# KIMBERLITE EMPLACEMENT by SOLITARY INTERFACIAL MEGA-WAVES on the CORE–MANTLE BOUNDARY

**Bradley L. Sim** *Department of Earth Sciences, University of Ottawa, Ottawa, Ontario, K1N 6N5, Canada.*
**Email:** sim@science.uottawa.ca **Fax:** 613 5625192
**Frederik P. Agterberg** *Geological Survey of Canada, 601 Booth St, Ottawa, Ontario ,K1A 0E8, Canada.*

## Abstract

If convection in the earth's liquid outer core is disrupted by turbulence and begins to behave in a chaotic manner, it may destabilize the Earth's magnetic field and provide the seeds for kimberlite melts via turbulent jets of silicate rich core material which invade the lower mantle. These (proto-) melts may then be captured by extreme amplitude solitary nonlinear waves generated through interaction of the outer core surface with the base of the mantle. A pressure differational behind the wave front provides a mechanism for the captured melt to ascend to the upper mantle and crust so quickly that emplacement may indirectly promote a type of impact fracture cone within the relatively brittle crust. These waves are very rare but of finite probability. The assumption of turbulence transmission between layers is justified using a simple three-layer liquid model. The core derived melts eventually become frozen in place as localised topographic highs in the *Mohorovicic* discontinuity, or as deep rooted intrusive events. The intrusions final state composition is a function of melt contamination by two separate sources, the (core contaminated) mantle base and subducted *Archean* crust. The *mega-wave* hypothesis may offer a plausible vehicle for early stage emplacement of kimberlite pipes, carbonates or orangeite melts and explain the age association of diamondiferous kimberlites with magnetic inversions.

***Key Words***

*Archean*, Boundary layers, Chaos, Complex systems, Carbonatite, **Core**, Crust, **D" Layer**, **Diamonds**, *Gaia* hypothesis, *Glatzmaier-Roberts* dynamo, *Gutenberg* discontinuity, Impact cone, Interfacial waves, **Kimberlite**, Mantle, **Mantle plume**, Mega-waves, *Mesozoic*, *Mohorovicic* discontinuity (Moho), 1/*f* Noise, Nonlinear waves, Orangeite, *Pareto* distribution, Polar reversals/ inversions, **Rogue waves**, Turbulence, Ultra-low Velocity Zone (ULVZ).

## Introduction

Kimberlites are one of the main source rocks for diamonds, consequently their occurrences within the Earth's crust have been reasonably well documented. However there is still a lack of consensus on their source and transport to a final state location [1][2], but now enough pieces of the kimberlite puzzle may be available to formulate the first complete picture of the unusual life of a kimberlite melt. The mega-wave model introduced here is an attempt to tie all the existing pieces of the kimberlite story together in a cohesive way with some basic assumptions and a simple unifying experiment. If we assume the *Gaia* hypothesis [3] stands true- which considers the whole Earth as one system behaving in a complex manner, that the Earth's mantle behaves as a liquid over geological time scales and there is a small percentage of residual silicate in the core. The chaos of interactions between eddies and swirls in the outer core will eventually permeate the whole planet in some form [4][5] and allow ferromagnesian silicate melt to escape the core and be captured by nonlinear boundary waves in the mantle. Although mantle convection is not usually chaotic [6], nonlinear waves along the mantle base would work to briefly disrupt whole mantle convection and linear waves along the top mantle boundary, Dalziel [7] notes the upper and lower thermal boundarys of the mantle appear to have been functionally linked since early in the Earth's history. It is proposed that a mechanism for the formation and emplacement of kimberlite melts may arise indirectly from periods of instability in the Earth's magnetic dynamo, seen as magnetic inversions [8][9][10][11] in the geological record. Magnetic inversions and the age of kimberlites appear coupled [12][13] as shown in Table 1, the result of $1/f$ noise which characterises the spontaneous rise of all systems to a critical state [14]. Core derived melts could be ferried quickly from the core-mantle boundary to the planetary crust via large amplitude solitary nonlinear waves. The fact that most diamondiferous kimberlites are Archean (2.8-4 billion years bp) or *Mesozoic* (65-245 million years bp) in age can be indirectly explained by compositional work done on kimberlites over the last 30 years. It has been concluded that the unusual mineral assemblages in kimberlites are a mixture of ultrabasic material (essentially ferromagnesian minerals) and subducted Archean crust [15][16][17]. The rock record shows that lithospheric plates were unusually active in the Mesozoic [18], proving the opportunity to subduct more surface rock (Archean or otherwise). While during the Archean, Archean terrains were at the mercy of (proto-) tectonic processes [19][20]. Recycled carbon dioxide [21] and biological material in the crust supplements the carbon available in the lower mantle to form diamonds [2].

*The ULVZ Separating the Core and Mantle.*

A zone exists between the core and mantle which appears to be a mixture of solid and liquid, inferred from seismic data. This zone may represent one of three things, it may be a layer in its own right, which implies own current understanding of planet accretion is likely flawed as the evolution of such a layer between the core and mantle has never been modelled. The second option is that the zone is part of the core, a kind of crust of lighter crystalline iron (± silicates) on the outside of the core or thirdly the zone may be the basal part of the mantle contaminated by core leakage, like the water logged underside of a timber floating in the sea. The authors favour a combination of the later two options as implied by buffett et al. [22]. The first option undermines all existing ideas regarding the Earths formation and its subsequent internal structure.

