through the ‘absolute’ geological time (a concept introduced by Patterson (1953) and Houtermans (1953b). Most of the hypotheses in dynamical tectonics that has been debated fall into one of three classes assuming one of the following states of the Earth, the “contraction” (Beaumont’s mountain formation model, the Dana - Hall model, the Suess model, the Barrell model), “expansion” (the Egyed-Jordan model, the Vogel model, the Carey model) and “steady state” (the Hayford-Bowie model, the Kreichgauer model, the Wegner – du Toit model, the Vine-Mathews-Morgan-Wilson model). There are a few more models like plume tectonics, surge tectonics, vortex tectonics, Belousov and Kosygin concepts (see, e.g., Kosygin, 1983), pulsating Earth concepts (Milanovsky, 1995) and the youngest hypothesis, namely the global wrench tectonics (Storetvedt, 2003) are not fit into the above three tier division, which is based on the radius of earth across time. Among the theories listed first, the geosyncline theory (Dana-Hall model) is existing for more than 100 years, though a large space is occupied by plate tectonics model (the Vine-Mathews- Morgan-Wilson model) since 1960s (see, e.g., Morgan,1971).

Despite the acceptance or rejection of a model, each of them contains facts which are evident – and each gives sufficient explanation only to a part of such facts. For example, the contraction tectonic school easily interprets tilted strata and mammoth relief features on the globe, but seldom looks at the jig-saw puzzle fit of continents across oceans (the Atlantic case). The hypothesis does not give an apt account of the “stripped pattern” of magnetic anomalies in north Atlantic ridge sector. Similarly, the plate tectonics and the expansion tectonics logically reason the “stripped pattern” of magnetic anomalies and the very existence of middle oceanic ridge structures, but keep silent about the trans-oceanic submerged bridges (having continental characteristics) connecting continents across oceans (Storetveld and Longhinos, 2011; Longhinos, 2012). The coincidence of the morphotectonic features and the subsurface geophysical characteristics across the north-south transect of Australia is interpreted as a deep mantle inflow channel, between Banda Strait (channel outlet) and the Australia-Antarctica Discordance (channel inlet) by the surge and vortex tectonic schools (Leybourne and Adams, 2008). On the contrary, the plate tectonics hardly foresee any Walker type mantle circulation in this tectonically active region (and envisages Hadley type circulation of lithosphere, alone). The tectonic activity in Alpine-Himalayan Belt is another arena of disagreement between hypotheses, where the degree of conflict rises with every new piece of data (geosynclinal versus subduction versus wrenching versus vertical uplift). In short, all proposed models in dynamical tectonics cover the truth only partly.

