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Misleading analogies that lead to the belief that the mantle of the earth is liquid

José Sellés-Martínez

Summary

The use of analogous models has proven to be a very useful tool for enhancing comprehension of complex scientific concepts but, in several cases, it may render undesired results. The structure, rheological properties and dynamics of the Earth's mantle are usually modeled using some fluid (water, oil, etc.) heated in a container. A survey through children's introductory science books has rendered alarming results. Most of the books, taking the analogous for the object of study, assign the properties of the materials used in the model to the materials of the earth, what is certainly not true.

This mistake is reinforced by at least two facts. The first is that most illustrations about volcanoes show these structures being fed directly from a "hot and mobile" mantle. The second fact is that scaling parameters are never taken into consideration when describing or performing the simulation.

The situation is not to be neglected. The misuse of these analogies have resulted in widespread misconceptions among the general public, many teachers, and worst of all, the authors of books on science education.

Several strategies to overcome this situation are proposed, focusing in the explanation of what models do accurately represent and what they do not. Scaling parameters, like size, time and -most important- the viscosity of the materials involved, need to be emphasized when using models.

Introduction

The importance of models in the process of learning/teaching is not under discussion. Models are mentally constructed out of a text or lecture by the learner itself or can be given as additional information in the class. The importance of mental models in the building of correct concepts about the structure and dynamics of the Earth's interior has been addressed by different authors but this subject is out of the scope of the present contribution (see GOBERT, 2005 and STEER et al., 2005 for extensive discussions and bibliography on the subject).

Analogous models, demonstrated in the class or described and illustrated in books, provide an efficient way to make the visualization of dimensions, processes and time spans that are far from every day experience possible. The fact that they only depict several aspects of reality and not others has, un-

fortunately, not been successfully addressed by teacher sand authors and, as a consequence, misconceptions have arisen and permeated to books for children and the general public. Research on the use of analogous for teaching about the structure and processes in the mantle, although scarce, has been addressed by several authors. NOTTIS 1999, offers an extensive description of analogous used for Plate Tectonics and their advantages and limitations and points out the need to aware the learner about their limitations in order to avoid misconceptions. WAMPLER (2002) even traced errors about the concepts involved in the description of flow of solid materials in books designed for University students.