## Solitary Mega (*Rogue*)-Wave and Transmitted Turbulence Model

Any ferromagnesian silicate melt expelled by turbulence from the core is free to be transported to higher elevations as a function of mantle-core boundary interactions and wave phenomena. Interfaces between discrete bodies are common in the environment around us, but more importantly, waves may develop along any of these interfaces as a function of differential density. For example, atmosphere partitions [23], ocean–atmosphere, liquid–liquid contacts within the sea water column (the result of e.g. salinity variation), solid-liquid interfaces [24] or solid–solid boundaries [25] can give rise to both linear and nonlinear waves in a thick medium. Waves along these interfaces are usually linear until some critical value in controlling variables is forced allowing the waves to degenerate to a nonlinear *chop*, with the possibility of chaos and spontaneous pulse formation of very high amplitude events like those observed from time to time on the oceans free surface or on interfaces within the ocean. The model introduced here arises by sequentially linking existing models from different disciplines together with some basic assumptions and applying the combined result to a complex geological problem. The Earth's interior is simplified to a basic three layer model (Fig. 1) which provides the backround for all further discussion. The model has a number of key components; chaotic instability of convection in the liquid outer core [8] (inferred through magnetic reversals), irregular topography along the core-mantle boundary (*Gutenberg* discontinuity) [22], rotation of the mantle (which convects, but does not rotate in its own right), the possibility of nonlinear wave effects along boundary layers within a stratified liquid [26] and the effects of turbulent layers on adjoining non-turbulence layers [27]. All these things have been independently studied by others and now enough information may exist to assemble a larger picture of the Earth's interior processes with specific reference to kimberlites. Everything mentioned above is bought together to form the mega-wave model, which explains the formation and transportation of kimberlite melts from the Earth's core to the suface. Each major component in the mega-wave model, representing a single piece of the kimberlite puzzle is introduced and summarized separately.

*Core Turbulence and Polar Magnetic Reversals*

When a higher density fluid is placed over a lower density fluid an unstable condition exists and the fluids will want to change places. Relic lower density ferromagnesian silicates gradually segregating to the outside of the liquid core below the more dense mantle would be an example of this unstable condition. However a perturbation is required in order to initiate the instability. This could take the form of turbulence in the liquid metal core. Glatzmaier & Roberts [8] have shown than core convection can destabilize, the result of chaotic interactions within the liquid core which sometimes result in polar magnetic reversals. The forcing factor for this turbulence is thought to be gravitation effects of the sun and moon in conjunction with the accelerated rotation of the inner core [28]. Ferromagnesian silicate melt expunged from the core as jets of turbulent material may fractionate into an a iron rich part and a silicate rich part [22, Eqn. 1], with only the silicate rich part escaping the core permanently. The iron enriched part settling back to the core as crystalline iron sediments within the D" layer to be reabsorbed by the liquid core but giving the core temporary topography and offering an explanation for the Earths axial wobble [22]. Dohan & Sutherland [27] have shown that jets of turbulent liquid shot out from a (higher density) turbulent layer into adjacent (lower density) non-turbulent layers in a stratified liquid model. These jets, which in the case of a turbulent core penetrate the lower mantle, represent potential kimberlite melts (Fig. 2). Experimental work also shows, decoupled nonlinear waves should develop on the layer boundary between the core and mantle at two scales; the scale of the turbulent jets and the scale of the experimental tank [27], in the case of the mega-wave model; the scale of the liquid core perhaps. These jets into the mantle may then create waves or be captured behind mega-waves forced by core topography. The jets initial escape from the core probably accounts for a large portion of the 25-50 million year lag time between magnetic inversions and kimberlite emplacement in the planetary crust (Tab. 1).