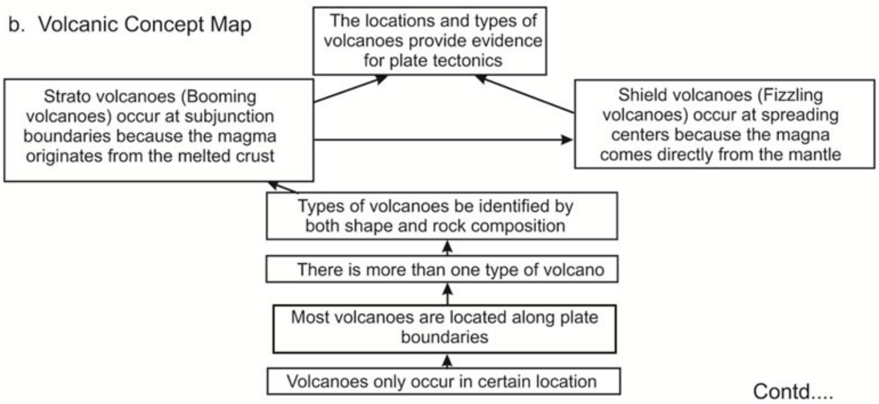
In modern dynamical tectonics, however, only one hypothesis, the plate tectonics, completely dominates. It was in beautiful accordance with the data, mainly geophysical, at the time of its formulation, being the same time amazingly simple and self-consistent. However, many new facts have been reported. In order to fit them, both the theory was modified and interpretations of facts were varied. This has made plate tectonics an object of critique (Meyerhoff and Meyerhoff, 1972; Pratt, 2000, and others). Even though an objective enquiry into the working parameters of plate tectonics has not been attempted so far, so that its application to real data is based on beliefs and assumptions, a graphic conceptualization (Figure 2) somehow substantiating the plate tectonics is presented by Shachter (2007). This is, to the authors' knowledge, one of the very few attempts of "parsing" the structure of this hypothesis proposed so far. Structurally, these graphs have anastomosis patterns (Fig. 2a), multiple paths to a singular node (Fig. 2, a, b, c), ambivalent relations (Fig. 2c) and nested nodes (Fig. 2c), the sense of which is not defined or explicated. Semantically, the graphs do not show definable relationships between the events (i.e., nodes). For instance, looking at Fig. 2a, it looks more or less reasonable the passage from "Earthquakes cluster in certain places" to "Most earthquakes occur along plate boundaries", but it is totally unclear to non-geologist (and to some geologists either!) even from the point of view of natural language why the next step is "Strike-slip faults usually occur at transform boundaries", "Reverse faults usually occur at convergent boundaries" and "Normal faulting faults usually occurs at divergent boundaries". Obviously, an explicit link between "earthquakes" and "faults" should be included in the conceptualization. Also, it is not clear what these diagrams mean to say in general – neither they introduce a theory nor prove it. Perhaps they show the compliance of the theory with considered evidence. Thus, in case of Figs. 2a, b, it clearly shows that compliance is not sufficient, as only "most" earthquakes and volcanoes are considered by the theory, and those minor which occur outside of plate boundaries, are not. However, even sufficient compliance with the evidence is not necessarily an explanation of this evidence, while explanation is exactly the purpose of the theory. Such explanation offered by a theory is not demonstrated by the quoted graphs. Nevertheless, even at this highly informal and superficial level it could be interesting to use such conceptualization for other tectonic theories (plume tectonics, geosyncline theory and others) to show (in)compatibility of theories against similar evidence. Finally, from the point of view of Earth science context, these plots seem to be very general and may appear misleading, as they do not go into necessary detail. E.g., stratovolcanoes and shield volcanoes may be well combined in similar settings and even built on top of one another, despite the enchanting simplicity of their separation in the plot (Fig. 2b). Also, it is not specified what fossils may be really indicative of spatial proximity of areas of their occurrence, while this issue is often debatable in paleontology, and similar fossils are sometimes found in areas which could not be adjacent by the same very theory of plate tectonics (Pratt, 2000).

While the compliance with facts should be likely addressed by the object-based methods as discussed in the previous section, the structure of the theory, as it describes the processes that are believed to operate in the Earth crust and mantle, may be a subject for event-based methods of knowledge engineering. Also, structure of other theories and their compliance with similar facts and with each other should be studied by the whole armory of concept- and event-based methods. These methods are truly new in dynamical tectonics

