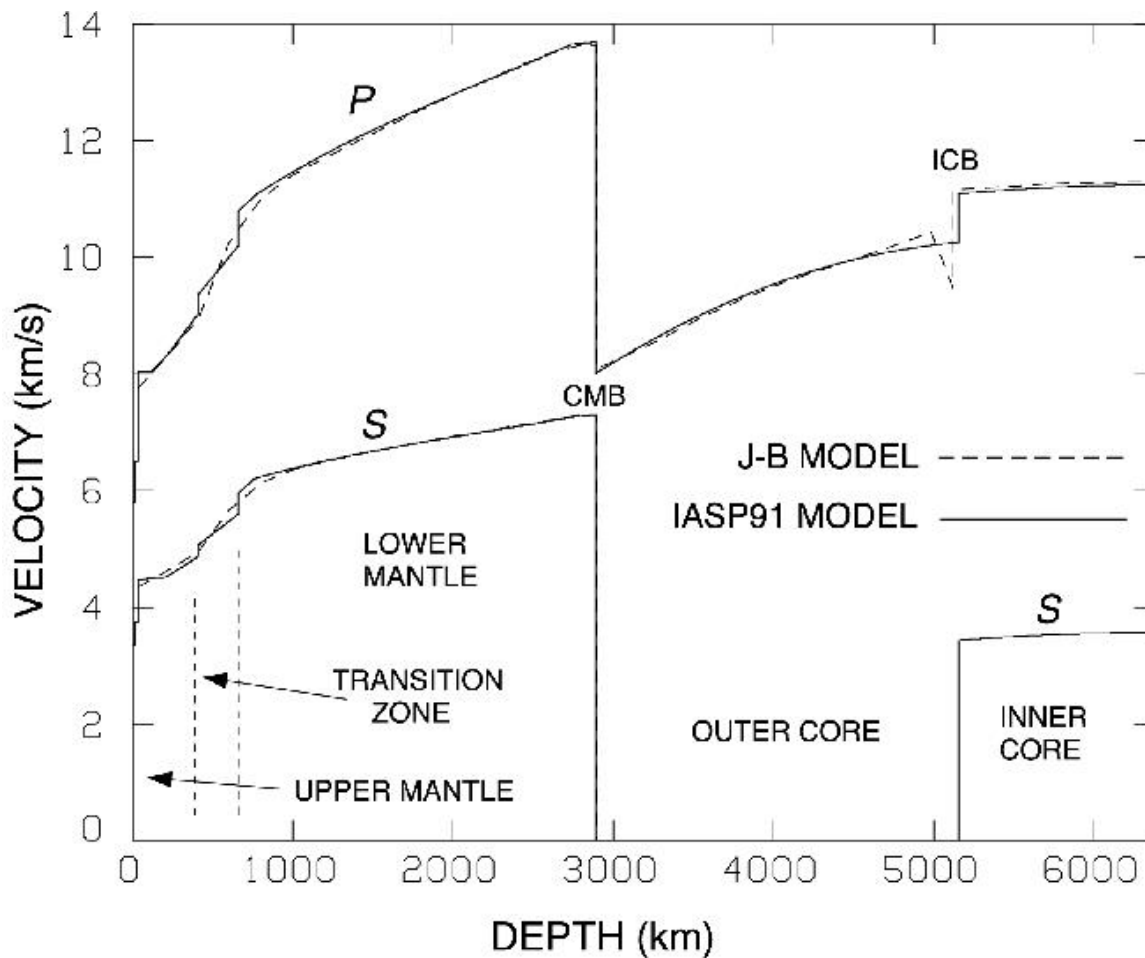## 2.3 VELOCITY STRUCTURE OF THE EARTH

In the following years, increasingly sophisticated models were developed. It became possible to compute travel time curves for media where velocity varies continously with depth so ray paths are curved and rays "bottom" at some depth. These seismological observations provide the primary data for our view of the basic features of the earth's velocity structure.
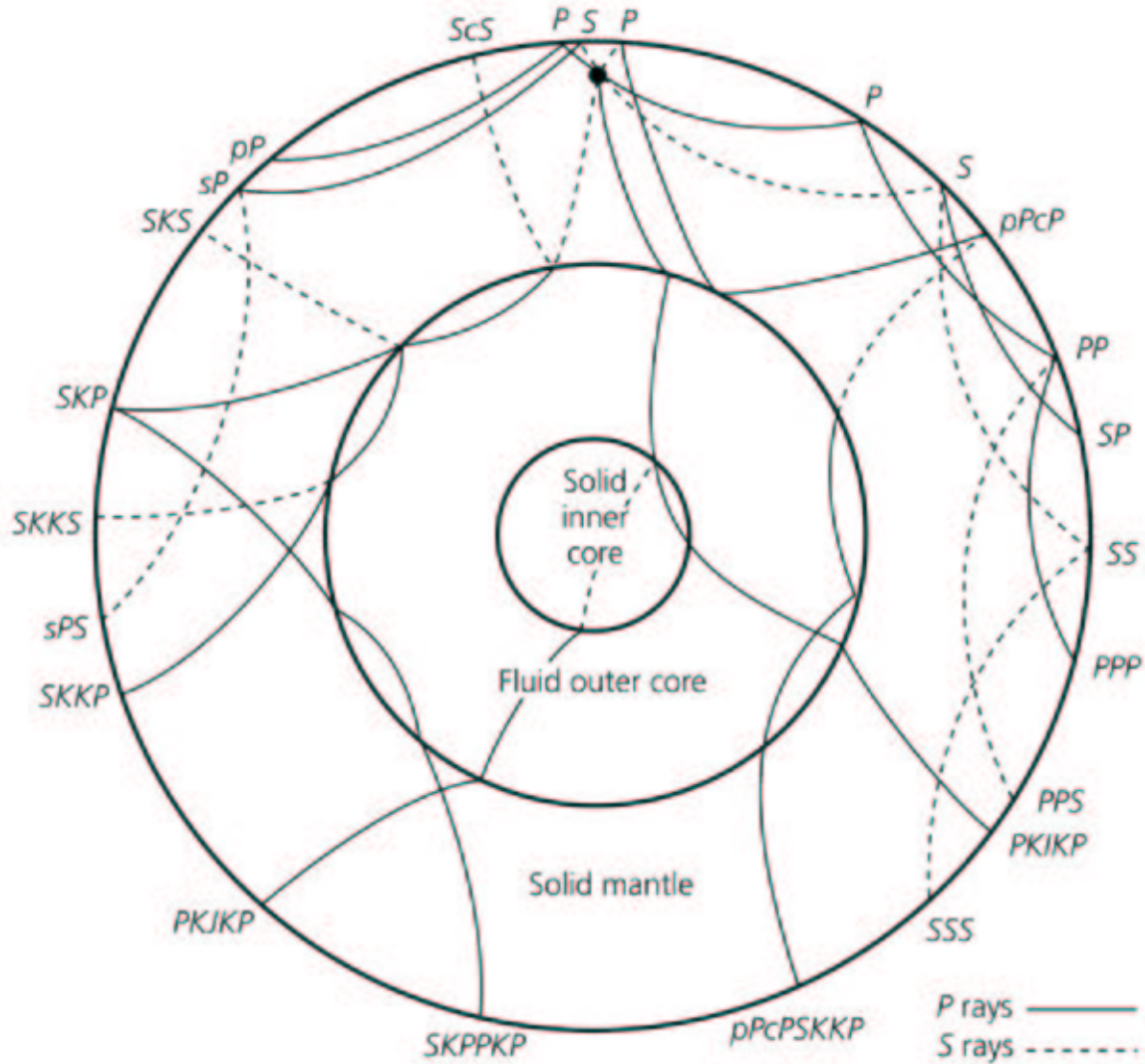
The Moho marks the sharp transition in seismic velocity between the crust and mantle. The mantle is divided into an *upper mantle* and a *lower mantle* both of which have smooth velocity gradients. These upper and lower mantle regions are separated by the mantle *transition zone* where velocities increase rapidly with depth. Below the *core-mantle boundary* (CMB), the core is divided into an *outer core* and an *inner core* separated by the *inner core boundary* (ICB).