*Topography of the core and extreme amplitude waves*

Nonlinear waves of large amplitude are observed in the world's oceans, these may result from wave combination, focusing of wave energy like *triple jumping* on a trampoline, constructive interference or the presence of topography on the oceans floor, with the deep ocean usually being treated as a medium of infinite depth. If we apply this idea to the Earth's mantle on the assumption that the mantle behaves as a liquid over geological time scales and join it with the idea of an uneven surface on the core-mantle boundary due to contamination of the mantle by liquid core jets and the formation of iron (± silicate) crystal aggregates on the outside of the core [25]. In order for the silicate enriched melt fraction to be sucked up by a wave front requires mantle rotation relative to the core. The mantle however, does not rotate as an ocean current would over the rough ocean floor, but the liquid core does rotate [29][30] (slower) and generate a torque against the mantle. So continuing the ocean analogy, the ocean remains still and the ocean floor rotates under it, producing the net effect of rotating the ocean or as in the mega-wave model; the mantle. This will provide the necessary forcing to generate extreme amplitude waves on the core-mantle boundary. Energy is also siphoned into the mega-wave from the turbulent layer plus other wave interactions and its amplitude increases until the surrounding waves are drained of energy, then the mega-wave peaks out. These mega-waves [31][32] which grow rapidly to great size (amplitude) and disappear the same way; in an exponential manner are consistent with a *Pareto* (hyperbolic) distribution of wave amplitudes [33][34][35] rather than a *Rayleigh* distribution (favoured by oceanographers) which appears to under-estimate the chances of very large amplitude events [36]. It has been noted [38] that in general, interfacial waves are noticeably larger than their free surface equivalents. On the core-mantle boundary the wave would initially require enough energy to exceed approximately 140 *giga* pa pressure, although this would decrease at the wave head as the wave grew in amplitude. Equations used to generate experimental nonlinear waves include *Schrodinger's* nonlinear equation [37] and the *Korteweg-deVries* equations [38][39]. Mega-waves although a rare phenomenon [40], harness great energy for a limited time and may be the indirect result of chaotic system behaviour in the outer core inevitably forcing wave motion along sharp chemical composition discontinuities such as the Earth's core-mantle (*Gutenberg*) and crust-mantle (Moho) boundaries [41][42] in sequence away from equilibrium, allowing the formation of nonlinear mega-waves, as random events. Primary melts expelled from the turbulent core and initially contaminated by the ULVZ, may extend further into the mantle by exploiting the pressure differential behind a mega-wave front and move rapidly towards the Earth's surface combining with subducted Archean crust along the way to produce the final melt composition (Fig 3.) seen in the rock record. The mega-wave model does not require melt pooling at layer boundaries, however direct ascent may be complicated by mantle convection trajectories. Because of differences in rheology and chemistry of the liquid core, mantle and crust, as well as localized differences in the contacts themselves, wave effects on the top and bottom of the mantle will likely vary. Nonlinear phenomenon may also be possible along deformable boundaries such as the lower-upper mantle contact [43]. Although the type of deformation around these wave fronts will depend on material properties of the country rock, a pressure and structural vacuum will be created behind the wave front [44][45]. On the core-mantle boundary, the transportation window these mega-waves provide for primary kimberlite melts would begin to build slowly and grow faster as they approached the surface probably accelerating to well in excess of the estimated *average* emplacement velocity of 300 metres/sec for kimberbite pipes [46]. This mechanism will also apply (at least in part) to generic mantle plumes [47] more accurately termed *core plumes*. In the course of the (proto-) kimberlite melts ascent to the crust, diamonds previously formed in the lower mantle are free to be absorbed by the rising melt [1].

*Final state of core derived melts*

The mega-wave striking the base of the planetary crust will result in a fracture cone of extensional structures (faults, dyke swarms or grabens) arising from the wave peak, like an impact cone [48], except the impact has come from within the Earth, this connects the wave via pipes to higher crustal elevations, creating an overall shape of one small cone sitting on top of a bigger cone, with both meeting at their apexes, the cone on top being upside down giving rise to the characteristic funnel shaped breccias seen in many kimberlite pipe complexes (Fig. 4). If the wave has enough energy, fractures may extend to the planetary surface resulting in a fissure type eruption. But assuming the later does not usually eventuate, degassing as the melt rises behind the wave front is like opening a Champaign bottle [49] into the fracture cone above the wave peak (which may be aided by inelastic behaviour of the kimberlite which occurs at > 1 *giga* pa impact stress [50] ), and the final stage of emplacement. The resulting effects if a waves amplitude were to exceed the critical convective amplitude of Holyer [51] or develop a Kelvin-Helmholtz instability [52] from excess shearing between the upper and lower layers and *break* is beyond the scope of this paper.

**Conclusions and Discussion**

Modelling done by the author and Dohan & Sutherland [27] suggest as Haggerty notes [53] that kimbelites may indeed be a *window to the Earth's core*. Subduction of Archean crust and the simultaneous development of a mega-wave along the core-mantle discontinuity provides a plausible vehicle for the emplacement of diamond bearing kimbelite pipes, or carbonitite melts within the crust depending on where exactly the mega-wave driver develops, if a core jet is sucked into the wave, the composition of the Archean part of the source melt which mixes with the primary ferromagnesian silicate material derived from the liquid core and local inhomogenaities in mantle composition. Melt contamination by Archean crust also implies active (Archean) plate tectonics. The turbulent jets from the outer core which penetrate the lower mantle provide the seeds for kimberlite, carbonatites or orangeite melts. These melts may not immediately be picked up by a mega-waves leaving them free for a time to mix with the mantle. In reverse, the melts derived from turbulent jets of liquid core could date fossil polar magnetic inversions. The proposed mega-wave model is theoretical and not built strictly on existing evidence in the geological record unlike existing data-driven models [46][54]. These later models explain the final detailed features of preserved pipes (Fig. 4), but do not properly address questions regarding the early stages of emplacement or initial triggers. The principal pieces of the early emplacement puzzle have been partly assembled by others [47][48] and only require the turbulent core jets and nonlinear wave carrier to complete a model for kimberlites, carbonatites, orangeites and generic mantle plumes (originally core plumes) based on the theory of boundary nonlinear mega-waves forced by core topography and an adjacent turbulent layer. The mega-wave model is consistent with all existing information regarding the Earth's interior and if this remains the case over time, there are clear economic implications. Diamond exploration potential will be maximized in rock units pre-dating specific magnetic inversions and interpreted to have formed in the vicinity of subduction zones capable of subducting (Archean) continental crust. These areas should also have well developed extensional fault complexes, narrowly post-dating the inversion event. If an upside down fracture cone does develop from the wave's impact with the base of the crust, kimberlite pipes should always be found in groups. If mega-waves are a real component of kimberlite emplacement, then there should be potential for diamond bearing pipes on any differentiated (core, mantle, crust) planets, but polygonal plate tectonics i.e. the chemistry of Archean rocks from the planetary crust and surface carbon might also be critical.

