INTERNAL GEODYNAMICS

(ENDOGENOUS PROCESSES OF THE EARTH)

İÇ JEODİNAMİK

(DÜNYANIN ENDOJEN OLAYLARI)

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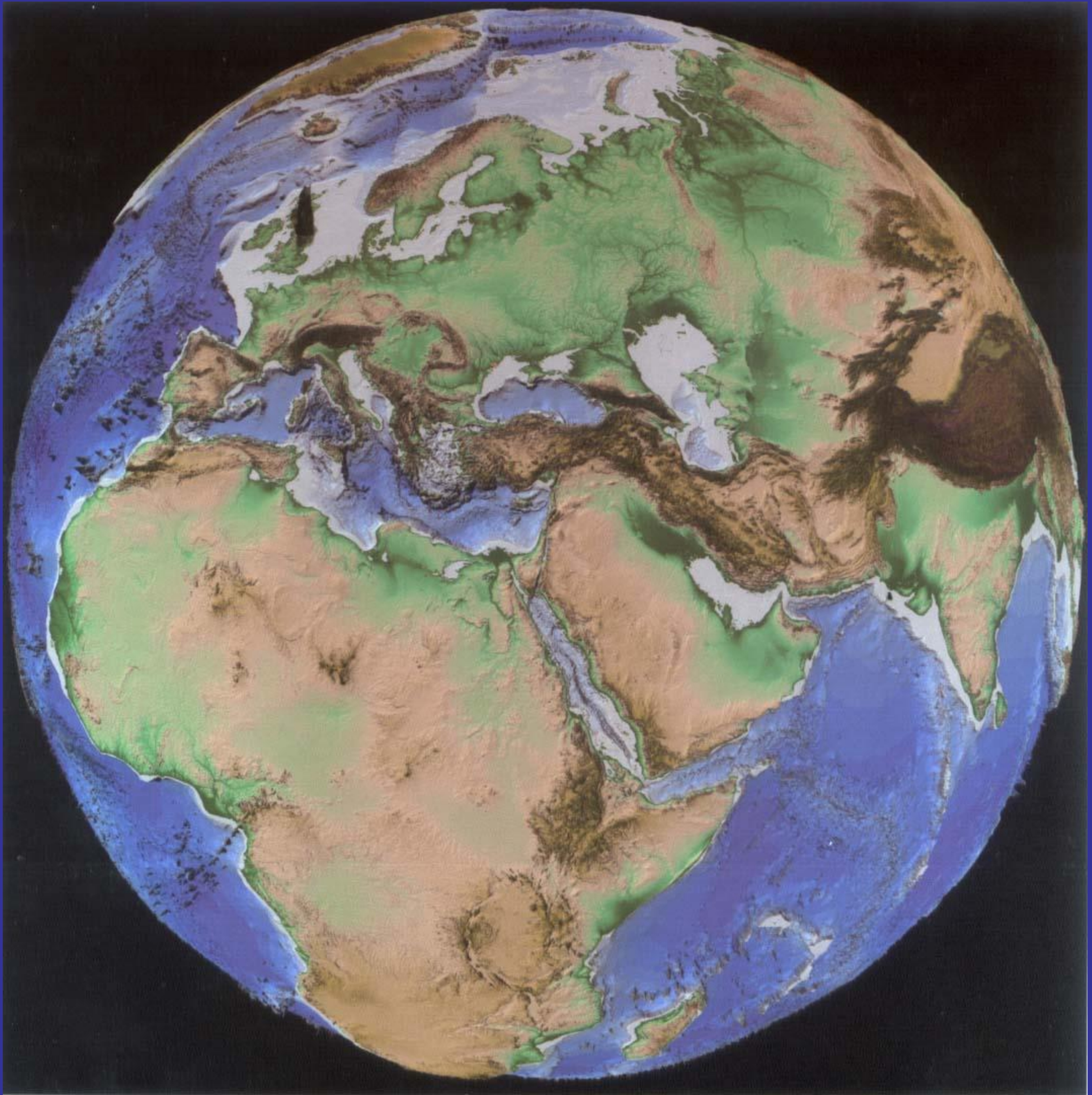
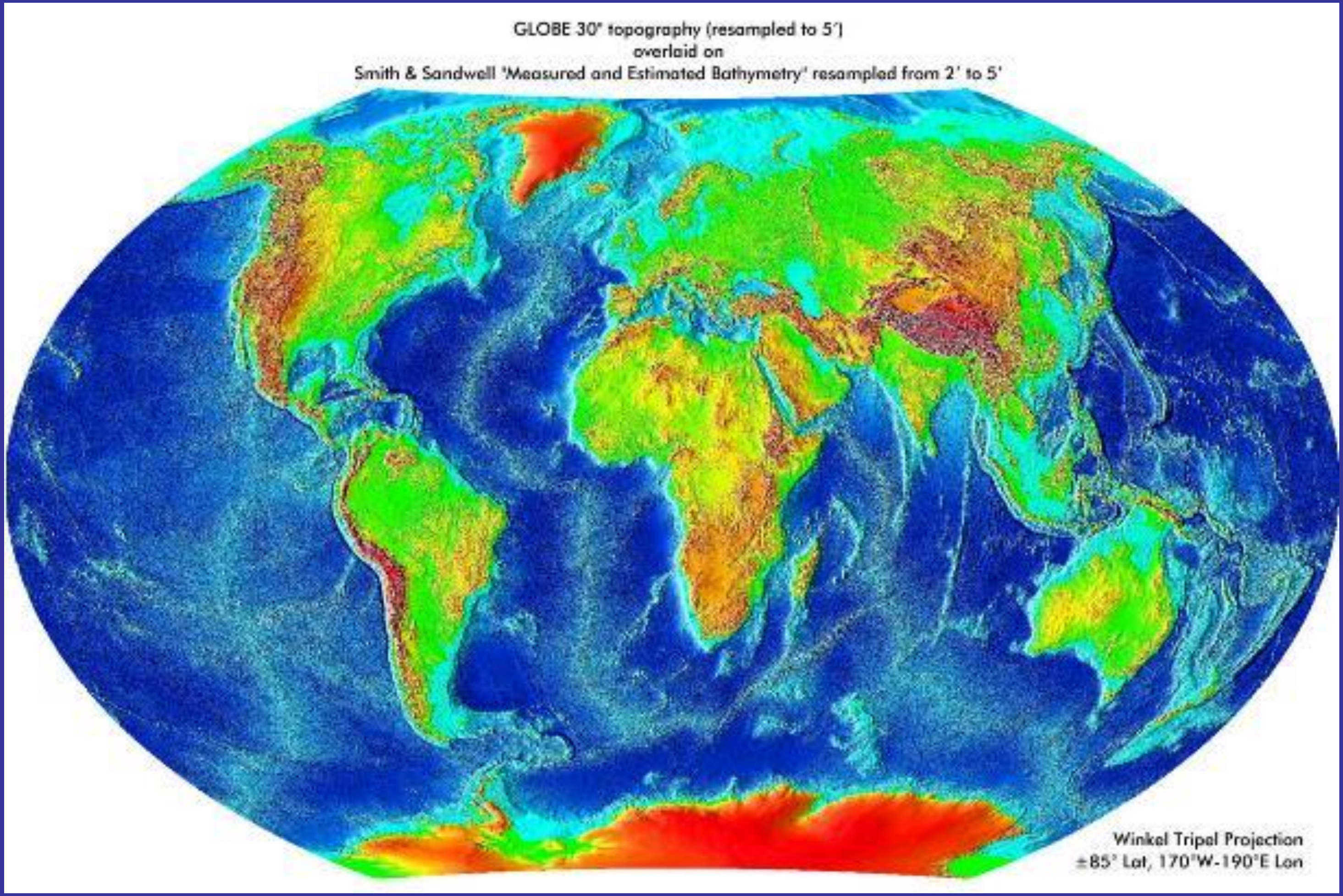
To the memory of Sir Isaac Newton