This picture, an essentially layered earth composed of a thin crust, a mantle, a liquid outer core, and a solid inner core, is key to our thinking about how the earth evolved and operates. More generally, by establishing the essentially layered structure of the earth, seismology provides the primary evidence for the process of differentiation by which material within planets becomes compositionally segregated during their evolution.
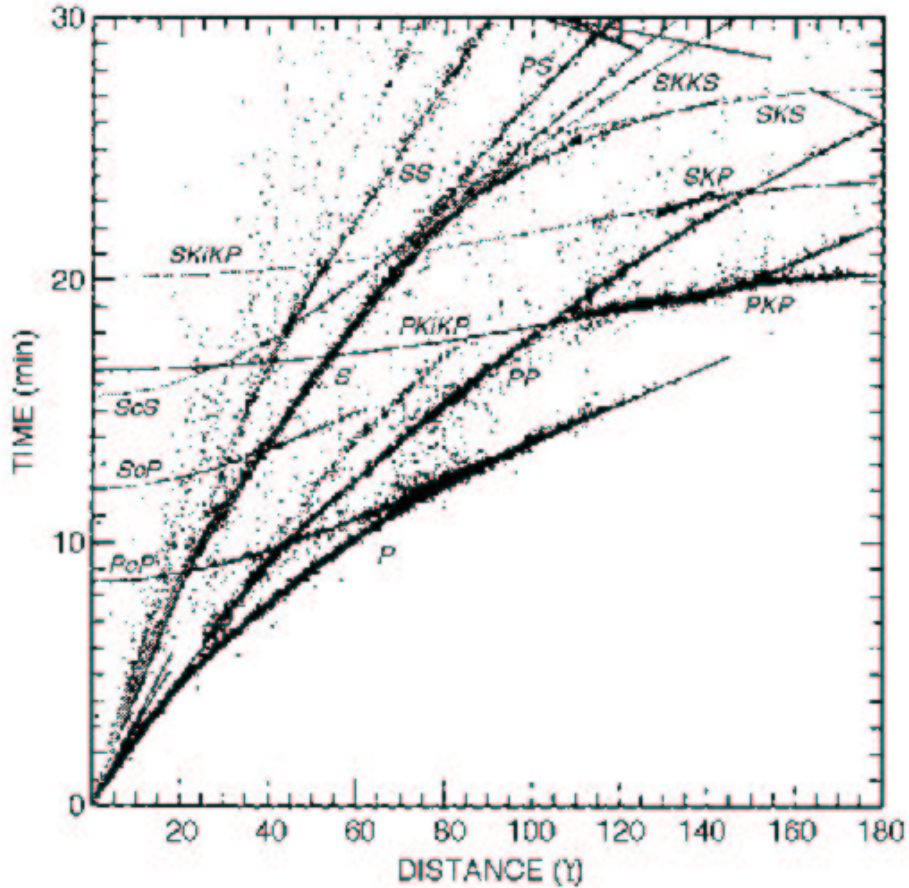

Seismic waves can travel between a source and receiver along multiple paths. Hence seismograms contain many arrivals, or *phases,* corresponding to different travel paths. This idea is illustrated below showing a few of the phases that are observed and some of the corresponding ray paths. All the phases shown are *body waves* that travel through the earth's interior.

Figure 3.5-5: Illustration of various body wave phases.

