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RESEARCH PAPER

Degassing of primordial hydrogen and helium as the major energy source for internal terrestrial processes

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Abstract Examples of the mightiest energy releases by great earthquakes and volcanic eruptions and hypotheses providing explanations for them are analyzed along with the results of some recently published researches and visualizations. The emerging conclusions are that the mechanism of the strong earthquake is a chemical explosion; that volcanic eruption is a special type of earthquake wherein the hypocenter rises to the earth-surface; and that there is an association between the seismic-volcanic processes and mantle "fluids" and the lack of energy for mantle plumes. A conceptual system of hypotheses is put forward to explain the conservation of energy during Earth's accretion, its quasi-stable release by primordial H- and He-degassing and of the crucial role of the energy of degassing-comprising-reactions in endogenic processes. Specific mechanisms and chemical processes are proposed for the gas-liquid mantle plumes melting through the solid mantle using heat-energy released in reactions of their metamorphic and chemical transformation under gradual decrease of pressure and temperature; volcanic gases are put forward as energy carriers. ^{3}He performance as a unique measuring transformer correlative to the internal heat flow was used for calculation of energy release by degassing; it equals to 5.12×10^{20} J/yr, an amount of energy five-fold greater than the entire energy loss involved in earthquake and volcanic activity. The hypotheses proposed are objectively testable.
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1. Introduction: energy sources in geological hypotheses

The inadequacy of numerous geological hypotheses trying to explain endogenic processes of the Earth is based on their lack of suitable energy-sources and energy-carriers (Gilat and Vol, 2005). Terrestrial processes, such as internal heat-flux, hot-spots, plate-tectonics, earthquakes and volcanic reactions are explained by only two stable, major traditional sources of energy: decay of radioactive elements (U, Th and others), and the heat from gravitational compression and differentiation. Obviously, these sources are dispersed, can supply only about half of the observed heat flow of the Earth (e.g., Francis, 1993), and, as we will try to demonstrate, are not the causes of most of the Earth's internal processes.

The currently accepted theories concerning terrestrial processes fail to account for a major source of internal energy which: (1) can be quickly focused, e.g., earthquakes and volcanic eruptions; (2) is of very high density; (3) provides very high velocities of energy release; (4) has very high density of the energy transport and relatively small losses during transportation over long distances; (5) is quasi-constantly released and practically limitless. This energy release is accompanied by mantle H- and He-degassing.

In our former article (Gilat and Vol, 2005) we hypothesized that during Earth's accretion primordial helium and hydrogen were trapped and stored in the planet's interior as He- and H-solutions and compounds, stable only under ultrahigh *pT*-conditions; some of them were discovered in laboratory experiments under similar conditions, some were deduced from their atomic structure and composition of natural He-rich gases. Since stabilization of the planet the energy spent on trapping H and He is quasi-constantly released by dominantly exothermal reactions of the Earth's degassing. Step by step (for each *pT*-condition) were described: H- and He-trickling from the solid and generating convection in the liquid core, flux-melting the solid mantle and generating gas-liquid plumes. Rising plumes scavenge incompatible elements from the mantle-rocks through which they pass, i.e., elements that are strongly fractionated into the liquid tend to be carried in the liquid and to accumulate in increasing concentrations (O, S, C, N, Cl, F, metals etc.) dispersed in it, forming He-H, He-O, He-C, He-S, He-N, He-metals and other compounds; thus those elements can be concentrated and transferred to the lithosphere for their future role as volcanic gases and ore-forming hydrothermal solutions. The sudden chain reaction of decomposition of these meta-stable compounds, triggered by decompression of the fault zone is proposed as the practically infinite energy source for earthquakes. In the case of further decompression of the upward moving hypocenter (magmatic chamber), elemental H, O, C, S, Cl, F etc., which are liberated as a result of exothermal decomposition of H- and He-compounds, will participate in the explosive reactions of synthesis (volcanic eruption), forming H_2O, SO_2, H_2SO_4, CO_2, H_2S, HCl, HF and other chemicals. Heat thus produced and continuous explosions neutralize adiabatic cooling, melt and bore through the solid rock, and produce all the manifestations of igneous activity in general and of volcanic eruptions in particular. ^3He performs as a unique measuring transformer correlative to the internal heat flow. Multiplying its flow from the lower mantle by the highest recorded coefficient of correlation, we (Gilat and Vol, 2005) obtained heat flow equal to half the present rate of heat flow from the Earth's surface, amount of energy five times greater than the energy loss involved in earthquake and volcanic activity (see Section 6 for a more detailed discussion).

The concept of hydrogen and helium trapping and subsequent outgassing as a major source of terrestrial energy proposed herein was not, to the best of our knowledge, put forward previously by anyone else. It is consistent with the existing hypotheses of planet-creation by accretion and amplifies them by taking into account the thermodynamically necessary endothermic reactions of hydrogen-helium absorption, which assists in effective cooling of the incipient planet and in prevention of its material losses by evaporation. It substituted "the primordial hydride Earth" hypothesis of Larin (1993), who suggested a dominantly metal-hydride Earth's core (though not very convincingly because of the comparatively low density of the iron and nickel hydrides). Because of the intimate relationship of the proposed energy-release with degassing of the planet it has something common with the hypotheses of Larin (1993) hydrogen degassing and of Yanizky's (1979) supposition of earthquake relation with the release of helium; at the same time we omit cosmogony-problems and the Hall-Larin hypothesis in the present discussion. Suffice it to say that a Larin's (1993) and Yanizky's (1979) hypotheses omit the concrete ways of energy release by degassing, which, to our opinion, solves problems of Earth's energetics and related the role of hydrogen and helium to them; they did not propose the explosion as a cause of earthquake, nor the mantle plumes as energy carriers.

In the article presented herein we added some new data to our basic article (Gilat and Vol, 2005) presenting this conceptual system of hypotheses in greater detail, but had to reduce the volume of description of introductory chapters and of the main hypotheses. Hence we refer the reader to the basic article (Gilat and Vol, 2005) for additional information and references.

