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Hrvoje Tkalčić
Excerpt
More Information

1

On the History of Inner Core Discovery

"...and this leads us to the perception that the Earth consists of an iron core with a diameter of approximately 10 million metres, enclosed by a rocky mantle with a thickness of 1½ million metres."[2]

Emil Wiechert (Wiechert, 1897)

"It is, however, by no means certain that a regular increase of the elastic constants to the Earth's centre is to be looked for; on the contrary, a sudden change is to be looked for where the wave paths leave the outer stony shell to enter the central metallic core which may reasonably be supposed to exist."

Richard D. Oldham (Oldham, 1900)

"We must therefore examine the possibility that the Oldham–Gutenberg discontinuity is also the outer boundary of the metallic core."

"There seems to be no reason to deny that the Earth's metallic core is truly fluid."

Harold Jeffreys (Jeffreys, 1926b)

"However, the interpretation seems possible, and the assumption of the existence of an inner core is, at least, not contradicted by the observations; these are, perhaps, more easily explained on this assumption."

Inge Lehmann (Lehmann, 1936)

"The first results for the properties of the inner core were naturally approximate. Much has been written about it, but the last word has probably not yet been said."

Inge Lehmann (Lehmann, 1987)

[2] Translation credit: Sebastian Rost

1.1 Early Days of Modern Science

Halley (1686) was likely the first to mention the Earth's core within the context of natural philosophy as a 'nucleus' or 'inner globe', detached from the Earth's external shell. According to Halley's model, the 'nucleus' or 'inner globe' of the Earth is a solid innermost sphere with two moveable magnetic poles which is detached from, and rotates differentially with respect to, the rest of the planet (Figure 1.1). Its existence was invoked to explain apparent observations of four magnetic poles, which were later understood to be evidence of the spatial variation of a magnetic field containing a superposition of both dipole and non-dipole components. In one of the model's variations, the Moon-sized inner globe is separated from the Earth's outer, 800 km thick shell by a liquid layer that has the same axis of diurnal rotation and the centre of gravity as the inner core (IC).

This 'Hollow Earth' model was driven by erroneous estimates of the Earth–Moon density ratio (Newton, 1687), but the idea persisted in literature for centuries. At the time in which it was published, this model was a paradigm shift that introduced some revolutionary concepts such as the existence of 'a planet within a planet', a time-varying magnetic field originating from the Earth's centre, and a 'differential rotation' of planetary shells – all of which are phenomena still lacking complete explanation.

The first estimates of the gravitational constant (5.48 g cm^{-3} by Cavendish, 1798) and Earth's mean density (5.46−5.52 g cm^{-3} by Poynting, 1891) exceeded those of the rocks found at the Earth's surface, which prompted speculation about a denser deep Earth's interior. The idea about a molten interior was gradually replaced in the nineteenth century by the belief that the interior is solid (see, for example, a historical review by Brush, 1980) and that density must increase gradually with depth.

1.2 IC Discovery in the Context of Seismology of the Early Twentieth Century

The Earth can classically be divided into four main shells: the crust, the mantle, the outer core (OC), and the IC. There are, therefore, three main discontinuities: the crust–mantle boundary (a.k.a. Moho), the core–mantle boundary (CMB), and the inner core boundary (ICB). The term 'boundary' is used interchangeably throughout this chapter with the term 'seismic discontinuity', or just 'discontinuity', which marks a significant change in Earth's elastic properties with depth. The magnitude of that change will determine whether the discontinuity is deemed major or minor. The reader is referred to some of the classic books on seismology and the Earth's interior to find out more about the definition of discontinuities in elastic properties (e.g. Stein and Wysession, 2003; Shearer, 2009).