Lesson 2:

The Earth As A Planet

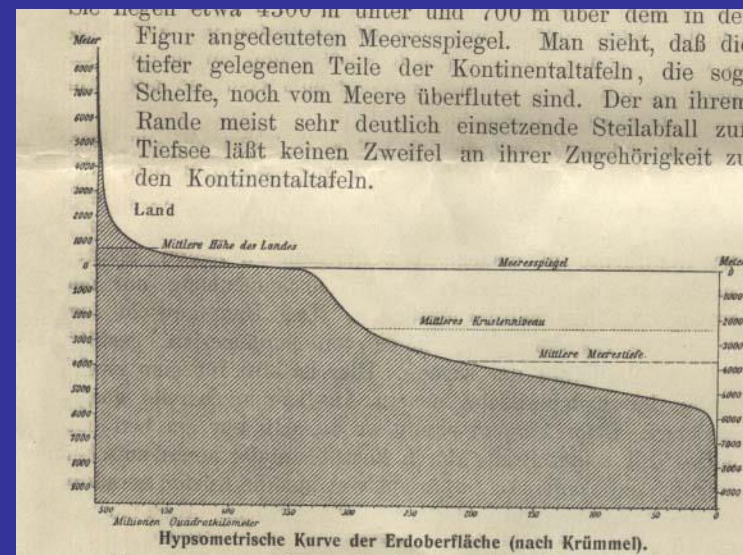
Part I: The structure of the earth before seismology





Colours show heights. Notice a peculiarity of our planet: the green and the navy blue dominate the map. In other words the flat continental plains and the flat abyssal plains are the most dominant landforms of our planet.

The great German earth scientist Alfred Wegener was the first to underline the importance of the double peaked nature of the earth's ***hypsometric curve***.

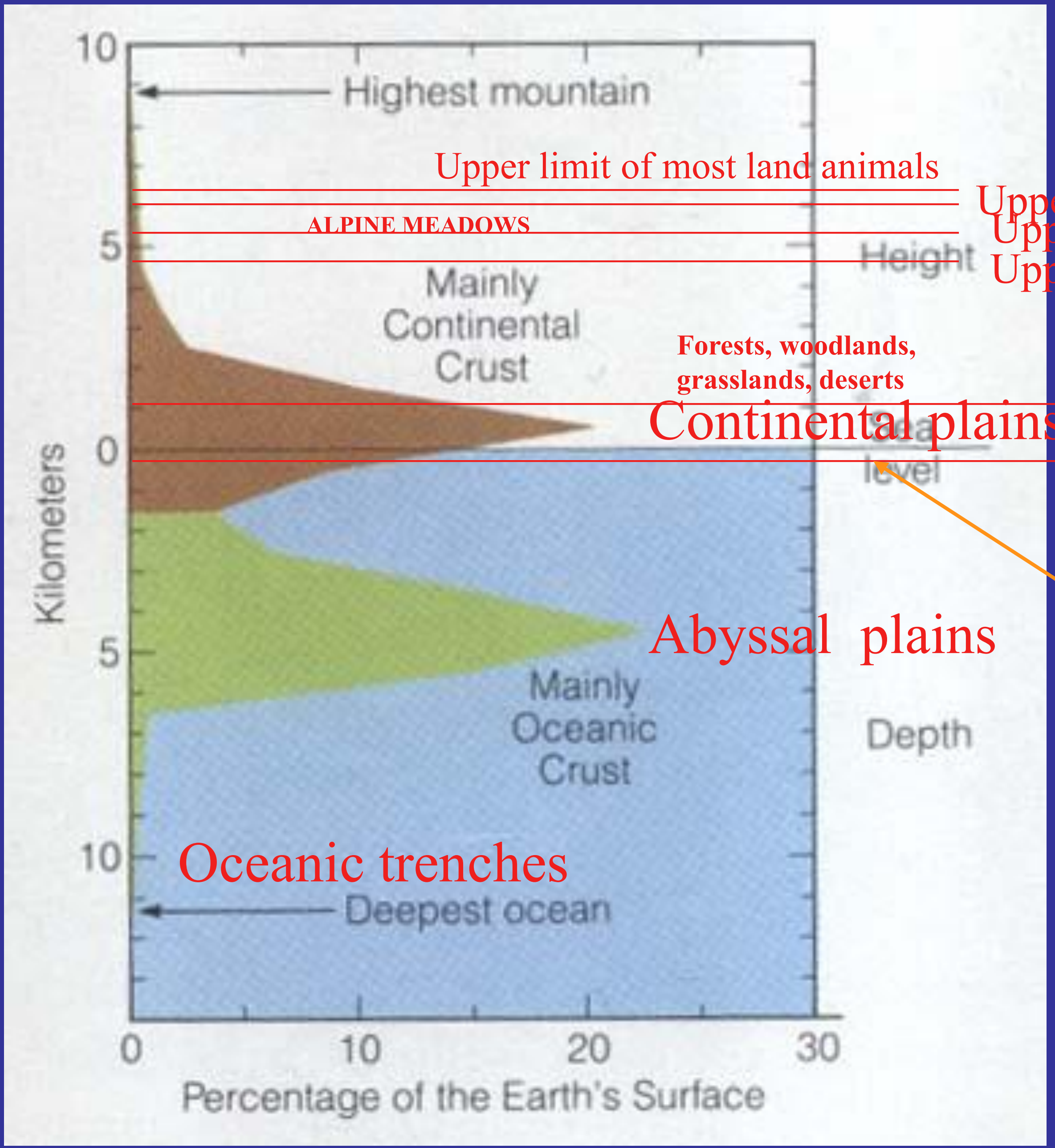

Figur angedeuteten Meeresspiegel. Man sieht, daß die tiefer gelegenen Teile der Kontinentaltafeln, die sog. Schelfe, noch vom Meere überflutet sind. Der an ihrem Rande meist sehr deutlich einsetzende Steilabfall zur Tiefsee läßt keinen Zweifel an ihrer Zugehörigkeit zu den Kontinentaltafeln.

Hypsometrische Kurve der Erdoberfläche (nach Krümmel).

Alfred Wegener (1880-1930)