*Future work*

Accurate monitoring of the position of the core-mantle and mantle-crust boundaries over time should determine if wave motion is a real phenomenon within the Earth. Ultra-deep drilling below the kimberlite *Root Zone* may show if the pipes are in fact one small cone sitting on top of a much larger frozen wave, with the angles of bounding structures intersecting at the wave crest. Identification of isolated iron rich silicate melts within the mantle and mapping their movement will also offer support to the mega-wave hypothesis. *Computational fluid dynamics* will hold the keys to wave mechanics.

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**Table 1.** Orthogonal and schematic cross section of the Earth showing geomagnetic behaviour (R: reverse, N: normal) and Ages of Kimberlite intrusions. Exact poliarities seem less important than the change overs between reverse and normal behaviour (*proposed* onset of turbulence). Dominant polarities (superchron) are solid lines, shorter periods with a mainly N or R polarity are dashed (subchrons). The flips/Ma curve is a frequency curve for polarity changes as a function of the time interval 5-160 Ma; AC (alternating current), DC (direct current) describe the geodynamo during rapid oscillations and periods acquiescence. Ages of kimberlites are shown in the upper portion of the diagram: Archangelsk (Ark), China (Ch), Canada (Ca), Zimbabwe (z), Siberia (s), Missouri (Mo), Colorado-Wyoming (CW), Tennessee (Tn), Kentucky (Kn), Swazilandland (Sw), Botswana (B) and Australia (Aus). The 80 - 120 Ma event is global. The arrow pointing in the direction of 1.1 Ga is for kimberlites throughout Africa (Af), Australia, Brazil (Br), Siberia, India (I) and Greenland (Gr). The ordinate is depth, the diamond-graphite stability curve is correctly placed relative to the lithosphere-asthenosphere boundary. Time span is schematic. O-Sil: Ordovician-Silurian, Dev: Devonian, PP: Permian, Tr-J: Triassic – Jurassic, Cret: Cretaceous. Figure & caption reproduced from Haggerty [53] modified.

**Figure 1**. Three layer experiment with induced disturbance, after Dohan & Sutherland [25]. The experiment confirms transmission of nonlinear effects between layers. Waves on boundary layers are primarily a function of density variation, in the case of the Earth's' onionskin structure; density is directly related to chemical composition. Turbulence is induced in the basal layer which is heated from below to simulate the geothermal gradient. Non-linear waves develop on the boundary between liquid 3 and liquid 2. Turbulent jets of liquid 3 shoot up into liquid 2. Liquid 1: *Pentane Density (ρ) = 0.5 g/l*, liquid 2: *Tungsten Polymer (LST) ρ* = 3.5, liquid 3: *Water ρ = 1 & Therminol 66 ρ = 1005*.

**Figure 2.** Core turbulence and the expulsion of relic ferromagnesian silicate melt from the liquid core as liquid jets.

**Figure 3.** Emergence of a mega-wave on a discontinuity. Amplitude continues to increase until energy is drained from surrounding waves or it breaks. The overall effect is to press the mantle-crust boundary to the Earth's planetary surface momentarily. *Order of events*: **A**. Chaos develops in liquid core, turbulent jets invade mantle and linear interfacial waves become nonlinear **B**. Melts mix: Subducted Archean crust and primary iron silicate core melt. **C**. Peak of wave front. **D**. Intersection with near surface structures or propagation of fracture cone and release of pressure. **E**. Eruption (optional). Collapse of secondary cone, near surface processes and development of a final state (Fig. 3).