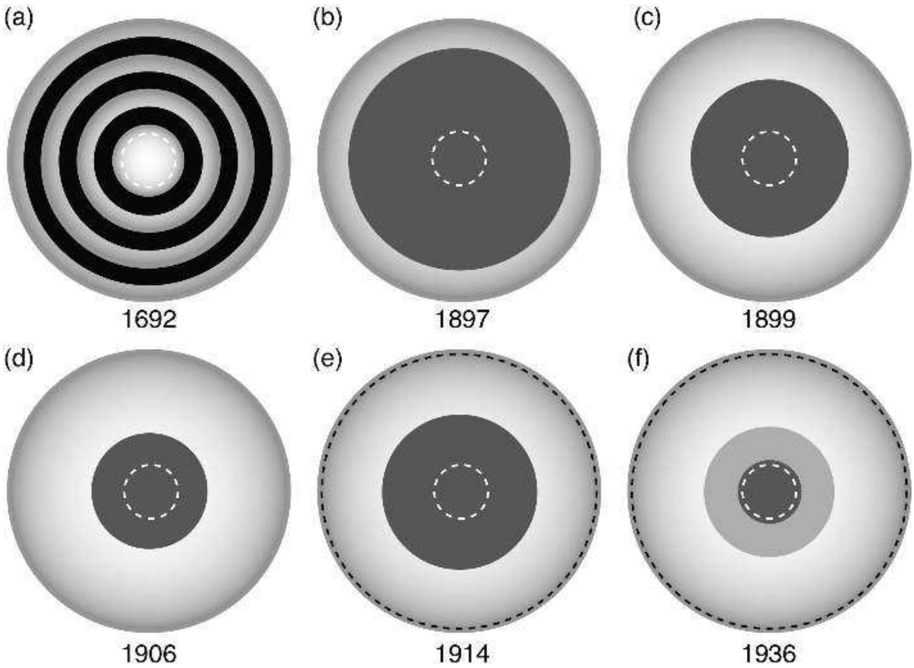

Figure 1.1 Conceptual representation (in chronological order) of early models of the Earth's interior featuring inner shells (represented by circles or rings), with published values for their radii scaled to the radius of the outer circle (Earth's surface). The white dashed circle in the centre represents the modern day IC. The black dashed circle near the surface in the last two models is the Moho. (a) Halley's 'Hollow Earth' model from 1686, based on philosophical considerations of Earth and Moon density estimates. The thickness of the outer three solid (light grey rings) and hollow shells (black rings) are 1/8 of the Earth's radius. The diameter of the 'inner globe', as Halley termed it, is 1/4 that of the Earth's diameter. (b) Wiechert's hypothetical model of the Earth from 1897, based on theoretical considerations of Earth's density. The solid core has a radius of about 4/5 of the Earth's radius. (c) Oldham's hypothetical model of the Earth from 1899 based on theoretical considerations of Earth's density and observations of earthquake waves at large distances. The solid core has a radius of about 0.55 that of the Earth's radius. (d) Oldham's model of the Earth from 1906 adjusted based on seismological observations. The solid core had a radius of about 0.4 that of the Earth's radius. (e) Gutenberg's model of the Earth from 1914, based on seismological observations and consequent analysis. The solid core had a radius of about 0.54 that of the Earth's radius. (f) Lehmann's model of the Earth from 1936, based on seismological observations and consequent analysis. The solid inner core (IC) had a radius of 1405 km. The liquid outer core (OC) had a radius close to the modern day values (2900 km).

Non-seismologists often think about probing the Earth in terms of seismic profiling with controlled sources where reflection and refraction principles can be used. However, probing the Earth's deepest shells using high-quality earthquake waves (passive seismology) was not easy, particularly in the early years of seismology when the data available were few and of low quality. It is important to realise that the Earth's radial profile is far from the simple, divided model described in the paragraph above.

Seismologists had to be innovative and develop different, often less direct, ways to detect and characterise discontinuities. For example, the Wiechert–Herglotz method of the early twentieth century was the first to determine radial profiles of velocity in the Earth (reference). The derivation of the Wiechert–Herglotz method is given in Fowler (2005) and Lowrie (2007). The profiles initially revealed a blurred and limited version of Earth. The restriction that velocity must increase with depth had to be relaxed and the number of observations had to be increased to construct more reliable travel time curves of various seismic phases.

At the turn of the nineteenth century, Wiechert suggested that the Earth's interior could be subdivided into two shells: a metallic core and a rocky mantle (Wiechert, 1897). Each had a constant density, which radically differed from the existing view that density gradually increased with depth. Wiechert performed a quantitative analysis using existing data for the principal moments of inertia and Earth's ellipticity (degree of flattening), and estimated a density of 8.2 kg m^{-3} for the metallic core and 3.2 kg m^{-3} for the mantle. His work yielded an estimate for the ratio between the radius of the core (α') and the radius of the Earth (α): $\alpha'/\alpha = 0.78$, where Earth's radius was considered 6378.2 km.

Oldham (1900) expressed a similar view about Earth's structure (see his statement at the beginning of this chapter), and without referring to Wiechert's earlier work, he concluded that the radius of the iron core is 0.55α based on hypothetical minimums for the variation of density. Oldham reported teleseismic observations of two distinctive body wave phases (P and S waves, at that time referred to as condensational and distortional waves) as well as surface waves. His empirical travel time curves reveal a regularly decreasing curvature towards larger epicentral distances and a lack of observations of seismic phases for epicentral distances beyond 90°. Assuming that the ray paths are part of a circular arc, he calculated that the epicentral distance of 90° corresponds to a bottoming depth of about 3000 km. He suggested that this depth coincided with the radius of the iron core, but did not establish a clear argument for why this would be the case. Brush (1980) suggests this may be why Oldham was not credited with discovering the core–mantle boundary (CMB) despite the fact that his CMB depth estimate was close to modern day values.