2. Energy of the strongest earthquakes and volcanic eruptions, their problematic explanations and hypothetical alternative mechanisms

The data accumulated during last 50–60 years from measuring and calculating the energy of major catastrophes make some of the theories and conclusions based on them less convincing. Thus, only 15 years ago it was practically axiomatic to say that "magnitudes as great as 9 have not been recorded historically on Earth. Such large earthquakes are not probable because rocks are not strong enough to build the required stresses; they are likely to rupture at lower stress levels and produce a lower magnitude earthquake" (Simkin et al., 1994, explanatory notes). Nevertheless, according to new information (e.g. Largest Earthquakes in the World since 1900), our planet shook many times because of "not probable" earthquakes: in 1952 – Kamchatka, $M = 9.0$; 1960 – Chile, $M = 9.5$; 1964 – Alaska, $M = 9.2$; 2004 – near Sumatra, $M = 9.1$; 2011 – Japan, $M = 9.0$. The cause of the conflict between the basic US Geological Survey (USGS) publication in 1994 (Simkin et al., 1994) and the recent data on the USGS site in Internet (Largest Earthquakes in the World since 1900) is simple: the paradigm cannot explain accumulation and well-focused release of the monstrous energy of great earthquakes. For example, the Chilean 1960 $M = 9.5$ earthquake released the energy of 4.0×10^{18} J, equivalent to 2.7 Gt TNT in terms of TNT explosive force (Richter magnitude scale, p. 7). For comparison, the explosion force of the largest thermonuclear weapon ever exploded (Tsar-Bomba) was 50 Mt TNT (ibid. p. 6).

How much elastic energy can be accumulated in lithosphere rock? Not knowing its exact mechanical properties, in place of unknown faulted rock, we looked for its upper limit, calculating the maximum amount of energy (ME) for a block of high-quality structural steel 600 km $\times$ 100 km $\times$ 20 km in size (the possible size of the lithosphere block in which the Alaska 1964 earthquake was generated). The answer is $ME = 29 \times 10^{16}$ J (Gilat and Vol, 2005), an equivalent to the explosion of about 70 Mt TNT, almost 15 times less than was released in the 1964 Alaska earthquake. We limited the thickness of our block of steel to 20 km because elastic stress can be accumulated only in the less-than-20 km thick upper part of the lithosphere. At a greater depth the rock-temperature is higher than 1/3 of the rock's melting temperature and the rock creeps (e.g., Rhoads, 2001). Thus, earthquakes with foci deeper than 20 km cannot be explained by the currently accepted theories. That is why explaining the 1960 Chilean earthquake as stress release between the subducting Nazca plate and the South American continent by rupture (with velocity 3.5 km/s) of the 800 km long segment of the Peru-Chilean trench at 33 km depth (Kanamori and Cipar, 1974) sounds unconvincing. Also, it is hard to imagine there a block of lithosphere 40 times larger, than the block of steel (above) with the rock as strong as high-quality steel, hence we have to look for an energy source better than accumulated elastic stress.

Visualizations of the Chilean 1960 and 2010 earthquakes (Fig. 1) illustrate not mechanical rebounds, but explosions, because the energy produced by fault-rupture would be directed to generation of seismic waves, development of fractures along the trench and to heat-production in the earthquake foci. Seen on the earthquake visualizations (especially of 1960) are the monstrously long and wide tongues of energy crossing the Pacific perpendicular to the Peruvian-Chilean trench, while their densities of energy blasts are practically not reduced along the first few thousands-kilometers-long way. In single explosion the energy stream decreases with the square of the distance; the blasts of energy shown below (Fig. 1) illustrate the distribution of multitudinous or cumulative voluminous explosions, where fuel or explosives come through and detonate sequentially along the feeding collectors or fractures enlarging them.

Mechanical rebound along the N–S trending trench also cannot explain the generation of the Tsunami wave front in the direction perpendicular to the fault; however such a wave (a few hundred kilometers long!) can be created by distributed cumulative voluminous explosions expelling half of the wave's volume. The velocity of fracture propagation (3.5 km/s [Kanamori and Cipar, 1974]) is close to the velocity of detonation or the velocity of S-waves, and orders of magnitude bigger than the velocity of crucial propagation of brittle fractures (less than 20 m/s for metals and about 300 m/s for water). No movements along the Peruvian-Chilean trench can explain westward displacements of the middle part of the S. American continent (Fig. 2) accurately measured in 2010 by GPS. However those could have been forced by the stable pressure from the Middle-Atlantic divergent plate boundary, their movements triggered by the earthquake and its aftershock explosions working like a giant vibrator. The explosion