Wegener's (1912) hypsometric curve

THE HYPSOMETRIC CURVE OF THE LITHOSPHERE AND ITS INFLUENCE ON THE BIOSPHERE



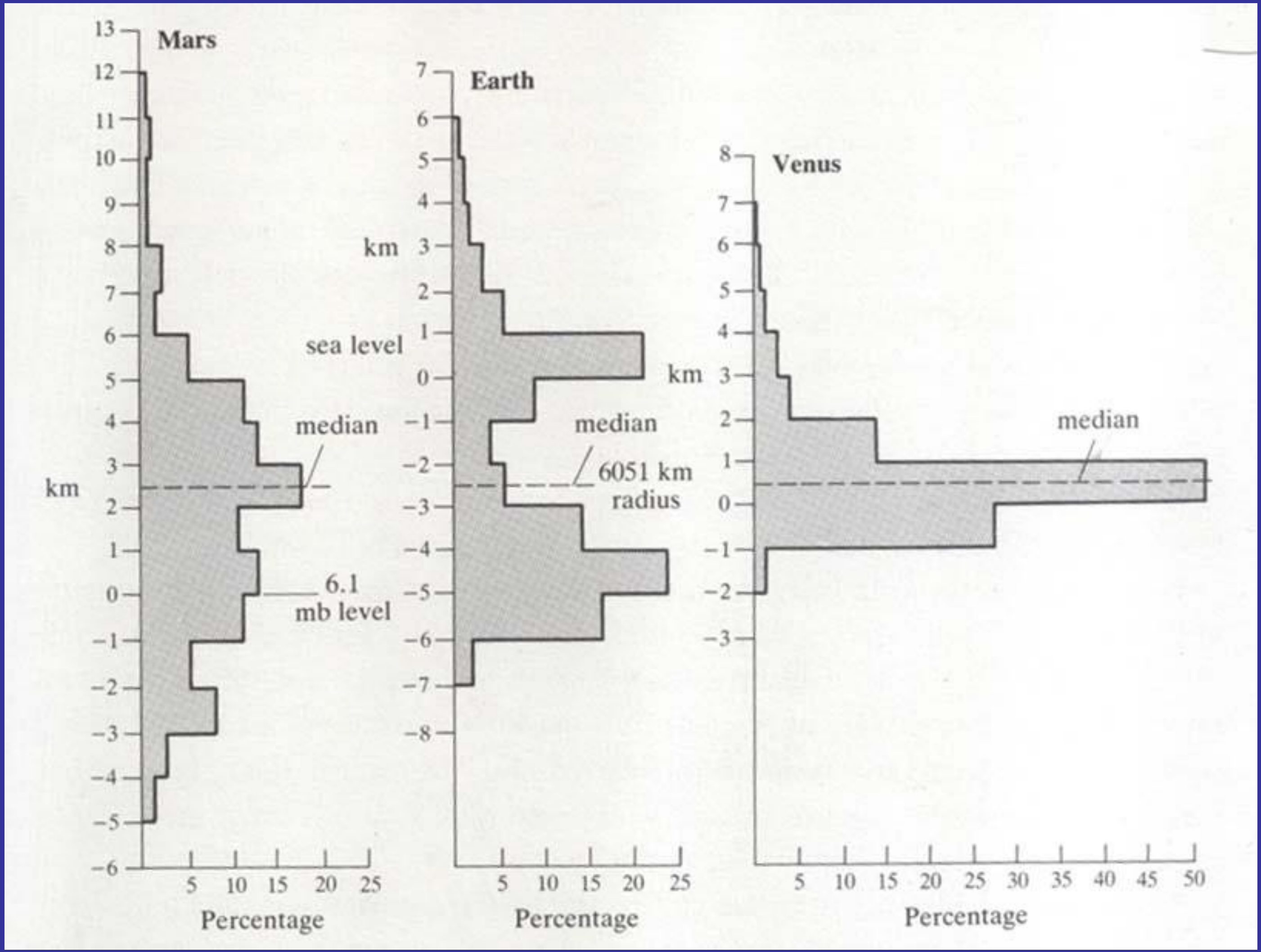
Airborne bacteria, stray birds and other organisms have been found at great heights

Most of the biosphere lives between these two limits

Sunlight extends down to about here (=photic zone)

Scattered bottom-living animals have been seen at the greatest depths reached by underwater cameras

Redrawn from Skinner and Porter (1987)



Comparison of the hypsometries of Mars, earth and Venus (from Cattermole 1994)

Notice how different is the hypsometry of the earth!

Limestone (ρ=2.23), marl (ρ=2.26) and shales (ρ=2.06-2.42) cut by normal faults around Kapaklı, Western Turkey.

Various speleothems ($\rho \approx 2.44$), in the Insuyu Cave Burdur.

The Grand Canyon, Arizona, USA.

In view are limestones (ρ=2.37-2.66), shales (ρ= 2.17-2.59), sandstones (ρ=2.41-2.50) and metamorphic rocks (ρ= 2.88-2.99)

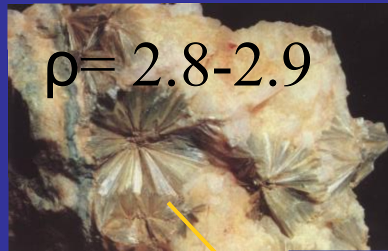
Pseudotachylite dykes cutting Archaean gneisses (ρ=2.61-269), Vredefort Dome, Transvaal, South Africa.

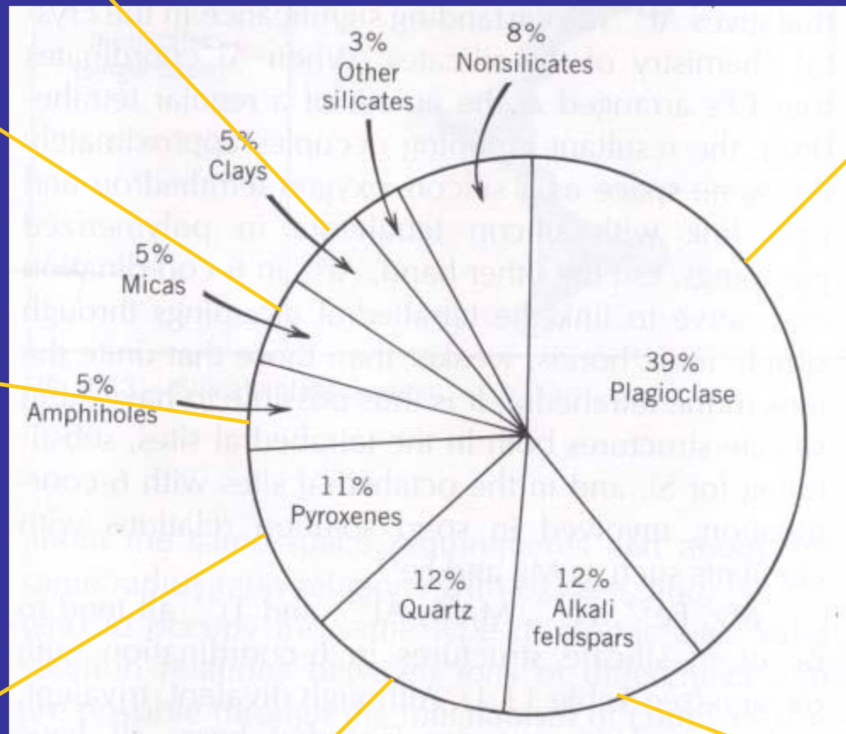
Exfoliating jointed granites (ρ=2.656-2.630), Krkonose Mts., Czech Republic.

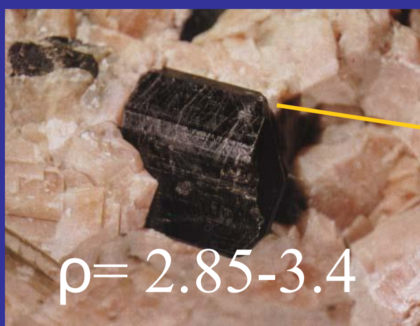
Pahoehoe-type basaltic (ρ= 2.85) lava flow, Serpovidnoe Lake, Russian Federation (SW of Lake Baykal)

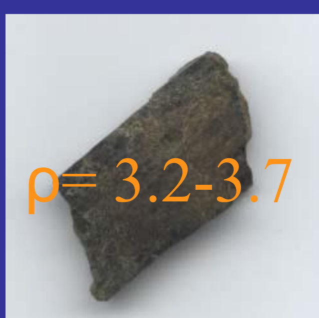
Traprain Law, a phonolitic trachyte (ρ= 2.45-2.48) laccolith in southern Scotland.

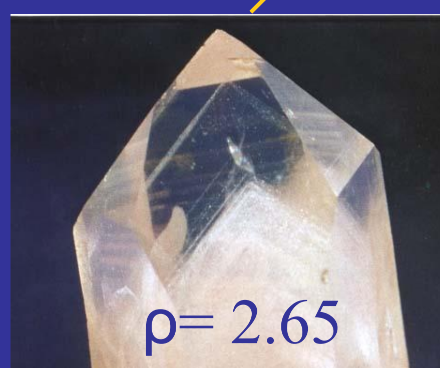
A dolerite (ρ= 2.76-2.8) dyke in the Barberton mountains, Transvaal, South Africa.