**Figure 4.** Kimberlite pipe near surface processes and features. Reproduced from Head and Wilson [46].

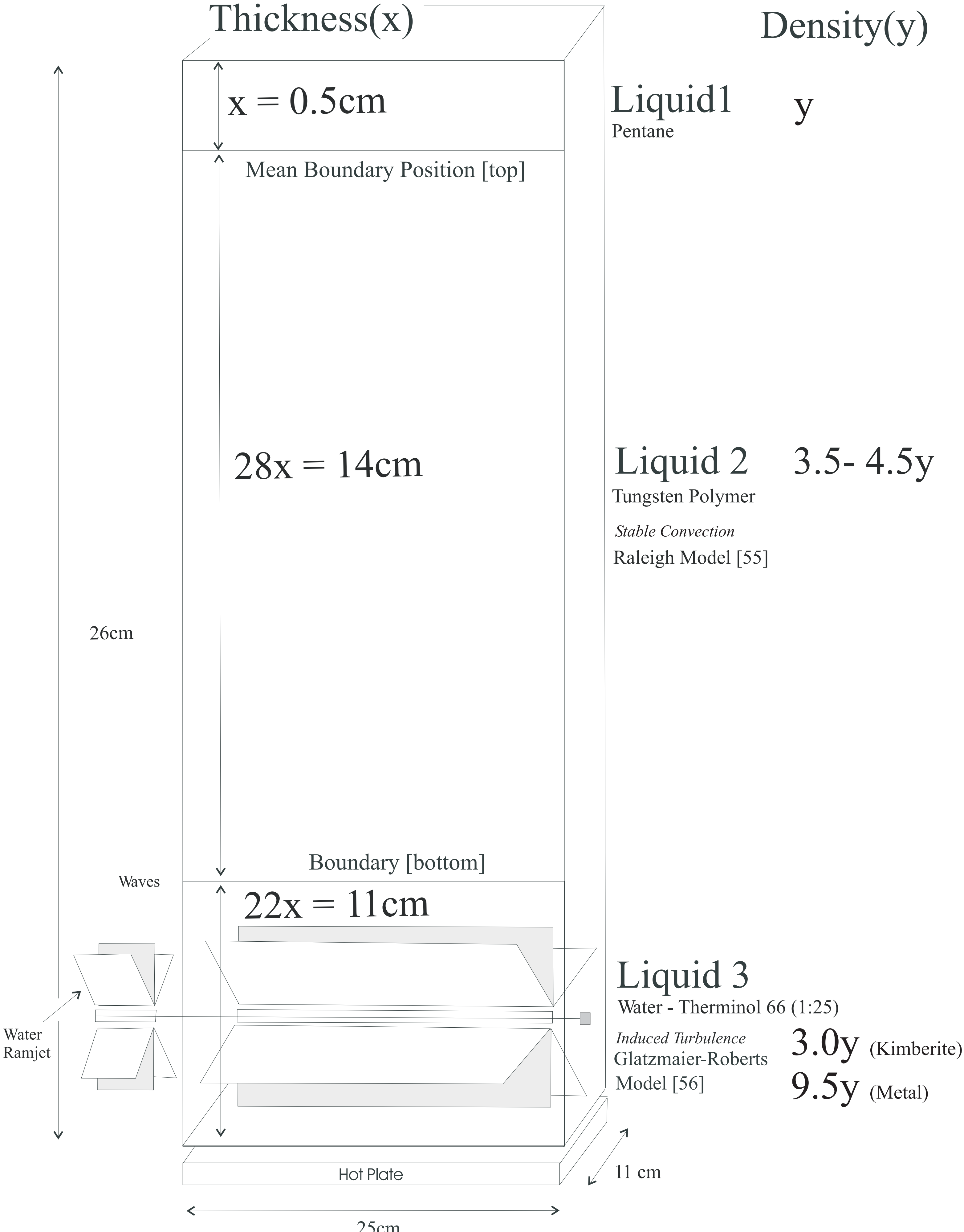

Thickness(x)
Density(y)
x = 0.5cm
Liquid1
Pentane
y
Mean Boundary Position [top]
28x = 14cm
Liquid 2
Tungsten Polymer
3.5- 4.5y
Stable Convection
Raleigh Model [55]
26cm
Boundary [bottom]
Waves
22x = 11cm
Liquid 3
Water - Therminol 66 (1:25)
Induced Turbulence
Glatzmaier-Roberts
Model [56]
3.0y (Kimberite)
9.5y (Metal)
Water
Ramjet
Hot Plate
11 cm
25cm

Figure 1.