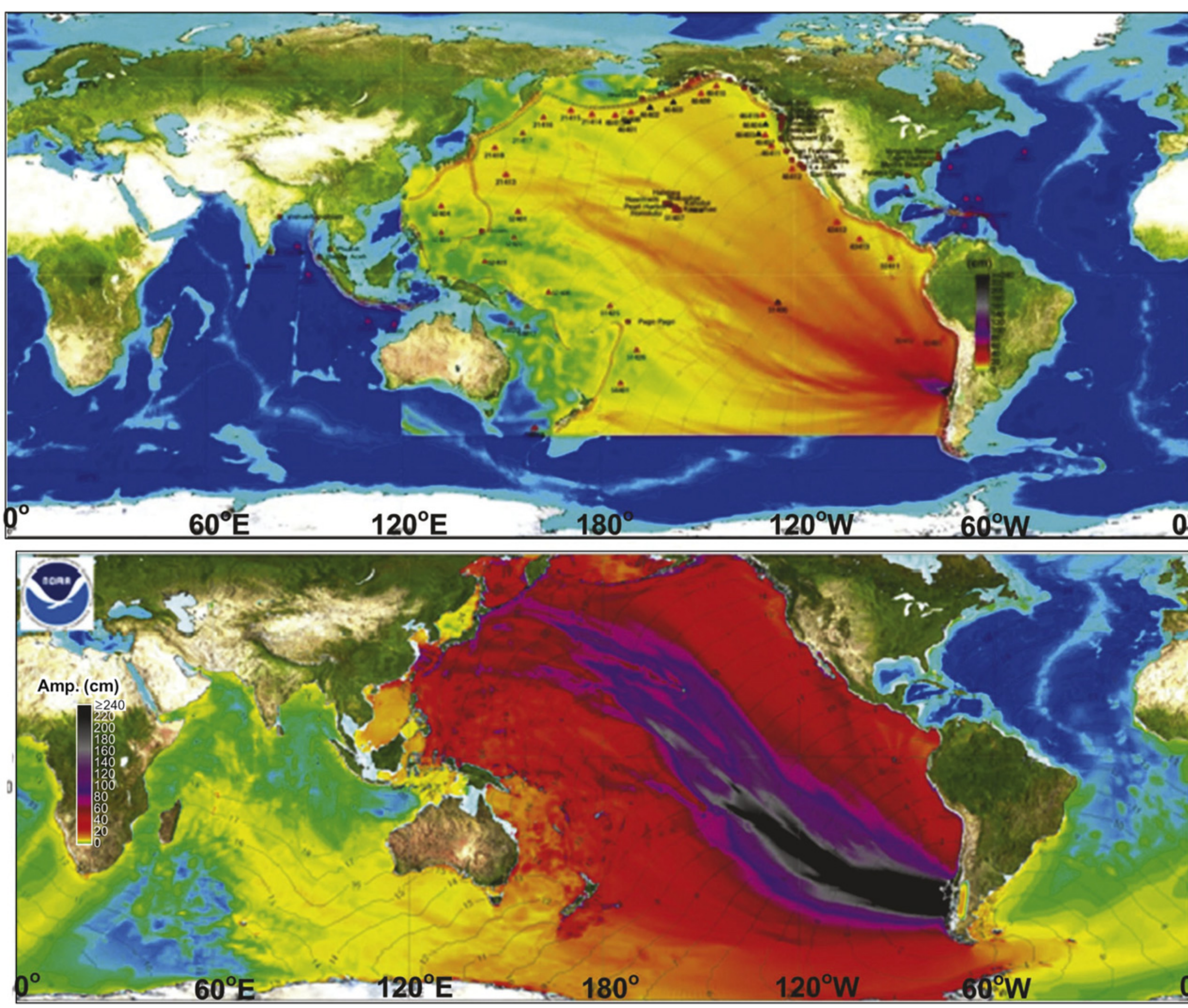

Figure 1 Monstrous tongues of energy blasted by the Chilean 2010, $M = 8.8$ (top), and 1960, $M = 9.5$ (bottom), earthquakes crossing the Pacific practically perpendicular to the Peruvian-Chilean trench while their densities of energy blasts are not reduced along the first few thousand-kilometer-long way (The National Oceanic and Atmospheric Administration (NOAA) visualization).

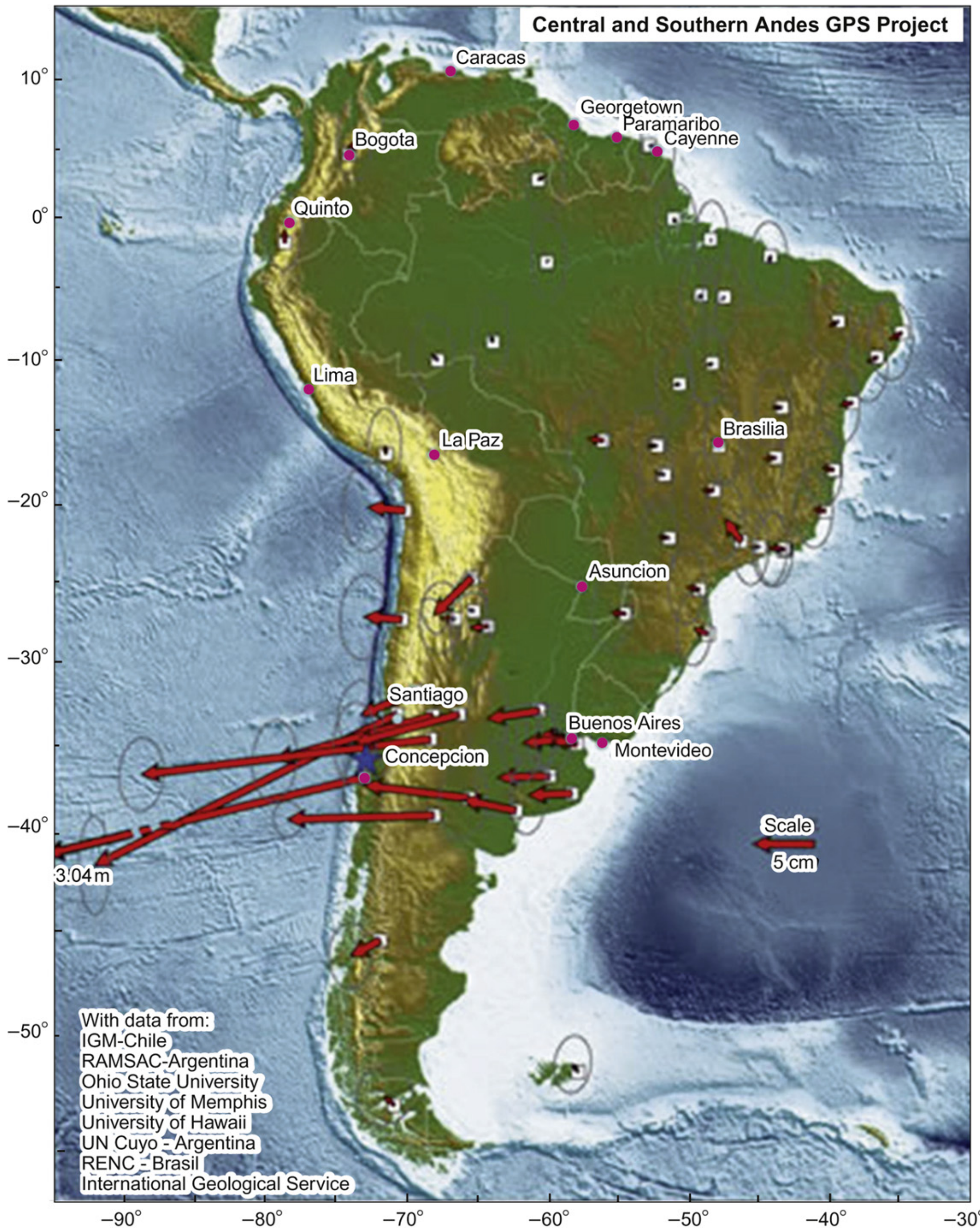

Figure 2 The 2010 Chile earthquake and its aftershocks displacing (in centimeters) the GPS stations in South America. Concepcion city was moved by 3.04 m. Image: University of Hawaii, the Central and Southern Andes GPS Project.

mechanism of an earthquake is also attested to by conspicuous similarity of the seismic signatures of the earthquake and the underground nuclear explosion (Eiby, 1989).

Other evidence is pulverization of a rupture gouge in earthquake foci to the nano-meter-size particles (Wilson et al., 2005). Before being pulverized the rock has to be melted. The melting temperature of the high-melting components of the rock is about 1670−1720 °C for quartz and about 1215−1260 °C for granite; in cases of eutectics (quartz, K-feldspar, Na-plagioclase, micas) the melting temperature can be close to 600 °C. For pulverization to be successful rocks must be in liquid form, then enough mechanical energy must be supplied to produce large surface areas of nano-particles "… 80 m^2/g, corresponds to a surface energy of 0.2−0.36 MJ/m^2 of the fault surface for a gouge zone 1 mm thick (for a specific energy of quartz of 1−1.8 J/m^2);" similar estimations were made for granite (ibid.). Pulverization also requires large magnitudes of the differentials in pressure; these can be easily provided by explosions and by generation of ultrasound or by gas/steam-bubbles forcing their way through liquid (process of cavitation), but not by mechanical slip in the fault zone. The authors (ibid.) mention the possibility of explosion as a part of the process, but do not suggest any concrete mechanism for it; they compare surface energies with energy theoretically available at the fault zone and conclude that gouge surface energy is not a negligible component of earthquake energy balance.