The composition of the earth's crust (after Ronov and Yaroshevsky, 1969; from Klein, 2002)

The crust makes up about 0.03839 of the total earth mass

So far we have talked about rocks. But what are rocks? We think we all know what they are, but do we? Is a fragment of a concrete wall or part of a brick a rock? Before we proceed any farther, it is useful to give a formal definition of a rock:

A rock is any naturally formed, firm and coherent aggregate or mass of mineral matter that constitutes a part of the universe.

But what is a mineral?

A mineral is a naturally occurring inorganic crystalline solid of a definite (variable within fixed limits) chemical composition.

For instance, although we speak of coal as a part of "mineral resources," of our planet it is not a mineral (why not?)

The rocks that we see at the surface of our planet are of the most diverse types. The overwhelming majority of them have densities ranging from 2 to 3. Rarely do their densities go beyond 3 (for example eclogites can have densities up to 3.45!).

The question now is, since the crust makes up only about 0.03839 of the total earth mass, what does the rest consist of? What do we know about that rest, and how?

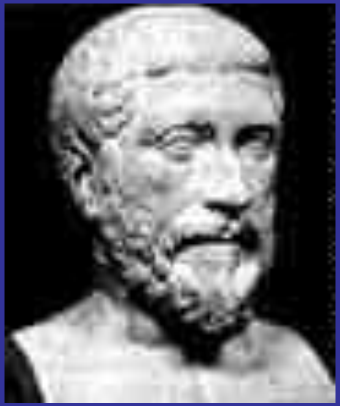
One way to answer this question is to calculate the *average density of the earth* and then to compare it with those of the surface rocks.

How do we calculate the average density of the earth?

Since *density* (ρ) is simply *mass* (m) divided by *volume* (*v*), all we need to know is the earth's mass and volume. But to calculate its volume, we need to know its *dimensions*.

How do we calculate the dimensions of the earth? What must we know?

First of all we need to have a general idea of its *shape*.

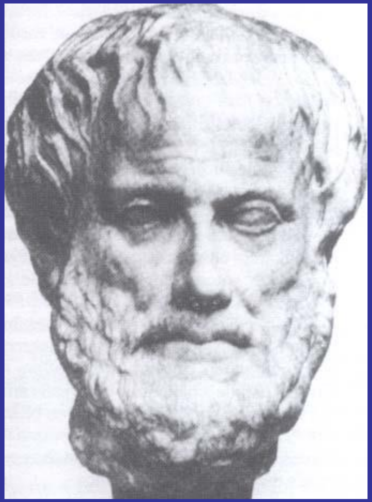


The Greek philosopher Pythagoras of Samos (569-475 BC)

The Pythagoreans (already in the earliest published Pythagorean account by Philolaus of Tarentum, now Taranto, S. Italy), of later half of the 5th century BC, thought that the earth was spherical, not, however, on the basis of any observations, but because Pythagoras considered the sphere the most perfect object.

Philolaus wrote: “The bodies of the Sphere are five: the fire in the sphere and the Water, and Earth, and Air, and fifth, the Hull of the Sphere”

This gives the picture of a spherical hull supporting water, earth and air and containing inside the fire. This also accords well with Simplicius’ (490-560 AD) testimony in his commentary on Aristotle’s *On the Heavens*: “Those however who have a better information place the fire into the interior of the earth as a creative power to vivify thence the whole earth, and to replace the cooling new heat.”



Aristotle of Stagira
(384-322 BC)

"If the earth were not spherical, eclipses of the moon would not exhibit segments of the shape which they do. As it is, in its monthly phases the moon takes on all varieties of shape—straight-edged, gibbous or concave—but in eclipses the boundary is always convex. Thus if the eclipses are due to the interposition of the earth, the shape must be caused by its circumference, and the earth must be spherical."
Aristotle, *On the Heavens* 297b25

Aristotle also had a theoretical argument for the sphericity of the earth:

“Its shape must be spherical. For every one of its parts has weight until it reaches the centre, and thus when a smaller part is pressed on by a larger, it cannot surge round it, but each is packed close to, and combines with, the other until they reach the centre.” *On the Heavens* 297a10

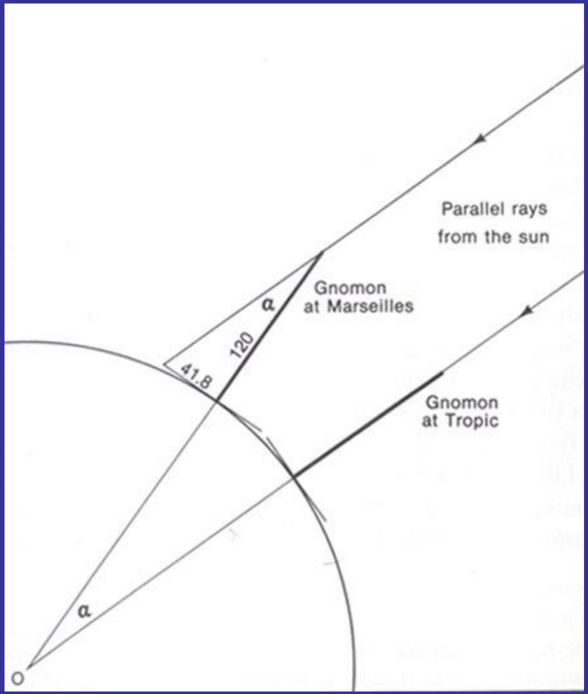
(This argument is still valid. Why? Hint: consider whether a planet of the size of the earth can exist in a cubic shape)

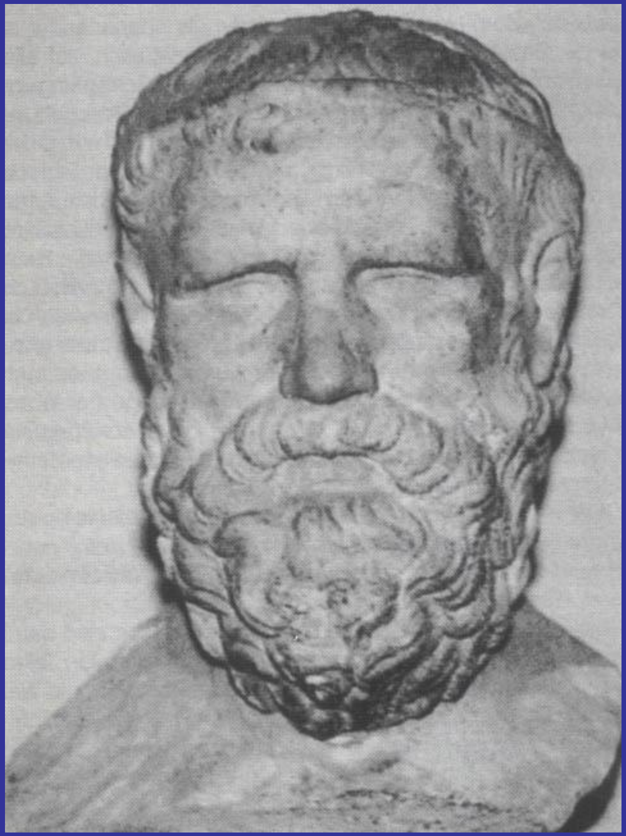
Aristotle also thought that the size of the earth could not be very large. Here is his argument:

"Observation of the stars also shows not only that the earth is spherical but that it is of no great size, since a small change of position on our part of the horizon, so that the stars above our heads change their position considerably, and we do not see the same stars as we move to the North or South. Certain stars are seen in Egypt and the neighbourhood of Cyprus, which are invisible in more northerly lands, and stars which are continuously visible in the northern countries are observed to set in the others. This proves both that the earth is spherical and that its periphery is not large, for otherwise such a small change of position could not have had such an immediate effect." *On the Heavens*, 297b-298a5

During the last years of Aristotle's life (between 325 and 320 BC), a Greek merchant from Massalia (now Marseilles), named Pytheas, made a memorable journey to Scotand and beyond to the Orkney Islands and possibly even farther to Iceland (which he called "Thule"). It was during this journey that Pytheas became the first person to relate systematically the latitude of a place to the length of the longest day, or to the height of the sun at the winter solstice (Harley, Woodward and Aujac, 1987). This too showed clearly that the earth is spherical and not very large.