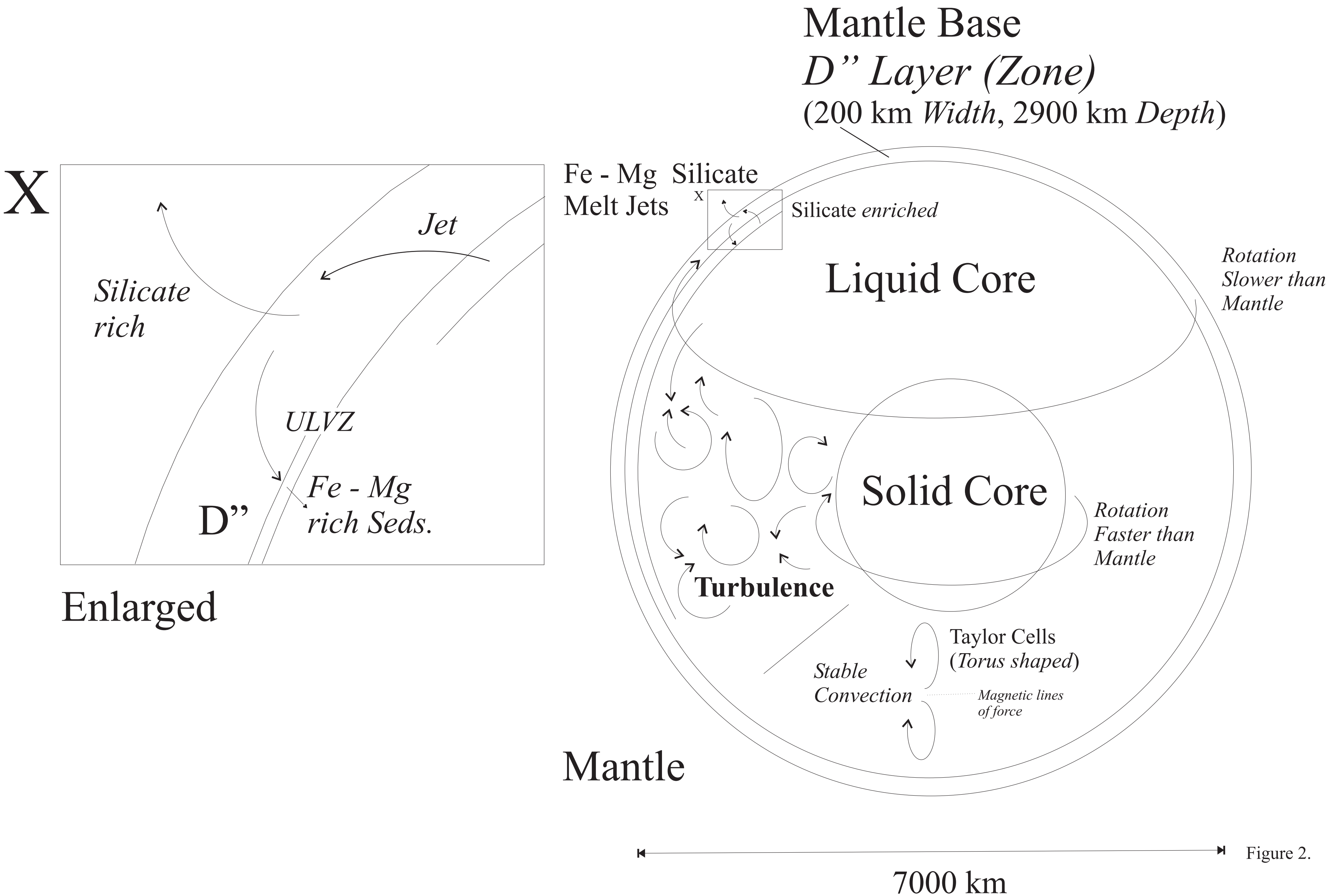

X
Jet
Silicate rich
ULVZ
D''
Fe - Mg rich Seds.
Enlarged
Mantle Base
D'' Layer (Zone)
(200 km Width, 2900 km Depth)
Fe - Mg Silicate Melt Jets
X
Silicate enriched
Liquid Core
Rotation Slower than Mantle
Solid Core
Rotation Faster than Mantle
Turbulence
Taylor Cells (Torus shaped)
Stable Convection
Magnetic lines of force
Mantle
7000 km

Figure 2.