Many of the geophysical and geochemical anomalies that are observed in relation to earthquakes, as well as the nature of their power sources are not fully understood. Among them are: (1) violent outgassing prior and during earthquakes (Ozima and Podosek, 1983; Soter, 1999); (2) anomalous infra-red radiation reflecting heat-release, which precedes also shallow earthquakes (Salman and Tronin, 1990; Hasiotis et al., 1996); (3) pre-earthquake radio and acoustic noise (Gufeld, 1992); (4) diffused glow and fireballs (Soter, 1999); (5) upward migration of earthquake hypocenters (Ponomarev, 1990); (6) measurable transitory deformations of the earth's surface before an earthquake (Ponomarev, 1990); (7) earthquake-related strain-cycling and mobilization of subsurface waters (Wood, 1994). Partial explanation of these anomalies may be found in Ponomarev's Thermo-Gas-Dynamic (TGD) earthquake model (Ponomarev, 1990). According to this model, stored elastic energy and initial mechanical processes trigger earthquakes in the hypocenter, behaving as a "steam-boiler" that is filled with a hypothetical "fluid" discharged from magma under variable pressures and super-critical pT conditions. That hypothetical "fluid" explodes in a closed volume, causing destruction of the rocks at the hypocenter. There is a linear relationship between the amount of energy released and the volume of the hypocenter. De-facto, the Ponomarev's TGD model remains a volcanic chamber; however it fails to explain the nature of this hypothetical "fluid" and of its latent energy. The energy discharge of a hydrothermal explosion is not big enough to generate a strong earthquake.

Kopnichev and Sokolova (2010) discovered that before many strong earthquakes seismic rings are formed in different regions of the world, which surround regions of relative calmness. Analysis of characteristics of seismicity and absorption field of short-period transversal waves (S-waves) in regions of those ring structures led them to the conclusion that the "mantle fluids" rising to the lithosphere and concentrating therein play an important role in the period before strong earthquake. Gufeld (2007) interpreted "fluids" as a rising from the mantle mixture of hydrogen and helium; changes in concentration of those gases causes changes (contraction-expansion-contraction) in rock-volume and related deformation of the rocks. Sokolova (2010) collected data evidencing systematic decrease of the mantle helium (parameter $R = {}^3He/{}^4He$) in the groundwater with the increase of distance from strong earthquake epicenters and large fault zones. Before Reid (1910) hypothesized his model of "earthquake as a result of rock displacement under accumulated elastic stress", it was thought that earthquakes and volcanic eruptions are generated by the same power; well-qualified and untroubled by any theories, eyewitnesses have clearly shown in their descriptions that underground explosions and surface eruptions of gases are an integral part of the observed earthquakes (e.g., Darwin, 1842–46; Lyell, 1875).

Earthquakes and volcanic eruptions are described in most studies separately and explained differently. However, these events are related in space and time: most earthquakes and volcanoes occur in deep-seated faults at plate boundaries, rifts and transform faults; earthquakes precede and accompany volcanic eruptions, but not every earthquake culminates in a surface eruption. Most hypocenters of the so-called "volcanic earthquakes" are situated at depths of 0–3 km, in the volcanic chamber filled by liquid magma, or adjacent to it, where no elastic stress can be accumulated. McNutt (1994) compiled a lot of data which define an empirical relation between tremor amplitude and eruption explosivity: as the tremor amplitude increases, the explosivity increases. Small amounts of water-steam accompanying liquid magma cannot explode before the pressure is lifted, and even then, their explosions would cause adiabatic cooling and would be unable to provide the energy necessary for melting the surrounding country rock and preparing the volcanic chamber. To ours and others' experience, volcanic eruptions sound like a train of explosions and the earth trembles, like during an explosion; when closely observed they look like a chain of TNT-explosions, the solids and liquids fly from their centers like in explosions; they smell like explosions - so, maybe - volcanic earthquakes are chemical explosions, liberating latent chemical energy? Those trains of chemical explosions rising from a few-hundred-kilometers depth are also capable in generating kimberlite-pipes.

The most popular explanation of the great volcanic explosions today is the "champagne-bottle-cork-model", where the strongest explosions occur at the opening stages of eruption, when some external factor (e.g., avalanche) lowers lithostatic pressure of the upper part of the volcano-mountain ("cork"); as a result, the water-vapor-bubbles accumulated in the magma-chamber during the pre-eruption period instantly expand, and their increased pressure blasts the mountain top. Nevertheless, the monstrous explosion of Tambora in 1815, which released 10^{20} J of kinetic energy (Vaganov et al., 1985), an equivalent to an explosion of 24 Gt TNT, occurred only after 7 months of eruption that lasted in all for 15 months; its build-up pressure reached tenths of a gigapascal (impossible for a steam-explosion). The incredible explosion of Krakatau in 1883, 3 months after the beginning of the eruption, blew up 18 km^3 of rocks and was heard at the distance of 4653 km on the Rodriguez Island. The initial velocity of some of the ejecta was in excess of 8 km/s (Vaganov et al., 1985), with those fragments leaving the Earth for ever. No steam-explosion could have provided those velocities; therefore for an explanation of volcanic explosions other explosives are badly needed.

3. Volcanic gases as energy carriers

The present paradigm postulates that only magma and its contents are responsible for all the energy supply for plutonic processes. However, the common observation is that the total amounts of chemicals released to the atmosphere by volcanic activity is usually many-fold greater than that which could be contained in the extruded amounts of lava or ash (see in Gilat and Vol, 2005). Fedotov (2006) calculated the heat-power of the eruption column of the northern Tolbachinsk (Kamchatka) fissure-eruption (6.7.1975–10.12.1976), which erupted during 72 days about 0.68 km^3 of small-size pyroclastics, it was 3.52×10^{10} cal/s $= 1.47 \times 10^5$ M_w"; for comparison, "the power of all the USSR power-stations in 1976 was 228,000 M_w, or 2.28×10^5 M_w". We think that there is a case of three-dimensional gas transfer by diffusion, and there is no correlation between volumes of magma and diffusing gases.