Pytheas' observation of the latitude of Marseilles (from Harley, Woodward and Aujac, 1987, fig. 9.1)



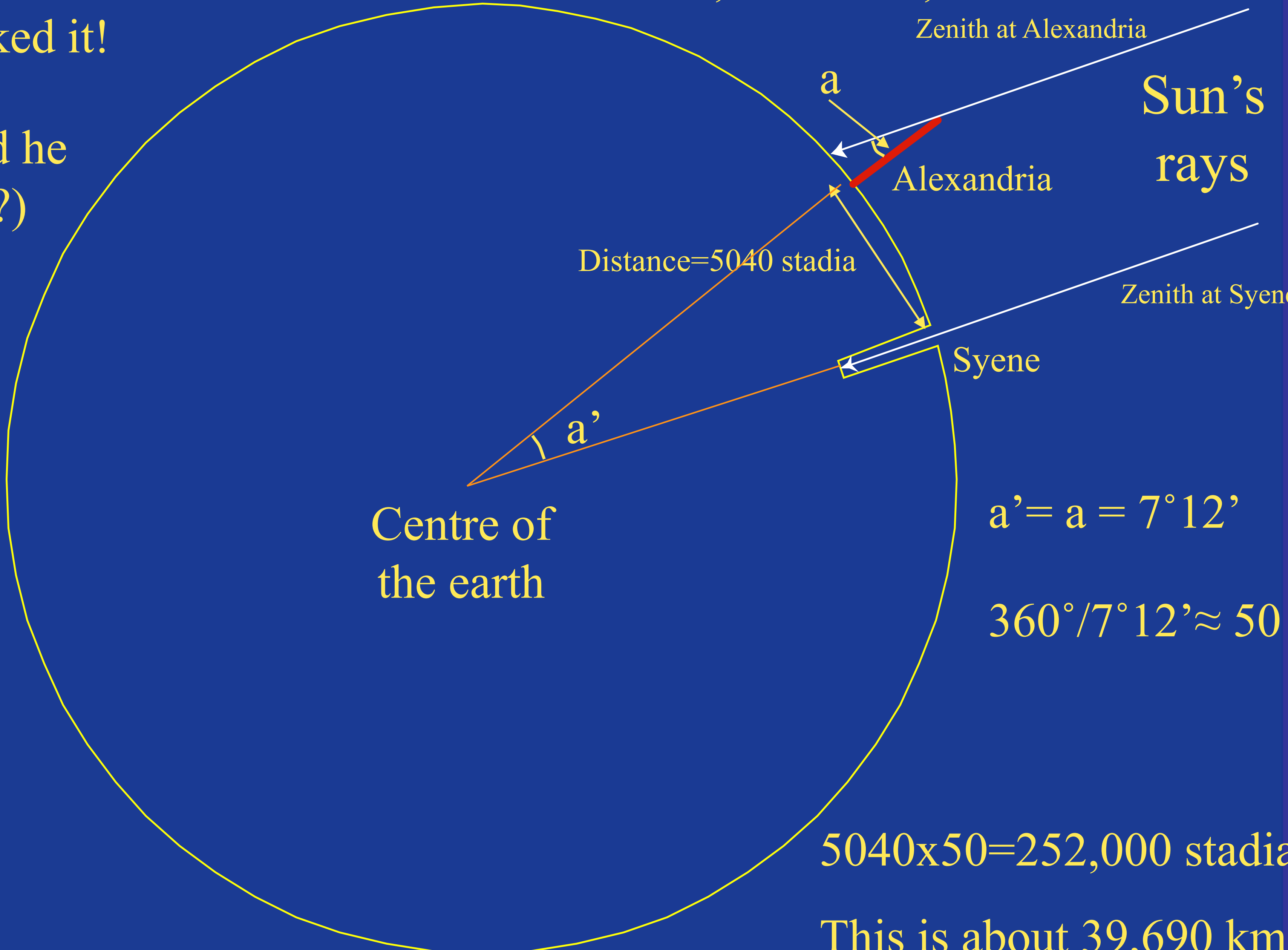


Eratosthenes of Cyrene
(274-194 BC)

Towards the end of the third century BC, Eratosthenes of Cyrene, possibly the greatest geographer of antiquity after Anaximander, calculated the circumference of the earth. For his calculation, he assumed that the Sun-earth distance was large enough to assume that the Sun’s rays were everywhere parallel with one another along a distance between the cities of Alexandria and Syene in Egypt and that these two cities lay on a great circle on the earth’s surface.

The method of Eratosthenes (with this method he also calculated that the Sun-earth distance to be about 40,000 stadia, but he disliked it!

How could he do it?)



$a' = a = 7^\circ 12'$

$360^\circ / 7^\circ 12' \approx 50$

$5040 \times 50 = 252{,}000$ stadia

This is about 39,690 km

If the circumference of the earth is roughly 40,000 km, then its radius must be 40,000/2p=6369.4 km (the presently accepted value is 6371 km)

From this it is easy to calculate its volume:

Volume of a sphere is $4/3\ \pi r^3$

So: $4/3 \times 3.14 \times (6369.4)^3 = 108.184 \times 10^{10}$ km^3

The presently accepted value is 108.321×10^{10}km^3

To get the average density of the earth, we now need to calculate its total mass!

To calculate the total mass of the earth, we can use Newton's law of gravitation:

$F=G(m_e \times m_o)/d^2$ (1)

Sir Isaac Newton (1643-1727) in the years when he formulated the law of gravitation

Here F is the force of attraction due to gravity, m_e the mass of the earth, m_o the mass of any object near the earth, d is the distance between the two and G is the universal gravitational constant.

But force F is mass times acceleration. So, the force with which the earth attracts an object of 1 kg mass on its surface is 1 kg x 9.81 m/sec^2 = 9. 81 newtons (remember that 9.81 m/sec^2 is the standard acceleration due to gravity at the surface of the earth). If we now solve the equation (1) for m_e:

$m_e = Fd^2/Gm_o$

The universal gravitational constant is 6.67×10^{-11} nt-m^2/kg^2

$m_e = 9.81$ newtons x $(6371000 \text{ m})^2 / 6.67 \times 10^{-11}$ nt-m^2/kg^2 x 1 kg = $\mathbf{59.67 \times 10^{23}}$ **kg**

From what we have so far learnt, we can easily calculate the average density of the earth:

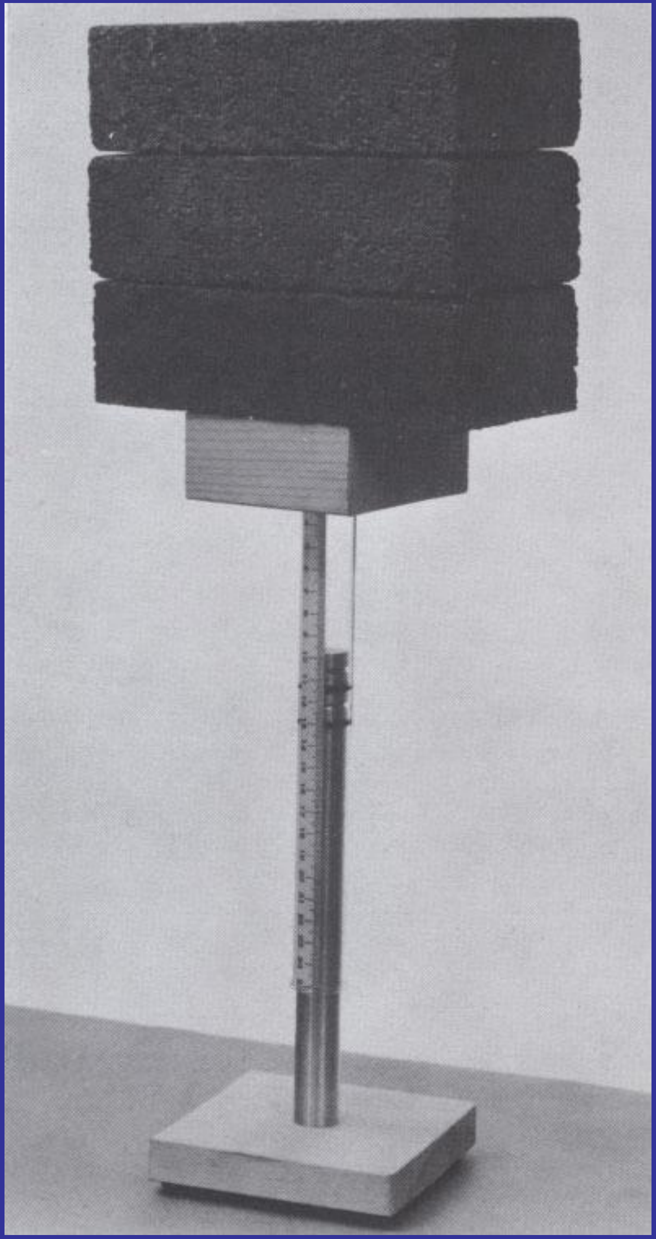
$\rho_e = m_e/v_e$

$= 59.67 \times 10^{23}$ kg/ 108.184×10^{13} m^3 = 5518 kg/m^3 or $\boxed{\mathbf{5.518\ g/cm^3}}$

At first sight this is a surprising result, because the densities of the surface rocks generally range between 2 and 3 g/cm^3!

The inevitable conclusion is that in the depths of the earth there must be denser materials.

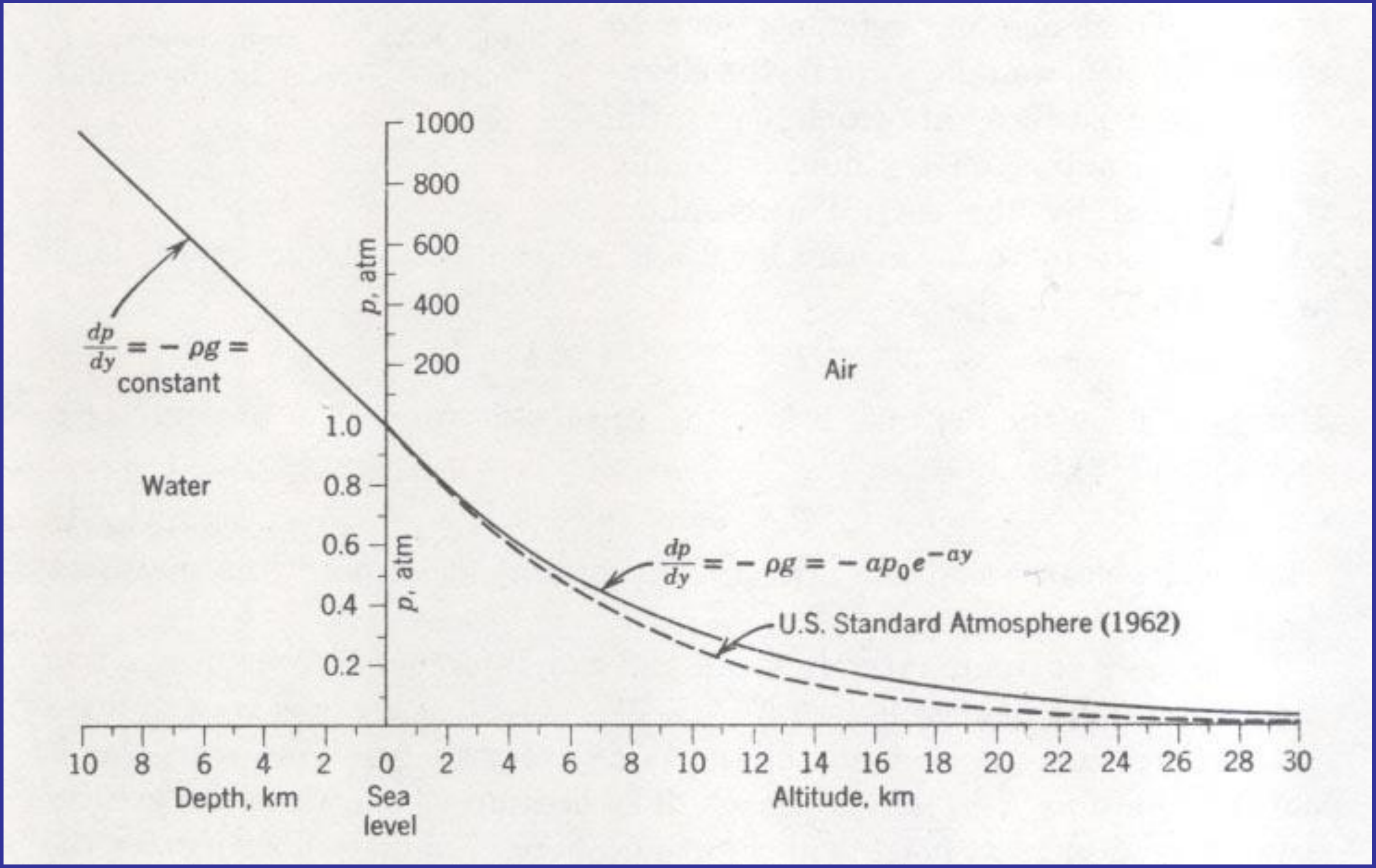
Whether that is really so,we can approach from two different directions: 1) From a *deductive* direction and 2) from an *empirical* direction. Let us first go the deductive way, because that does not require us to leave our desk, so we can do it right here:



MASS (KG)	PRESSURE $\left(\frac{\text{NEWTON}}{\text{m}^2} \times 10^{-4}\right)$	VOLUME $(\text{m}^3 \times 10^5)$	1/VOLUME $\left(\frac{1}{\text{m}^3} \times 10^{-3}\right)$
AIR			
2.20	4.9	28.5	3.51
4.22	9.4	21.5	4.64
6.26	14.0	17.4	5.75
8.36	18.6	14.8	6.76
10.40	23.2	12.8	7.81
12.47	27.8	11.1	9.01
PROPANE			
2.86	6.4	25.5	3.92
4.88	10.7	19.7	5.08
6.82	15.2	16.4	6.10
9.02	20.1	14.0	7.14
11.06	24.7	12.1	8.26
13.13	29.3	10.8	9.26
CARBON DIOXIDE			
3.52	7.85	23.5	4.26
5.54	12.4	18.5	5.41
7.58	16.9	15.5	6.45
9.68	21.6	13.3	7.52
11.72	26.1	11.7	8.55
13.79	30.8	10.3	9.71

The masses in the first column include the mass of the platform and piston as well as the mass of the bricks. In the case of propane we started with one brick and an additional mass of 0.66 kg. We then added bricks one at a time. The same was done in the case of carbon dioxide, except that we started with one brick and an additional 1.32-kg mass. This was done to separate the points on the graph for the different gases.