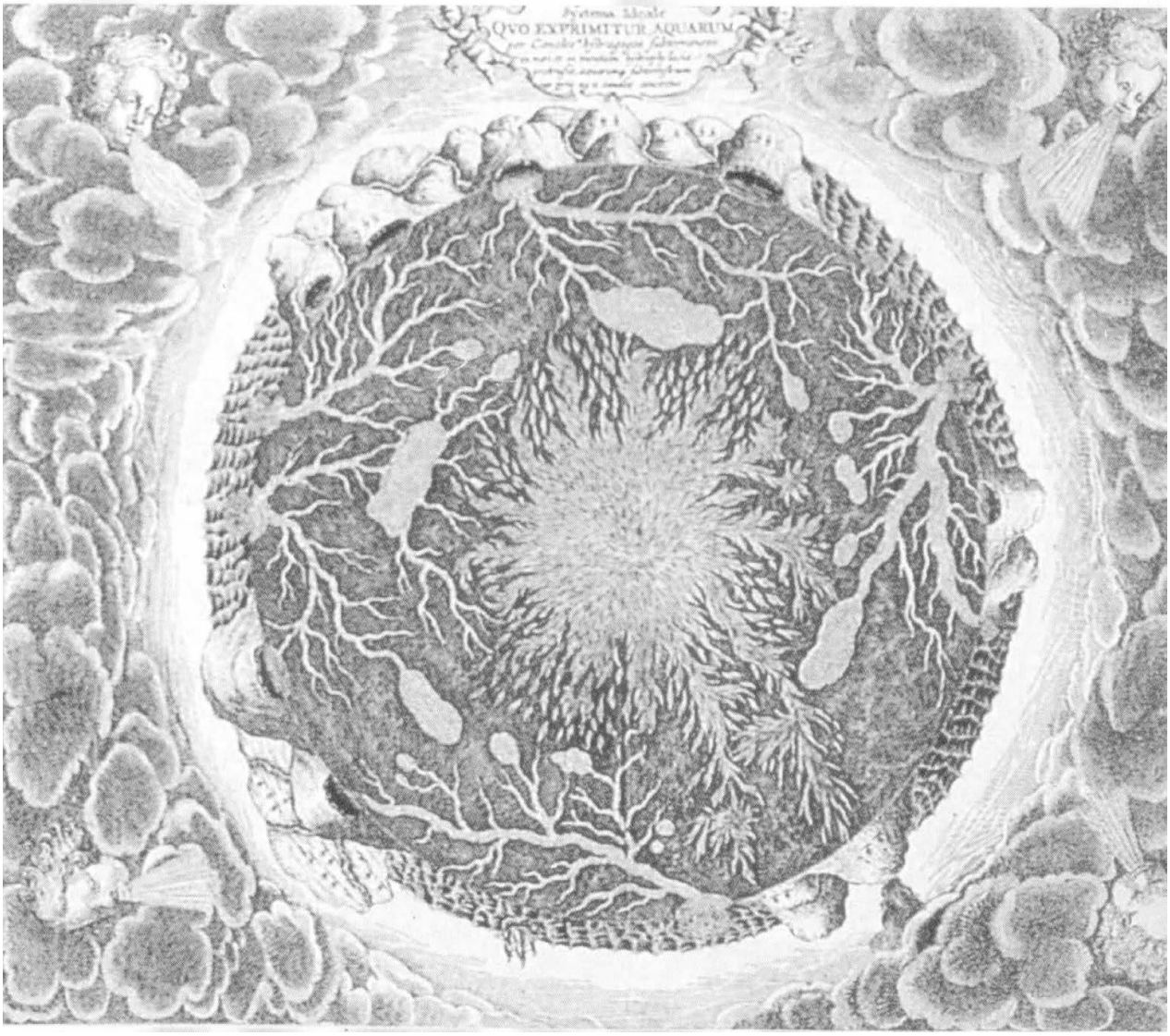

Figure 1: Old models for the Earth structure assumed that there was fire, or at least incandescent material in the interior of the Earth. This imaginary picture from A. Kircher proposes an Earth with an incandescent core feeding rivers of lava that reach the surface at the craters.

The goal of this contribution is to provide some clues to prevent the unaware teacher or learner about the limitations of the model and how to improve its use.
In order to address this subject, a review of some books designed for the children to construct their knowledge of the Earth is presented, and texts and/or illustrations that contain errors or lead to misinterpretations are quoted. This is followed by a comment on a book about good science teaching practices which also includes misleading and erroneous analogies. It concludes with some suggestions of ways to overcome the limitations of the models.

Nice but dangerous

The widespread use of containers filled with more or less viscous liquids that are heated in order to show the formation of convective cells, has lead to undesired but generalized misconceptions about the state of the mantle. It is important to underline that present day belief in a molten interior of the Earth is not related to ancient theories about the structure and composition of the planet (Figure 1), as is the case of the idea of mountains being the result of the contraction of the Earth (a widespread theory that lasted until the decade of 1950 in many science books and is still common in the scientific imagery of many people). The belief in a liquid and boiling mantle is the result of oversimplifications of the real picture and this misinterpretation is strengthened by literal interpretation of verbs "float" or "dive" when referring to plates and subduction zones and the fact that hot and molten material is generally undifferentiated in the illustrations. The real facts, a