Mighty gas ejections from the volcano can continue for years without eruption of any solids or liquids, heating the vent-comprising rock, e.g., Mt. Etna's Bocca Nuovo crater in 1969–1970 (Tazieff, 1980). Tazieff's team used rapid chromatographic techniques for the gas-analyses; perhaps the most remarkable feature in their results is the surprisingly small amounts of water in the gases of Mt. Etna: CO_2 was about 50%, while H_2O was less than 40% and fell as low as 3%−4% during short bursts of hot gas (Tazieff, 1970). Even during quiescent periods, the plumbing system of the Mt. Etna volcano discharges about 200 t/d of gas, containing helium with mantle-type isotopic composition; monitoring of gas manifestations located in the southern and eastern parts of the volcano has shown that the gas is sometimes carbon dioxide, and sometimes methane dominated (Caracausi et al., 2003). The amount of CO_2-released is estimated to be around 25 Mt/yr (Allard et al., 1991). According to Vaganov et al. (1985), analyses of gases from fresh lavas of Kamchatka volcanoes made by I.I. Glustchenko show that primary explosive gases uncontaminated by meteoric water and air (H_2, Cl_2, CO, OH, F_2, Br_2, H_2S, CH_4) comprise 10%−70% of total volcanic gases. A detailed information on earthquakes, volcanic eruptions, volumes and chemistry of volcanic gases can be found in Gilat and Vol (2005).

As of today there are also no theoretical explanations for the source of aggressive chemicals, such as HF, which cannot be stored in magma prior to eruption (in the laboratories it is stored in paraffin bottles), but thousands of tons are expelled (e.g., 0.2 million tons of HF were released during 1919 by "smoking furnaces" in the ignimbrites of the Valley of Ten Thousand Smokes; Zies, 1938). We agree with Vaganov and Glustchenko (Vaganov et al., 1985), that this is a good reason to believe that the erupting lavas and at least some of the erupting gases came from different sources in the mantle. Continuous discharges of gases (which include very active F_2, Cl_2 and Br_2) even during quiescent periods of volcano activity have to be "leftovers" of incomplete, low-order explosive chemical reactions, and super-active compounds (e.g., HF) form after their components are exhausted into the atmosphere.

It is a common knowledge that under certain conditions chemical reactions between some of the gases begin as combustion and develop as a chemical chain-reaction culminating in explosion. Active reagents − free atoms and radicals − in the course of that chain-development react also with molecules of the initial gases and with the end-products, generating new active centers. The mixture of oxygen and hydrogen explodes when hydrogen concentrations vary between 6% and 95% (volume). When even small amounts of water-vapor are present, explosion occurs at a temperature of about 600 °C; the water is a catalyst accelerating explosive reactions a thousand-fold. These and similar reactions, typical for explosive mixtures, generate a great amount of enthalpy; following are some examples (J/mol):

$$2C + O_2 \rightarrow 2CO + 221 \times 10^3;$$
$$2CO + 2H_2 \rightarrow CH_4 + CO_2 + 247 \times 10^3;$$
$$2CO + O_2 \rightarrow 2CO_2 + 556 \times 10^3;$$
$$2H_2 + O_2 \rightarrow 2H_2O + 572 \times 10^3;$$
$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + 804 \times 10^3;$$
$$2H_2S + 3O_2 \rightarrow 2H_2O + 2SO_2 + 1122 \times 10^3;$$
$$2SO_2 + O_2 \rightarrow 2SO_3 \rightarrow 193 \times 10^3.$$

The 1815 Tambora eruption blew out (among ash and other chemicals) about 52×10^6 t of sulfuric acid (Devine et al., 1984), whose synthesis from primary elements could produce an energy equivalent to 96 Mt of TNT. Erupted chlorine and fluorine gases mix with the water-steam and form acids (e.g., USGS publications on volcanic gases). The synthesis of 50×10^6 t of water from a hydrogen-oxygen mixture ("detonating gas") could produce the energy equivalent to 150 Mt of TNT.

4. Inadequacy of the energy source in the mantle-plume theory

The conclusions of many of the last years' studies are that geodynamics of the high-seismicity regions and the nature of great earthquakes are related more to the mantle plumes, and not to movements along the particular faults (e.g., Nusipov et al., 2005). Moreover, the slowing of Africa's motion between 67 and 52 million years ago and the synchronously unusually rapid motion of the Indian plate, its push to collision with Eurasia causing huge scale seismicity and eruption of the Deccan flood basalts were all convincingly related to the force of the Reunion plume head (Cande and Stegman, 2011). Mantle plumes, the hypothetical thermal diapirs that are supposed to solve the energy problems of the theory of plate tectonics, do this by carrying heat from the liquid core upward to the lithosphere in narrow rising columns supposedly driven by convectional heat exchange and independent of plate motions. Their driving force is the hypothetical temperature-difference between the uppermost liquid core and the lowermost mantle. The big difference between the magma's specific heat capacity (0.35 cal/g degree) and it's heat of fusion (120−165 cal/g under atmospheric pressure) for melting magma demands an amount of energy higher than for heating it to 400 °C; thus, being 300−400 °C hotter than the surrounding rock as the only energy resource at the core-mantle boundary, these plumes are supposed to melt-through the almost 3000 km thick solid mantle. Does not this model remain *perpetuum mobile*? Even more doubtful is the possibility that the plume head could provide the described-above additional energy-supply of a planetary scale (Cande and Stegman, 2011). And, in any case, if this *perpetuum mobile* operates over geologically-long periods, e.g., in the thermodynamic system of the zone of subduction, the local thermodynamic equilibrium would be set so that it cannot be changed from within the system without an additional inflow of energy (the first low of thermodynamics). The continent-shaping outburst of the Chilean 1960 earthquake energy could not have burst forth from nothing. Attempts at explaining the adjacent volcanic activity and the mighty heat-flow from the subduction-zone by intrusion into its asthenosphere blocks of the cold oceanic crust are in conflict with the second low of thermodynamics: energy will not flow spontaneously from a lower temperature object to a higher temperature object. Devolatilization of the oceanic crust (formation of the super-critical fluids from the subducting sediments rich in hydrous minerals and clays), promoting melting of the mantle wedge and generation of magma, surely are not a source of energy which can be concentrated and used for mega-earthquake or volcanic eruption, or provide a continuous heat-flow from the subduction zones and the spreading ridges on plate boundaries; it has to be mantle plumes - they were invented for explanation of those heat-flows. So, what is the source of energy of the mantle plumes, of the heat coming from plate boundaries, what power raises continents and blows up volcanoes?

5. Properties considered necessary for the sought-for energy source

Evidently, properties of the sought-for forces are as follows: (1) they are tremendous and quasi-constantly discharged; (2) they can be quickly concentrated and focused; (3) they have very high velocities of energy released, which must be equal to or higher than crack propagation velocities, otherwise the crack will stop;

(4) they provide increasing intensity of the energy released during earthquakes and volcanic eruptions; (5) they provide fast accumulation of energy between shocks and eruptions; (6) they have very high density of energy transport and relatively small losses during transportation over long distances; (7) they supply to the lithosphere highly energized gases for igneous processes, and concentrate minor and trace elements for ore-forming hydrothermal solutions; (8) they correlate with ^{3}He outflow.