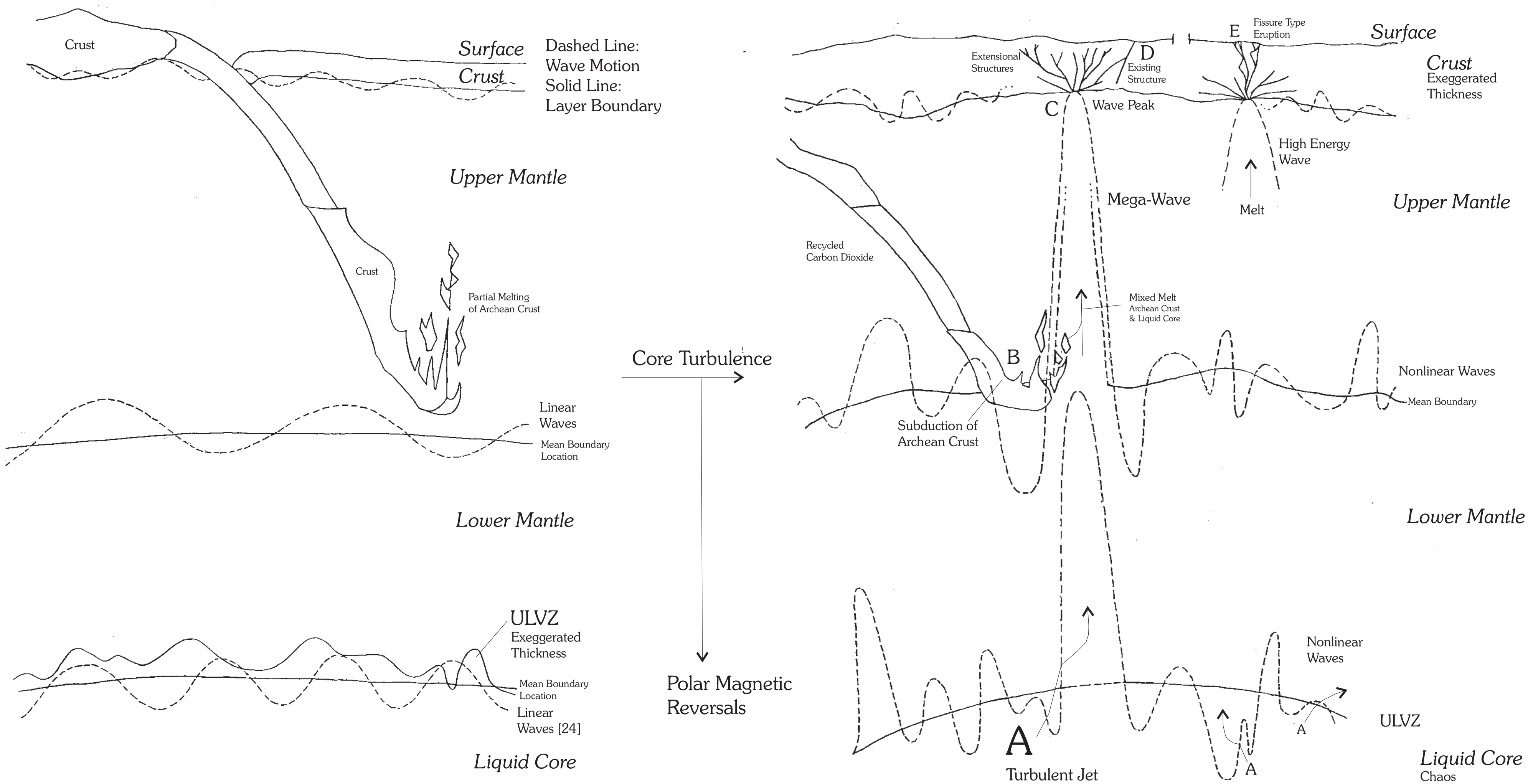

Crust
Surface
Crust
Dashed Line:
Wave Motion
Solid Line:
Layer Boundary
Upper Mantle
Crust
Partial Melting
of Archean Crust
Linear
Waves
Mean Boundary
Location
Lower Mantle
ULVZ
Exeggerated
Thickness
Mean Boundary
Location
Linear
Waves [24]
Liquid Core
Core Turbulence
Polar Magnetic
Reversals
E
Fissure Type
Eruption
Surface
Extensional
Structures
D
Existing
Structure
Crust
Exeggerated
Thickness
C
Wave Peak
High Energy
Wave
Mega-Wave
Melt
Upper Mantle
Recycled
Carbon Dioxide
Mixed Melt
Archean Crust
& Liquid Core
B
Nonlinear Waves
Mean Boundary
Subduction of
Archean Crust
Lower Mantle
Nonlinear
Waves
ULVZ
A
Turbulent Jet
A
A
Liquid Core
Chaos

Figure 3.