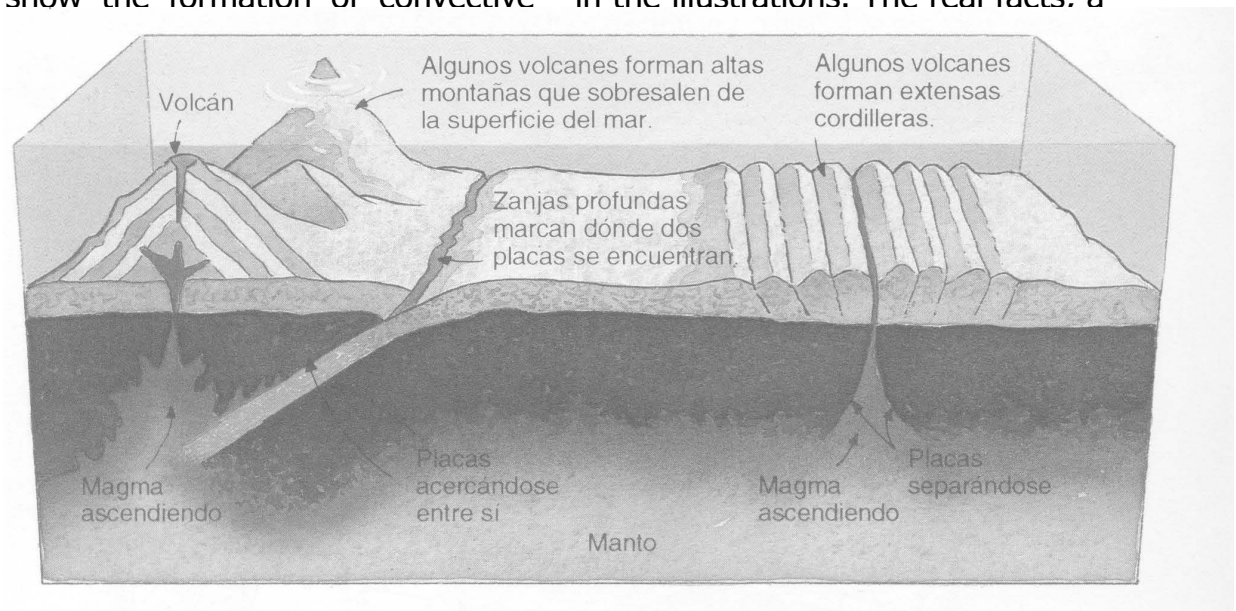

Figure 2: In most illustrations there is no visual way to differentiate liquid from partially molten or solid materials, as long as different shades of red are used only to give the idea of very high temperatures (taken from Thata, 1995).

solid mantle that flows along geological times and the presence of a small percentage of molten material in the mantle is converted into the existence of a whole molten mantle that, for several authors, is even boiling.

Misleading descriptions

The following are examples taken from different books. Although some of them have only been available to the author as translations into Spanish from the English originals, the nature of the mistakes been taken into consideration is clearly not a consequence of translation. Most probably no scientific reviewing was involved in the edition process of these books, despite the fact that they might have been deeply reviewed in their pedagogical aspects and carefully designed and illustrated. Attractive illustrations that introduce conceptual mistakes make detection of errors by the unaware reader even more difficult.

Case 1: Farndon (p. 33, 1992). In his very popular book states in the Introduction to the chapter "The structure of the Earth": "The center of the Earth is an incandescent oven, so hot that it can even melt rocks. Under our feet, the interior of our planet is boiling continuously with such an impressive strength that can shake the surface, rise mountains and volcanoes and make continents collide or separate at the time they cross the enormous molten lava currents that circulate under the Earth's crust. On page 40 of the same book, when introducing the item "The Earth's Mantle", the text explains: "May be you think the soil under your feet is solid and immutable. But it moves continuously. The soil where you are is like a slice of bread floating in a dense boiling soup. Some scientists believe that in the Earth's mantle matter boils and shakes, driven to the surface by the high temperatures in the interior of the planet and that, afterwards, it gets cold and sinks again. This circular flux of matter is known as "convective cells" and is valid for any liquid to which heat is applied. Due to the fact that the mantle is composed of solid rock, the upward-downward flux is very slow." Although in the last phrase -and in many other parts of the book- it is stated that the mantle is composed of solid rock that moves very slowly, the above quoted sentences are too "strong". Being in contradiction with the many other conceptually correct paragraphs elsewhere in the book introduces, at least, a lot of confusion in the young reader. Where does literature end and science begin? It is not in the hands of the young and unaware reader to identify and locate the frontier.