Seismic phases are named based on their paths through the earth. The direct *P*-wave and *S*-wave arrivals are denoted *"P"* and *"S"*. Another class of arrivals involve reflections at the earth's surface. The *P*-wave arrival corresponding to a single surface reflection is called *PP*, that for two reflections is *PPP*, and so on. Similarly, *SS* and *SSS* correspond to *S* waves reflected at the surface. Because *P* waves can convert to *S* waves and vice versa, *PS* is a *P* wave converted to an *S* wave upon surface reflection, and *SP* is the reverse. Consideration of the ray paths shows that the travel time for *PP* at a given distance should be twice the travel time of *P* at half that distance, i.e., to a point midway between the source and receiver. Similarly, the travel time for *PPP* should be three times the travel time for one-third the distance.

Because earthquakes occur to depths of 700 km, seismic ray paths go up from earthquakes as well as down. Lower-case *"p"* and *"s"* identify upgoing compressional and shear waves. *pP* goes up as a *P* wave and reflects near the epicenter, whereas *sP* goes up as an *S* wave and converts to a *P* wave at the surface. These reflections are useful because the travel time difference between direct *P* and *pP*, for example, indicates the depth of the earthquake. After an upgoing wave reflects at the free surface it can undergo later conversions, so *pPP, sPS,* etc. are possible arrivals.

Body wave phase nomenclature

Name	Description
P	Compressional wave
S	Shear wave
K	P wave through outer core
I	P wave through inner core
J	S wave through inner core
PP	P wave reflected at surface
PPP	P wave reflected at surface twice
SP	S wave reflected at surface as P wave
PS	P wave reflected at surface as S wave
pP	P wave upgoing from focus, reflected at surface
sP	S wave upgoing from focus, converted to P at surface
c	Wave reflected at core-mantle boundary (e.g. ScS)
i	Wave reflected at inner core-outer core boundary (e.g. PKiKP)
P′	Abbreviation for PKP
P_d or P_{diff}	P wave diffracted along core-mantle boundary

After *Bolt* [1982].

The contrast in properties between the solid mantle and the liquid core, which has lower velocity than the mantle above, makes the core well suited to seismological study using reflected, transmitted, converted, and diffracted arrivals. Core reflections are of great interest because the core-mantle boundary (CMB) is a solid-liquid boundary, and thus a strong reflector for shear waves. Reflections off the CMB are denoted by a lower-case "c," so *ScS* is an *S* wave reflection and *PcP* is a *P* wave reflection. Conversions at the CMB also occur. *ScP* goes down through the mantle as a shear wave and returns as a compressional wave, whereas *PcS* does the reverse. Some phases undergo multiple reflections at both the core and the surface; *ScSScS* (or *ScS2*) bounces twice at the CMB and once at the surface. Such reflections are known as multiple *ScS*. *ScS* is a more distinct arrival than *PcP* because the liquid core does not transmit shear waves. The SH part of the motion in the incident *ScS*

In fact, the ray path names (SCS, etc...) are ways we humans use to think about a complex pattern of seismic waves propagating in the earth. What really happens is that a complex series of wavefronts are generated within the earth.

The mantle has been found to have important velocity structure as well, from detailed studies. A *low velocity zone* exists between about 100-200 km depth. Velocities increase smoothly through the upper mantle, to a depth of 410 km. The mantle transition zone, from about 400 - 700 km depth, contains depth intervals, known as discontinuities, near 410 and 660 km where the velocities increase rapidly. These intervals cause *triplications* in the travel time curve as shown below. Although these regions are often referred to as the 410 km and 660 km discontinuities, their exact depths vary from place to place. From about 700 to 2890 km depth the velocities increase smoothly throughout the lower mantle. At about 2890 km, the P velocity drops sharply, and the S velocity goes to zero, corresponding to the liquid outer core. The outer core extends to a depth of about 5150 km, beneath which the solid inner core has higher velocities including a finite *S*-wave velocity. As we will see, these variations in velocity with depth are thought to reflect important changes in the physical, chemical, thermal, and mineralogical state of the materials present.