As the number of recorded teleseismic earthquakes grew, Oldham (1906) measured more P and S waves. He noted that P waves propagate more slowly in the core. He also observed a seismic shadow zone on the side of the Earth opposite the earthquake, where no P waves were recorded. He attributed their absence to P-wave refraction along the CMB. Due to misinterpretation of seismic waves at large epicentral distances (e.g. surface reflecting mantle SS waves were mistaken for S waves penetrating through the core), he concluded that the radius of the core is 0.40α, but he was unable to recognise that the core was liquid. Despite these deficiencies, the official discovery of the Earth's core is attributed to Oldham, who followed up with a number of papers addressing the nature of the core.

Mohorovičić (1910) used differential calculus and ray theory to solve for the depth of the discontinuity between the crust and the mantle. His approach combined geophysical forward and inverse methods. A critical finding that underlined his rigorous mathematical approach and subsequent discovery was the observation of two distinct arrivals of P and S waves on seismograms at a specific epicentral distance range. The observation required a sudden change in elastic properties at a depth of 54 km, which he interpreted as the depth of separation between the Earth's crust and mantle. This value agrees well with modern estimates for the study area (northeast of Croatia) (e.g. Stipčević et al., 2011).

Gutenberg (1914) estimated the CMB to reside at a depth that is not very far from today's figure of about 2889 km (Kennett et al., 1995). Jeffreys (1926b) observed an S wave shadow zone beginning at an epicentral distance of about 103.8° from the earthquake. This result indicated that the core was molten, since shear waves do not propagate through liquids. Interestingly, Stjepan Mohorovičić (the son of Andrija Mohorovičić), makes the following remark in his 1927 paper: "At the depth of 6000 km, there will be a dominance of the heaviest and noblest metals, predominantly gold and platinum, thus we can call this core Ptau. Maybe it would have been more correct to only call this hypothetic core 'Core'."[3] (Mohorovičić, 1927).

These discoveries and the state of knowledge established a solid observational basis in the first quarter of the twentieth century to accompany advances in theoretical seismology, then a relatively new discipline, and technological advances in analogue instrumentation for recording ground motion associated with earthquakes.

1.2.1 Lehmann's Discovery of the IC

In the framework of Halley's philosophy, Lehmann's discovery (Lehmann, 1936) of the Earth's IC, as she termed it, could be thought of as proof of the existence of an inner globe, separated from the outer shells of the planet by the liquid OC.

[3] Translation credit: Christian Sipl.

Lehmann observed arrivals of compressional waves, termed P', at angular distances from earthquakes not predicted by an entirely liquid core model. She accommodated her observations by modelling the Earth's interior with a smaller solid core inside the liquid core. In her model, earthquake compressional waves travel faster through the IC than through the OC, so that apart from transmission, a reflection occurs when the waves reach the IC. Due to insufficient data, Lehmann assumed the compressional velocity of the IC and OC to be 8.6 and 8.0 km/s, which are lower than modern day estimates (e.g. Dziewoński and Anderson, 1981; Kennett et al., 1995), and as a result obtained an IC with a radius of about 1405 km. The theoretical predictions matched the available observations at the time, but as more data gradually became available, the radius of the IC was adjusted to 1221 km. The 'IC' became a modern term and was used in the new edition of travel time curves published in 1939 (Jeffreys, 1939).

Birch (1940) suggested that the IC was solidifying from the OC and that the inner-core boundary (ICB) was a phase transition. Bullen (1946) suggested that the IC was solid. It was recognised that the solidification results in latent heat release (Verhoogen, 1961) and compositional buoyancy (Braginsky, 1963), which drive convection in the OC.

1.3 Confirmation of the Discovery and Early Seismological Studies

Two important objectives were established once the IC hypothesis was proposed. The first was to confirm its boundary within the OC and the second was to confirm its solidity. Surprisingly, it took more than three decades to achieve this confirmation, and less surprisingly, it happened during the Cold War. The need of the world powers to discriminate between nuclear explosions and earthquakes drove significant progress in observational seismology at that time. Non-proliferation seismology was in its infancy during the 1960s, resulting in unprecedented seismic arrays comparable to large radio antennas. The most remarkable undertaking was the construction of the Large Aperture Seismic Array (LASA) in Montana, which consisted of more than 500 instruments distributed over an area of about 100 km in radius. Each of 21 clusters consisted of 25 elements that were distributed in a regular shape. By amplifying the signal and cancelling out microseismic noise (see Section 2.4.2), it was possible to detect signals, for instance, from the underground nuclear explosions in Nevada.

It was not until 1971 that a seismological study of Earth's free oscillations (Dziewoński and Gilbert, 1971) produced evidence for the solidity of the IC, which will be discussed in more detail in Chapter 3. This was accompanied by a number of papers presenting supposed observations of the PKJKP phase (compressional waves that convert to shear waves at the ICB, propagate through the IC, and convert back to the compressional waves as they exit the IC) (e.g. Julian et al., 1972); more details on this will be given in Chapter 3.