Case 2: Royston (p. 6, 2000) introduces "Volcanoes of the world" saying: "The most external part of the Earth, the crust, is divided into 15 wide tectonic plates that "float" over molten rock. A great number of volcanoes is located in those places of the crust where two different plates collide". No matter the word

"float" is between inverted comas, the expression "over molten rock" leaves no place for any doubt about the misconception.

Case 3: As MAYES (p. 4, 2000a) explains "Floating plates" the caption reads:
"The plates float over the mantle. In it there is a liquid rock, steaky and hot, that is called magma. The magma shakes and causes plate to move". Here again the mantle is described as being "liquid".

Case 4: The same author (MAYES 2000b, p. 20) explains "What is there inside the Earth?" saying that: "The Earth is like a ball, covered with very hard rock. Some places are weak, fissures and movements are frequently present there. Under the crust there is the mantle, formed by hot and soft material that is moving all the time. The center of the Earth is the nucleus, which most external part is hot metal, almost liquid. Its interior is of hard metal and is the hottest part. Sometimes, the interior of the Earth moves so much that surprising effects take place in its surface". The description "Hot and soft material" is an ambiguous statement that does not accurately describe the material in the mantle if we take in account the everyday meaning of the word "soft". The statement that the external part of the nucleus is "almost liquid" is also misleading. What does "almost" mean there? Equally confusing and misleading is the relationship between movements in the interior of the planet and those in it's surface. The unaware reader will easily conclude that earthquakes generate when the whole interior of the Earth moves more quickly, what is nonsense.

Case 5: THATA (p. 18, 1995) describes "The bottom of the sea" as follows: "The surface of the Earth is composed of big fragments called plates. They move slowly over a layer of hot rocks called mantle. The illustration shows some plates that form the bottom of the sea. The submarine volcanoes form from molten rock, called magma, coming through the bottom of the sea. Magma gets cold and hard forming layers of rock. It grows slowly until it becomes a volcano." The illustration (see Figure 2) shows volcanoes being fed directly from the mantle. Taking in account that no where in the text any reference is made to it being only partially molten, the reader has the right to interpret the mantle as completely molten. The caption "magma ascendiendo" (magma going upwards) adds more confusion to the problem because no difference between completely or partially molten materials has been introduced.

Case 6: COOTE (p. 6, 19??) answers the question "What is inside the earth?" by stating: "There are four main layers. The outer one is a layer of solid rock called the crust. Below is the mantle. This is solid at the top, but deeper down it is so hot that the rocks have melted.

Next is the outer core, made of hot liquid metal. At the center is the inner core, which is solid metal". This text introduces a new variation in the misunderstanding: the mantle is presented as progressively hot until the temperature reaches the melting point. From there on, down to the core boundary, the mantle is presented as being liquid. The concept is reinforced in the illustration by using a continuous change of color from dark red in the top, to yellow in the mantle-core boundary.

A misleading translation: The American Museum of Natural History has produced a booklet on Earth Sciences for children containing descriptions, illustrations, explanations and activities (Our Dynamic Planet, AMNH, 1999) that is also provided in a Spanish version. In page 7 of the Spanish translation an Earthquake Shake also falls in the mistake. No matter the English version of the song says that "The plates creep on the mantle" the translation states that they swim ("Las placas nadan sobre el manto"). The difference may seem unimportant at first glance but is fundamental. Nobody swims in a solid body, it needs to be liquid. Unfortunately this is not the only mistake or misleading idea introduced by the translator, but a discussion on the role of translator falls far out of the scope of the present contribution, no mater it clearly highlights that translation of science matters requires science literate translators.