All processes of stress-accumulation, deformation, and fracturing are irreversible, have a very long relaxation period and do not provide the observed short-time cyclic sequence of the energy release and accumulation causing foreshocks and/or aftershocks. Nuclei processes are independent of external conditions (at existing conditions on Earth) and cannot respond to their changes with intensity of energy liberation or absorption. "Pressure of the gases contained in magma" cannot provide the adequate energy, pressures and velocities observed, nor even the amounts and chemistry of the observed erupting gases. A comparison between limits of intensity of the energy flows, accessible by convection, thermo-conductivity or by transfer of the latent energy of chemical compounds shows that the latter is the most favorable.

The conceptional system of hypotheses described below is based on the much more powerful energy source of the mantle gases. In very many publications (Ozima and Podosek, 1983; see additional references in Gilat and Vol, 2005) it was noted that earthquakes and volcanic eruptions are accompanied by significant outflows of mantle helium, hydrogen and other gases. This interrelationship between tectonic and chemical processes indicates the possible involvement of these gases in the generation of energy. The direct proof of this participation is the excellent correlation between mantle helium-3 concentrations and internal heat flows, observed since 1970th by many researchers in seafloor hydrothermal flows (e.g., Ozima and Podosek, 1983; and numerous later articles, e.g., Jean-Baptiste et al., 1998).

6. Accumulation, transformation and release of energy within planet Earth: primordial hydrogen and helium as its most abundant and most important agents

During the Earth's accretion period (4.2–4.5 Ga ago), primordial hydrogen and helium, comprising 98%–99% of space matter, were trapped and stored in the Earth's core and mantle as a solid and liquid solutions and chemical compounds, stable only under conditions of ultrahigh pressure-temperature (*p-T*) conditions. Endothermic reactions generated by these solutions and compounds provided effective cooling of the planet and the end-products of these reactions were more compact, than the initial gases. Since stabilization of the planet exothermic processes of hydrogen and helium degassing became dominant; these are accompanied by release of the energy, which was invested in their generation (specific energy, see the Table 1).

Release of the mantle hydrogen and helium, accompanying concentrated flows of the heat energy of the Earth, justifies the assumption that the planet is still left with enormous quantities of these gases in its core and mantle. Helium is an inert gas under atmospheric conditions, however its compounds He-H, He-O, He-Si, and He-metals, stable only under pressures higher than 14 GPa and temperatures higher than 1000 K, are well known (Rhee et al., 1989; Aver'anov and Khait, 1995; Nuccio and Paonita, 2000).

Table 1 Specific stored energy of H- and He-solutions in the Earth's interior (from Gilat and Vol, 2005).

Depth (km)	Pressure (GPa)	Temperature (K)	Internal free energy (J/mol)	
			Helium	Hydrogen
0	0	300	12,480	8652
10	0.33	500	20,800	14,420
100	3.4	1800	74,880	51,912
500	18	2000	83,200	57,680
1000	40	2500	104,000	72,100
2000	88	3500	145,600	100,940
3000	160	5500	228,800	158,620
4000	238	5800	241,280	167,272
5000	321	6000	249,600	173,040
6000	358	6200	257,920	178,808
6370	370	6200	257,920	178,808

Compounds He-F, He-Cl, He-C and He-N structures can be deduced from their atomic structure and composition of natural He-rich gases (Ozima and Podosek, 1983). Decomposition of He-H compounds releases very large amounts of energy (e.g., more than 2 kcal/(g mol) for the He-H system, estimated from published data (Kleinekathoefer et al., 1996; Vos et al., 1996), and from standard energy conversion factors). The more exact estimation was made in recent studies of ^{3}He gas endothermic formation of solutions in solids and liquids. For example, Saunders et al. (1994) described a chemical shift of the helium nucleus, demonstrating a high binding energy of helium with surrounding matter. This shift was observed experimentally and the potential barrier of solution formation was estimated as maximum 10 eV, which corresponds to 230.5 kcal/(g mol); this amount of stored energy is, for example, far beyond that of the heat of water formation from hydrogen and oxygen (68.3 kcal/(g mol)).

A solution of 138.2 cm^3 of hydrogen in 100 g of iron only increases the alpha-iron lattice constant from 0.28590 to 0.28612 nm (Vol, 1962), which demonstrates the thermodynamic necessity of formation of solid solutions. Under a temperature of 1500 °C and pressure about 36 MPa the hydrogen solubility is close to 240 cm^3 per 100 g for nickel and about 120 cm^3 per 100 g for iron (Shapovalov, 1999). Shapovalov proposed a corresponding phase diagram and concluded that hydrogen lowers the melting temperatures of metal and also expands the regions of stability for those polymorphic forms in which it is more soluble.

The H_2-H_2O binary system forms at high pressure a novel 1:1 type of clathrate, where H_2O and H_2 form two interlocking networks, both with a diamond structure, stable up to at least 30 GPa (Vos et al., 1996). Single-crystal X-ray diffraction studies of the H_2-CH_4 system under similar pressure revealed four different solid compounds with molar ratios of 1:2, 1:1, 2:1 and 4:1 (stable to at least 30 GPa [ibid.]). The conclusion is that at high pressures the "gas-ice" (gas-hydrate) compounds are ubiquitous. This data supports the hypothesis proposed by Gold (1979) of the existence of an enormous reservoir of methane, deeper within the Earth than any organic deposits. This data also suggests that at least part of the immense methane resources discovered by ocean drilling in the oceanic crust (e.g., Evans, 1996), and of methane hydrate in the oceanic sediments (e.g., Kvenvolden, 1988), the amount of which (2×10^3–4×10^6 Gt) greatly exceeds that in other reservoirs of the global carbon cycle (ibid.) are mantle derived.

The continuous process of the Earth's degassing needs transportation of hydrogen and helium from the core to surface. The step by step process for different *pT*-conditions (Fig. 3) are described in our former work (Gilat and Vol, 2005, Section 7.1–7.6): H and He emanating from the solid core and generating convection in the liquid core, flux-melting the solid mantle and generating auto-focusing gas-liquid magma ("pyromagma") plumes or diapirs. The structure of these mantle-crossing flows is composed of the gas-saturated liquid layers on the plume-mantle boundary and its main liquid part, where convective transportation of hydrogen, helium and their compounds is dominant. Plumes melt through the solid mantle using heat-energy released in reactions of their metamorphic and chemical transformation under gradual decrease of pressure and temperature.