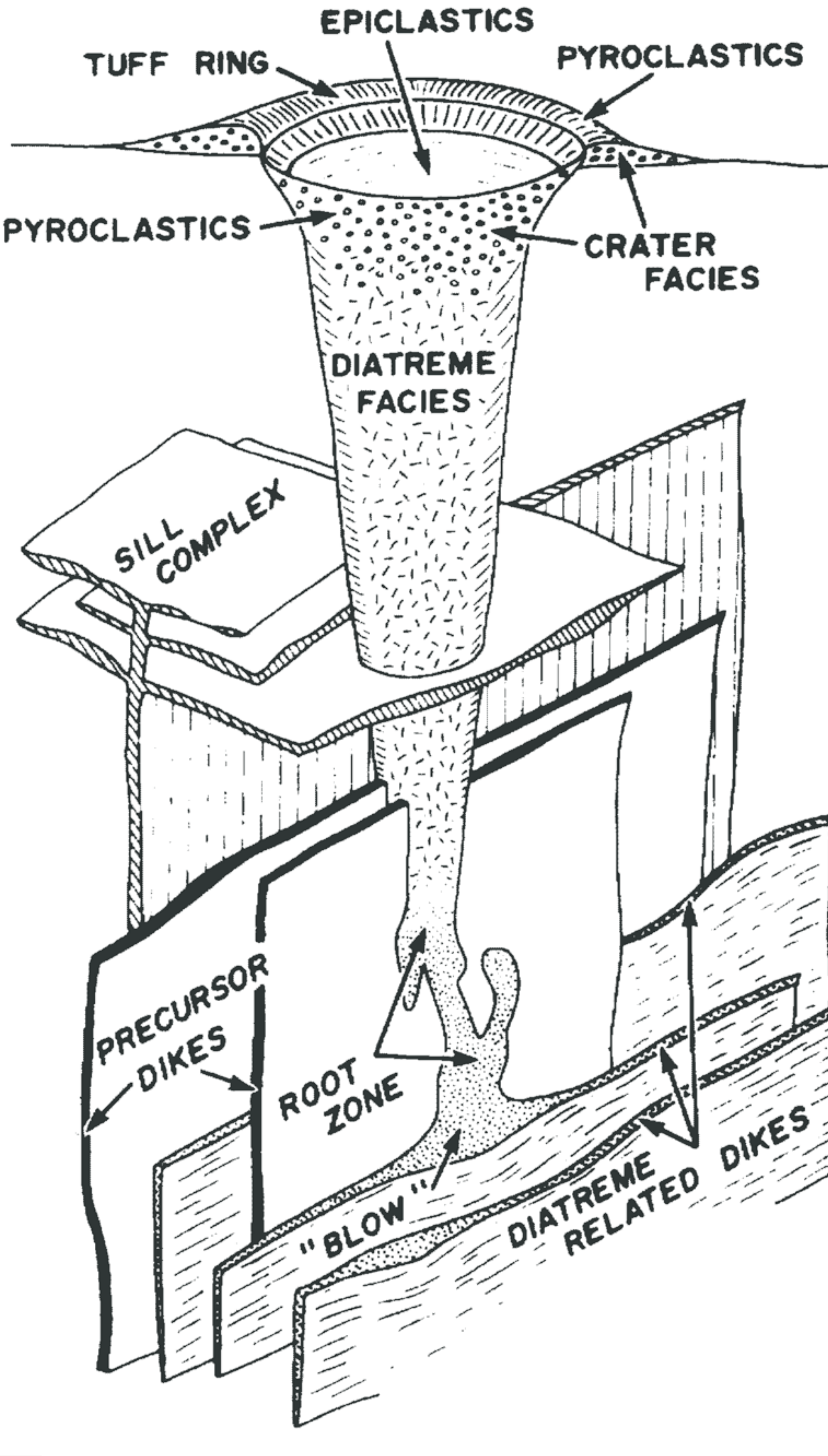
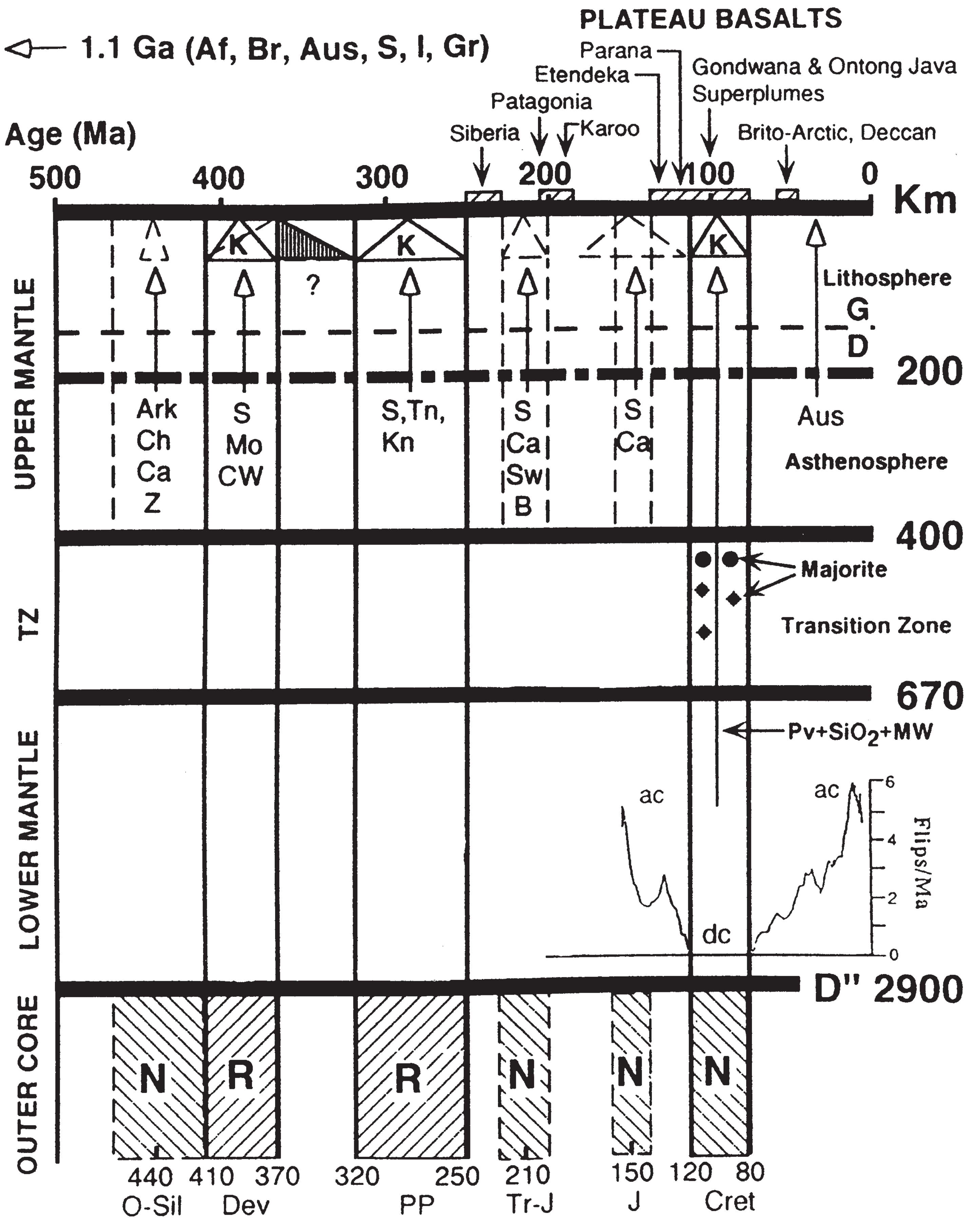

EPICLASTICS
TUFF RING
PYROCLASTICS
PYROCLASTICS
CRATER FACIES
DIATREME FACIES
SILL COMPLEX
PRECURSOR DIKES
ROOT ZONE
"BLOW"
DIATREME RELATED DIKES

Figure 4.




Superchrons

Table 1.