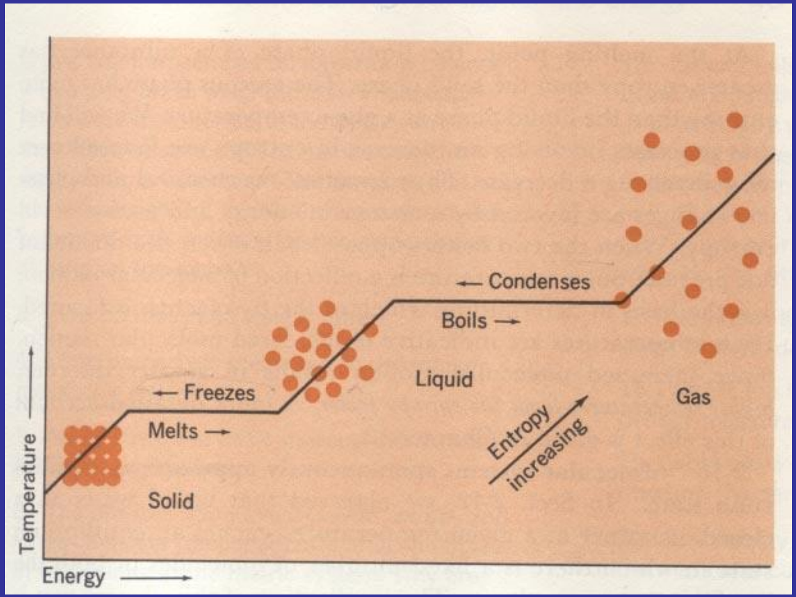
The syringe experiment to show how the volume of a gas decreases with increasing pressure on it (from Haber-Schaim et al. 1971). Thus with increasing pressure its density increases.



Variations of pressure in the atmosphere and in the oceans (from Resnick and Halliday, 1966, fig. 17-4)

Note that density of air changes with altitude and the density of water is assumed to be constant

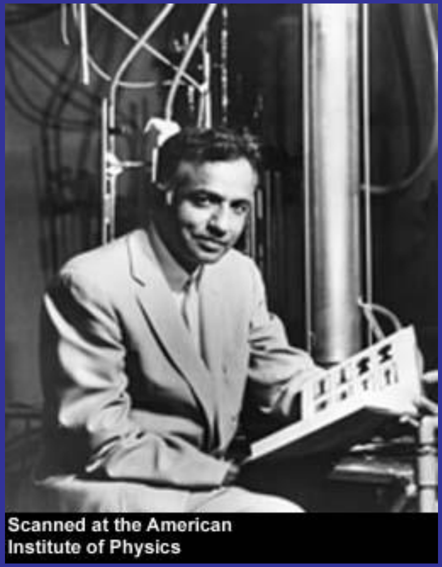
The condition of unchanging density under pressure is also known as *incompressibility*, i.e. the inability of a substance to change its volume despite increasing pressure. However, all substances are made up of atoms and molecules which consist mostly of empty space!



From Toon et al. (1968)

Phase changes are accompanied by volume changes because they change the inter-molecular distances and thus the entropy of a system. The figure here shows phase changes due to temperature changes. But we can also bring about phase changes by altering the pressure.

When high enough pressures apply, no substance can remain incompressible. In some stars, for example the pressures get so high that even the atoms themselves shrink (once the critical mass passes what is known as the *Chandrasekhar's limit*) to create matter so dense that the heavenly objects formed from it consist only of neutrons (because they can have no electrons orbiting a nucleus). If further compression occurs, the star would not allow even light to escape from it. That is why such theoretical objects are known as "black holes". Any body can be compressed to a size that would increase its density so much that no light can escape from it. This is known as the *Schwarzschild radius*.



Subrahmanyan Chandrasekhar (1910-1995)

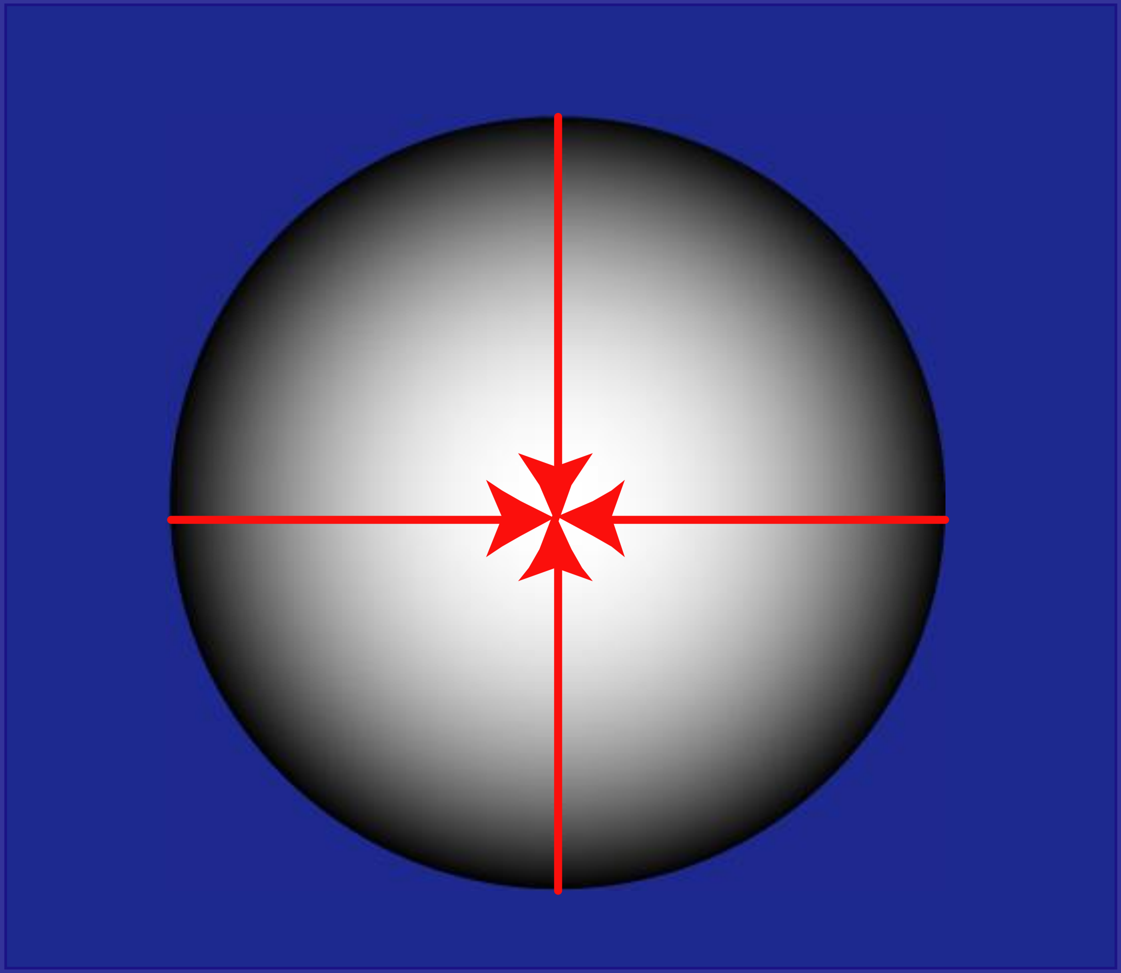
For our Sun, the Schwarzschild radius is 3 km (its present equatorial radius is 695,000 km!).