A case to worry about: The presence of the mistake seems to pervade the school and, judging from the following example, may be many teachers and inspectors have no clear understanding about the nature of the mantle. OGBORN et al (2002) states: "David, explaining plate tectonics to a class (10th grade) with a demonstration using gelatin, anticipated its failure with a mix of sadness and preoccupation. ...with some luck I will show you an experiment -but surely it will not work- thus we will have to imagine that we are performing an experiment that should work. (...) but let me explain what do we have here. It is a dense mix of something similar to jam (...). It is blue at the bottom and has a white layer in the upper part. Now I will try to heat it little by little, because what I want to show you is something we have talked about several times before: convection. (...) I have the feeling this is so hard that all is going to break down. (...) The pot actually broke into pieces and any movement of the blue layer was, at most, imperceptible. In that sense the experience failed. But the students had seen that something more or less "solid" was heated and was supposed to start moving. The objective of the experience was not to make a convective cell in the gelatine, but to present a parallel between convection and the processes in the interior of the Earth. The meaning of the practice was still clear, continents go adrift because they are conveyed by

moving molten rocks that circulate in the interior of the Earth; the underlying process being not exotic, but familiar, something from everyday life. The experience offers a mental model and not a fragment of reality".

This long text is "self explaining" about what is being under discussion and, avoiding any reference about what a good science experience in the class must be, it clearly shows that Ogborn et al., believe in "continents going adrift because they are conveyed by moving molten rocks that circulate in the interior of the Earth".

How can we face this situation?

The mistake about the physical state of the mantle is kept alive by at least two different facts. The first is the case that in almost every reference to volcanoes, they appear to be fed directly from the mantle in texts where magma and lava are always defined as molten rock (thus fluid). It is easy for the unaware reader to extrapolate that if magma and lava are liquid and they are coming from the mantle, the mantle has to be molten. Sometimes the text is correct but the fact that hot material (solid or liquid) appearing in every figure depicting the Earth, is almost always painted red, leads to the confusion.

The second factor affecting misinterpretation of the heating pot model is that scaling parameters are never taken into consideration. There is not any kind of awareness about the time and space scales separating the analogy of the boiling pot from the reality of the convecting mantle. The same happens about shape and rheology in nature and in the model.

A key point in this discussion is that science books, no matter they are designed for children, ought to be reviewed by geologists, but this is far outside of our control. My suggestion to educators is that, in order to help correct the misconceptions involved when using the analogy of a heating pot to illustrate convection in the mantle, they should prevent misinterpretations by stressing:

a. The fact that models are not a sample or a piece of nature but one of a suite of tools we can use to help understanding it.
b. The differences in spatial and temporal scales between nature and model.
c. The differences in material properties (i.e. rheology) of the natural and analogous substances.
d. The difference in the geometry of the Earth's mantle and that of the model.
e. What the model reproduces well, and what not, of the natural process being studied.
f. The difference between being "partially molten" and "liquid":

This last is a key item. Most of the survival potential of the misunderstanding is based on the fact that illiterate people can not develop by themselves the idea of a mix of solid and molten mantle. An accurate illustration for this question is the example of an aquifer or, may be just