Mantle-matter under high *pT*-conditions has to be capable of evolving solutions and melts. Under super-critical high-velocity-deformations (e.g., chemical explosions) of the gas-liquid-solid mantle-matter, systems of dynamic fractures are generated in the plume-mantle contact zone; higher deformation-velocity causes wider propagation of fractures. These reversible (pushed open by pressure wave – closed when pressure decreases) fractures perform as very effective pump jacks, promoting transfer of the chemically active compounds and their latent energy from the mantle into the plume. Depletion of the plume-adjacent mantle-matter of gases and other reagents reduces absorption of the shock-waves caused by a decrease in their splitting on the phase-boundaries; these are bound to cause lengthening of dynamic fractures and associated magnification of the volume of the plume-feeding mantle. The combination of these processes – gathering and accumulation of active reagents, realization of their latent energy stored under the specific *pT*-conditions, generated by exothermal-reaction compressional (shock) waves and incited by those waves accelerating pumping into the plume of a new quantity of reagents from the mantle by dynamic fractures – ought to be one of the main mechanisms of the plume self-focusing. This combination of the principally non-linear processes leads to earthquakes and volcanic eruptions.

Rising plumes scavenge incompatible elements from the Si-Mg-Al-Ca-K-Na mantle-rocks through which they pass, i.e., elements that are strongly fractionated into the liquid tend to be carried in the liquid and to accumulate in increasing concentrations (O, S, C, N, Cl, F, metals etc.). These elements form He-H, He-O, He-C, He-S, He-N, He-metals and other compounds; compounds are concentrated and transferred to the lithosphere for their future role as volcanic gases and ore-forming hydrothermal solutions. Heat thus produced and continuous small-scale explosions neutralize adiabatic cooling, melt and bore through the solid rock, and produce all the manifestations of igneous activity in general and of volcanic eruptions in particular. Repeated explosions and releases of pressure related to them cause disintegration of rocks and generation of fractures and cavities; those promote decomposition of He- and H-compounds, release of elemental H, O, C, S, Cl, F, etc., and outbursts of energy (low-order seismicity); those produce new fracture-systems, sometimes concentric that can be filled by pyromagma "fluid" (Kopnichev and Sokolova, 2010), an explosive for the future mega-earthquake. The sudden chain reaction of the decomposition of these meta-stable compounds, triggered by decompression of the fault zone, is proposed as the practically infinite energy source for earthquakes. In case of further small-scale decompressions of the upward moving hypocenters, self-oscillating (harmonic tremor) in response to concentrations, H, O, C, S, Cl, F, etc., which are liberated as a result of exothermal decomposition of H- and He-compounds, will participate in the explosive reactions of synthesis, melting rocks and forming a magmatic chamber. Thus volcanic eruption is generated by the energy of magmatic gases, producing and liberating H_2O, SO_2, H_2SO_4, CO_2, H_2S, HCl, HF and other chemicals.

^{3}He performs as a unique measuring transformer correlative to the internal heat flow. The total heat flow produced by these can be estimated, according to the data summarized by Jean-Baptiste et al. (1998), as follows: The ^{3}He/heat ratio in vent fluids of various hydrothermal sites ranges from 4.3 to 47.0 (10^{-18} mol/J); thus the lowest ratio of 4.3 corresponds to 2.326×10^{17} J/mol of ^{3}He. Multiplying it by 2200 (mol/yr, the ^{3}He-flow from the lower mantle estimated by Allegre et al. (1986/87)), we obtain 5.12×10^{20} J/yr, which is equal to half of the present rate of heat flow from the Earth's surface (see Chapter 1.1), and is five times larger than the energy loss involved in earthquake and volcanic activity. These data may be considered as the direct proof of participation of helium in the heat-producing processes, and an indirect support for the hypotheses proposed herein.

7. Discussion

There is good reason to think that the proposed model for conservation of energy during the Earth's accretion by the endothermic formation of H and He solid solutions and compounds and its release by degassing and accompanying exothermic reactions described herein is a main source of tremendous energy for terrestrial dynamics. This mass-transfer-related energy, in contrast to energy from traditional sources, generates convection in the Earth's liquid core; it produces liquid magma in the mantle and supplies energy to rising plumes; it can be easily transferred along major faults, quickly concentrated and explosively released, thus producing very high velocities of energy release and all the geophysical and geochemical anomalies typical of earthquakes. The proposed sequence of mutually induced reactions supplies active reagents and highly energized mantle gases to the lithosphere, where they melt the asthenosphere and the upper mantle, by melting and explosions bore conduits and chambers for generated magma, rise through the brittle rocks and provide the energy for igneous activity and volcanic eruptions with all their manifestations. We regard the "tectonic earthquake" as a chain reaction, as cumulative chemical explosions of active compounds (H-He and others), which result in multistage degassing with helium and hydrogen release; these explosions are often accompanied by movements along faults and fault-zones. The volcanic eruption is viewed as a special type of earthquake whereby the hypocenter rises to the surface; the volcanic tremor does not accompany eruption but generates it.

The processes of mass- and energy-transport described above are self-focusing, depending on kinetics of these processes and on the matter-viscosity conditional to phase-transition and the movement of shock-wave fronts. Self-focusing causes decrease in the internal energy of an open system, which is well known in physics and electrochemistry.

The concept proposed herein is symmetric: conservation of energy, on the one hand, and its release by degassing of the planet, on the other hand. We think that the mechanism, on which it is based, the most powerful that nature has for conservation of energy, would not remain unexploited. This conception is supported by undeniable facts, namely: (1) continuous tremendous