a. Earthquake Concept Map



b. Volcanic Concept Map



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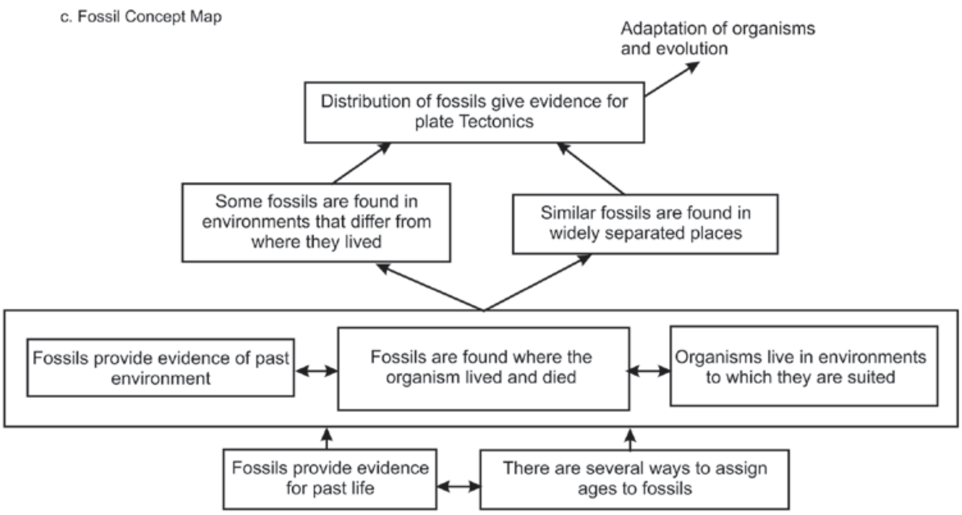

Fig. 2. Concept maps for plate tectonics, a – earthquake evidence-based reasoning map, b – volcanism evidence-based reasoning map, c – fossil evidence-based reasoning map, (Shachter, 2007)

5 Discussion

The modern state of tectonics urges wide application of knowledge engineering approaches mainly to handle psychological and social aspects of this science (traditions, bias, herding and so forth) and to reduce their impact on scientific results. At present, however, these approaches are being dramatically underestimated and underused. Two dimensions of their application are straightforward in tectonics, (i) development of hierarchies and ontologies of geological knowledge used in tectonics and adding probability distributions to determine the probability of interpretation given the data and (ii) plotting the mechanisms suggested by each tectonic theory and corresponding scenarios of Earth evolution. The former corresponds to morphological tectonics, treats knowledge in a static way and can be performed by object-based methods of knowledge engineering. The latter relates to dynamical tectonics, models dynamic knowledge and needs event-based methods of knowledge engineering.

While the hierarchies and ontologies have been abundantly developed and their integration with Bayesian computation based on assumed probability distribution has been discussed (Poole et al., 2008), creation of an event-based framework for geotectonics is a perfect terra incognita. Existing attempts are scarce and methodologically incomplete. Nevertheless, exactly these methods are required to

- Assess whether a theory is self-consistent and how well it covers the domain it pretends to cover (i.e., how well it describes the tectonic processes that lead to the observed results), identify gaps, uncertainties and ambiguities in a theory, as well as its "protective belts" (Lakatos, 1970) introduced artificially to protect the core of the theory;

- Find out how many alternative theories may describe similar phenomenon;
- If there are a number of theories describing similar phenomenon, determine how well each theory covers the domain of interest;
- Estimate the relevance of contradictions between the theories (which may appear purely verbal)
- Enquire whether the mechanism proposed by a theory must be necessarily global or may operate locally in space or time (for instance, whether the plate tectonics may develop only where the asthenosphere is thick enough to enable the plate motion and whether it may wane and give way to other mechanisms otherwise). and
- Look for compatibility of mechanisms from different theories. For example, spreading of the oceanic floor may appear the case not only a driving force of plate growth in plate tectonics but, without subduction, also a consequence of expansion of the Earth.

6 Conclusions

1. Modern geotectonics requires application of methods and approaches of knowledge engineering.
2. Static knowledge engineering techniques (hierarchies, ontologies and others) work well in structural geology or, broadly speaking, in morphological tectonics.
3. In dynamical tectonics the need for application of knowledge engineering methods is much greater; what is required in this domain is methods of modeling events, states, processes and scenarios, or engineering of dynamic knowledge.
4. These methods have been largely unused in the discussed domain, and up to now, even if used, are applied mainly not to compare theories and develop a self-consistent tectonic body of knowledge but to show the advantages of one given theory.

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