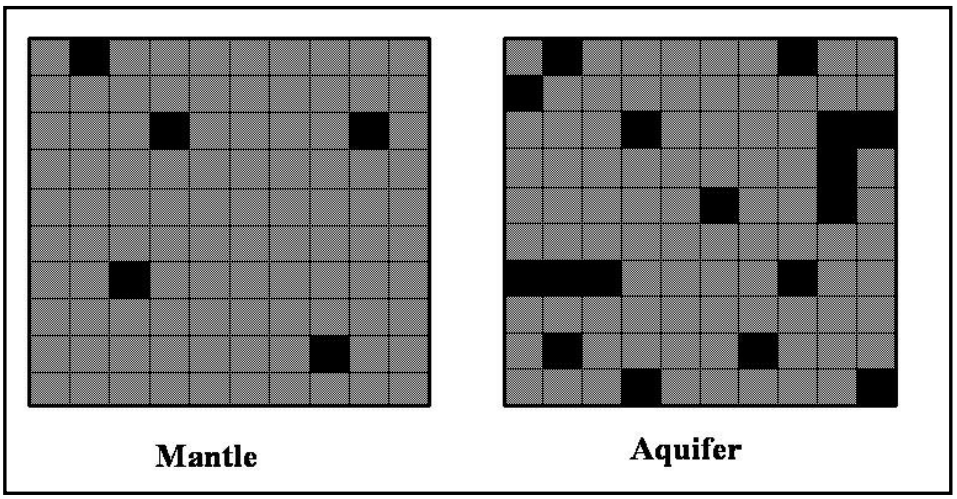

Figure 3: A simple sketch to illustrate about percentages of water in a wet soil and in the partially molten mantle.

a sample of wet soil in a pot that, although having a high percentage of water, would never be considered a "liquid". This idea may be stressed further when comparing the 3% to 5% fraction of molten rock in the mantle to the 15% to 20% or more water that may be present in the pores of a rock or sediment (Figure 3).

Some additional suggestions to strengthen the correct concepts are as follows:

a. State clearly that the mantle is solid in the same paragraph or caption when the heating pot model is presented if writing a document. Say it as many times as possible if giving a talk.
b. Make your class aware that there are materials (like tar and several silicones) that behave as solids and break when hammered, but that can flow under stress when given enough time. This will help students modify the idea that being solid implies no possibility of change of shape by flow.
c. Use, show and explain or even ask the elder students to prepare by themselves a table (like Table 1) containing information about the relationships between physical parameters in the mantle and those in the analogous model.
d. Viscosity, although a parameter difficult to understand for young children, is a very good one to

Table 1: Comparison of parameters in the model and in nature

	Size	State	Temperature	Density	Time
Mantle	12.000 km	solid	700-2800 °C	3-4,6 g/cm^3	100 My
Model	20 cm	liquid	100 °C	1 g/cm^3	minutes

Table 2: Viscosities of different "surface" materials and that of the mantle. Note that there is some discussion going on about the distribution and exact value of viscosity in the mantle but no matter this, the average value is about twenty orders of magnitude higher than molten basalt in the near surface. Data from KING (1995) and BAKER et al. (2004).

Material	**Depth**	**Viscosity (in Pa s)**
Water	Surface	10^{-3}
Ketchup	Surface	10
Basaltic magma	Near surface	10^{2}
Asphalt	Surface	10^{3}
Ryholitic magma	Near surface	10^{4}
Mantle		10^{22}

highlight differences between reality and models. It can be described as the "difficulty" for a given substance to deform by flow. Viscosity must be clearly distinguished from density (a common but erroneous association), this late being the relationship between the weight and the volume of a given material. BAKER et al. (2004) provides several measurements of the viscosity of every day materials (ketchup, road-building asphalt) that hardly compare with the estimated values for the mantle (see Table 2). Units (Pascals per second) can be disregarded and focus placed on the relative values that are many orders of magnitude different.

Conclusions

To avoid introducing misinterpretations when explaining convection in the mantle using the analogy of a fluid heated in a pot, a few items should be addressed that are of great significance:

a. Point out the differences in scale, state and time between the model and nature.
b. Refer to the fact that models are limited and imperfect and only attempt to reproduce several aspects of much more complex processes. Describe what the model accurately describes and what not.
c. Explain that matter can be solid but bear pores full with fluids, which can strongly modify its physical properties. Point out the differences between "dry solid", "wet solid", "partially molten", "liquid" and "melt".

d. Explain that the solid mantle can flow if we give it enough time to do so, provided a small percentage of fluid is present in it.
e. Emphasize that although materials there are at very high temperatures and eventually reach the melting point, there is no boiling in the mantle.
f. Go further if possible and explain that earthquakes have no direct relationship to the movements in the mantle. Remember that many people believe that they are caused by the boiling of the mantle.

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