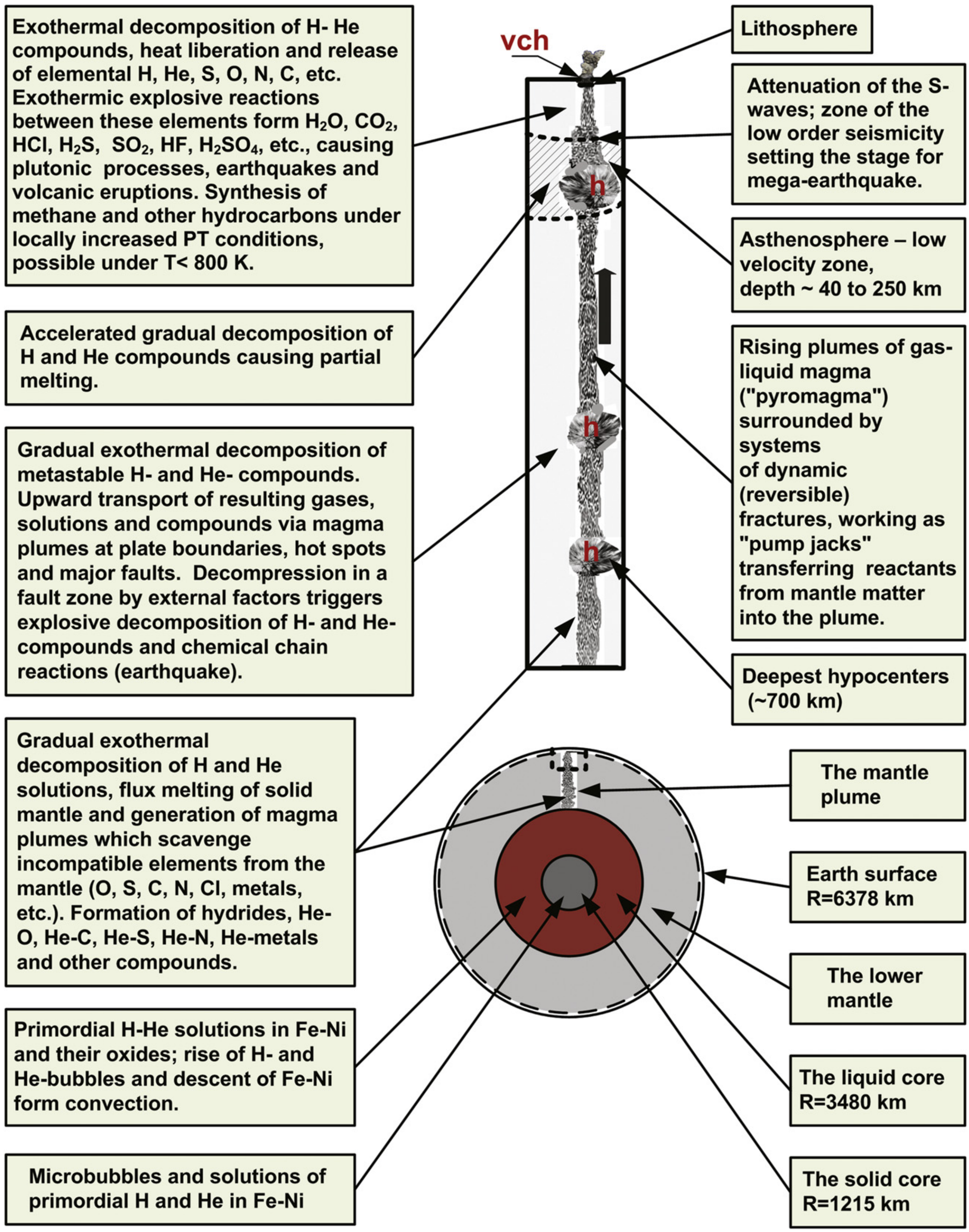

Figure 3 Suggested states and phase transforms of hydrogen and helium degassing from the Earth's interior; h: earthquake hypocenters; vch: volcanic chamber. Volcanic eruption is considered a special case of earthquakes whereby hypocenters ascend to the Earth's surface (Modified from Gilat and Vol, 2005).

degassing of primordial hydrogen and helium from the Earth's interior; (2) very high energy-capacity of H- and He-compounds, some of which have already been studied in laboratories under ultra-high *pT*-conditions similar to those of the Earth's interior; (3) good correlation between the mantle helium- and the internal heat-flow. It is based on published and accepted geological data, on the most basic geological theories, which include plate tectonics and surge tectonics theories, and on the universal physicochemical laws. The comprehensive model proposed herein may help to find solutions to practically all enigmas and questions related to the lack of a plausible energy source for the main terrestrial processes (Section 1), and for the man-made earthquakes. It also provides a clue to the origin of abiogenic hydrocarbons (mostly methane), which are produced parallelly to volcanic and plutonic processes by synthesis from elemental products of decomposition of He- and H-compounds; the often-encountered in oil exploration and still poorly understood abnormally-high formation pressures (AHFP), characteristic to a very large number of hydrocarbon reservoirs (e.g., Sahay, 1999), may be a demonstration of their close relationship with the mantle. Synthesis of hydrocarbons from C and H under AHFP conditions is thermodynamically beneficial because it decreases the quantity of molecules, thus decreasing the overall pressure; similar processes are of great industrial importance.

8. Conclusions and possible research avenues

Release of energy of the primordial He- and H-compounds through a sequence of dominantly exothermal transformations (phase-transfer) is the quickest and most efficient process of energy transfer and entropy production. Trajectory of formation and evolution of the planet through degradation of energy to lower temperatures are governed by the law of maximum entropy production (Swenson, 2000; Kleidon and Lorenz, 2005). Self-organized order, evolution and autocatakinetics of plumes also follow this law. Because of the universal nature of the physicochemical laws and of the H- and He-abundance in space (99%), the hypotheses include the premise that they were absorbed by every cosmic body; the part of them still left there depends on the size of the body and of its age; the processes described herein are also universal and are bound to work on any planet in the solar system and elsewhere. Thus the H-He-degassing hypothesis may also offer a better understanding of, e.g., volcanic and seismic activity on the moon, which has had similar volcanism and moonquakes, but only on its near-to-earth side and which usually occurred at a fixed phase of the lunar tidal cycle (Taylor, 1975). The cessation of volcanic activity on the moon, and the relatively low energy represented by moonquakes (2×10^{13} erg/yr or 2×10^{6} J/yr), compared to 10^{24}–10^{25} erg/yr or 10^{17}–10^{18} J/yr by earthquakes (Taylor, 1975) may be indicative of the final stages of He- and H-degassing of the moon. Its degassing must be several orders of magnitude quicker, and its primary resources smaller than in the case of the Earth. On the other hand, our giant planets give off huge amounts of energy, probably owing to H- and He-replacement in their cores by heavier elements (gravitational differentiation).

The hypotheses proposed herein appear to be objectively testable. For example: it was thought that observations of the direction of the initial movements on the seismograms would give a very simple method of distinguishing between underground explosions and earthquakes due to elastic rebound, but this is not so: most records of both of them show similar signatures (Eiby, 1989). This similarity is conspicuous, maybe all of them are underground explosions - cumulatively chaining up to 1 min long in a great earthquake or a concentrated, few milliseconds-long single atomic blast; seismograms recording earthquake-shock on the millisecond scale can be enlightening.

We suppose that for "any small earthquake… cascading into a large event" (Geller et al., 1997) some monstrous energy must in some way be concentrated at a certain point, in a certain form, in a certain medium, and by some means triggered to explode. The main question that arises is how do these energy concentrations of planetary scale manifest themselves before a major explosion? We think, by intrusion of millions of tons of the "mantle fluids" into the lithosphere that causes attenuation of the S-waves (e.g., Kopnichev and Sokolova, 2010); maybe, by changes in gravity field, or perhaps by geomagnetic anomalies sensed by the super-sensitive system Super Grad (Bass, 2010). We hope that the conceptual system of hypotheses presented herein will be helpful also in a search for short-term precursors of earthquakes.

About 15 years ago we (a geologist and a chemist) started this work in order to explain the driving force behind earthquakes; the problem was concentrated on the Earth's degassing (the role of hydrogen and helium). Later it became clear that the physicochemical energy source suggested herein is universal, i.e., it may participate in any terrestrial process, filling numerous holes in the theories concerning evolving Earth.

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