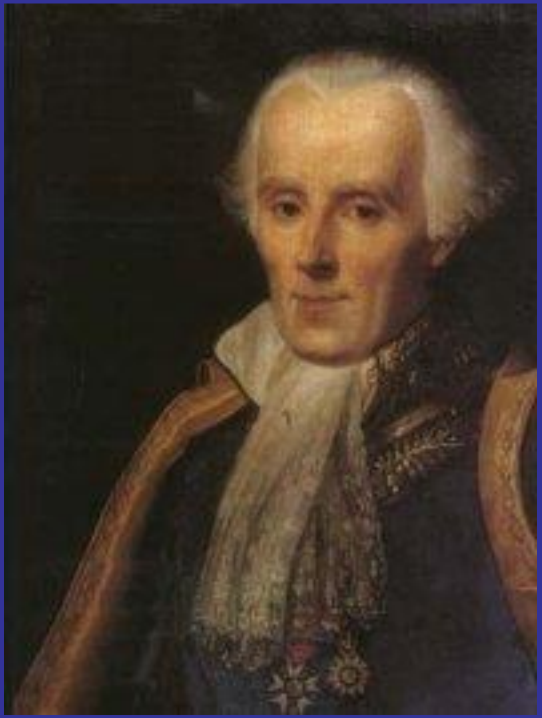
For a human being, the Schwarzschild radius is 1.7×10^{-23}m

(From Kippenhahn, 1980)

Karl Schwarzschild (1873-1916)

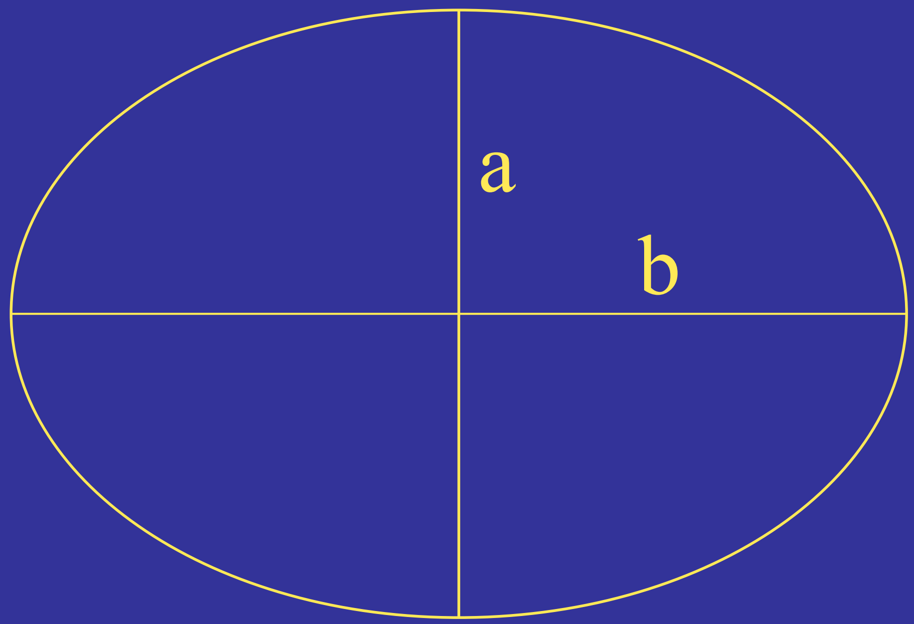
Thus with increasing pressure, density must also increase in any material





Hydrostatic pressure for any depth h is
$P_h = P_0 + rgh$

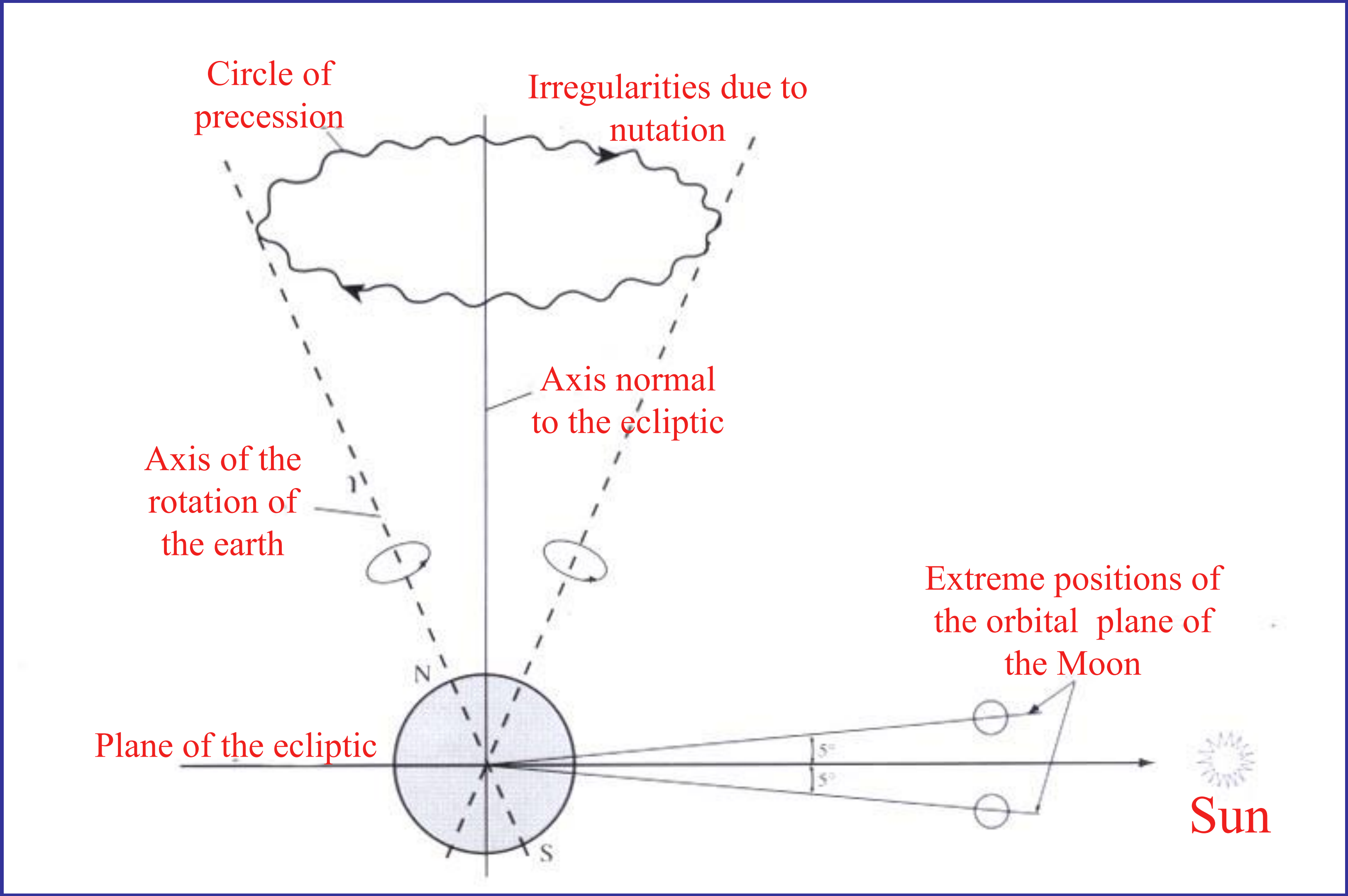
In 1799 Marquis Pierre Simon de Laplace (1749-1827) pointed out that according to the principles of hydrostatics, in the earth pressure, and therefore density, must increase with depth. (Why did Laplace use principles of hydrostatics for a solid earth?)



A homogeneous earth would have been an ellipsoid of revolution about its axis of rotation (a)

Sir Isaac Newton (1643-1727) calculated the flattening (b-a/a) to be 1/230.

Present satellite observations help us estimate it to be 1/298,257 with an accuracy of 1 part in 200.000 (Bott, 1982)



From Deparis and Legros (2002, fig. III.12)

The equatorial bulge of the earth and the attraction on it by the Sun and the Moon cause its axis to precess and to nutate

The flattening of the earth due to rotation (hydrostatic equilibrium, he) is calculated by the following relation:

$$\boxed{f_{he} = (5/2)\,(w^2 R_e/g_e)[1+\{5/2 - (15/4)(I_{33}/\mathcal{M}R^3)\}^2]^{-1} + \mathcal{O}\,(f^2)}$$

The terms that enter this equation are the following:

I_{33} = moment of inertia with respect to the x_3 , i.e., rotational, axis
$= \int_{\mathcal{M}} (x_{3+1}{}^2 + x_{3+2}{}^2)\, d\mathcal{M}$

w = angular velocity of the earth = 7292115 x 10^{-11} rad/sec

R_e = mean equatorial radius = 6378136 ± 1 m

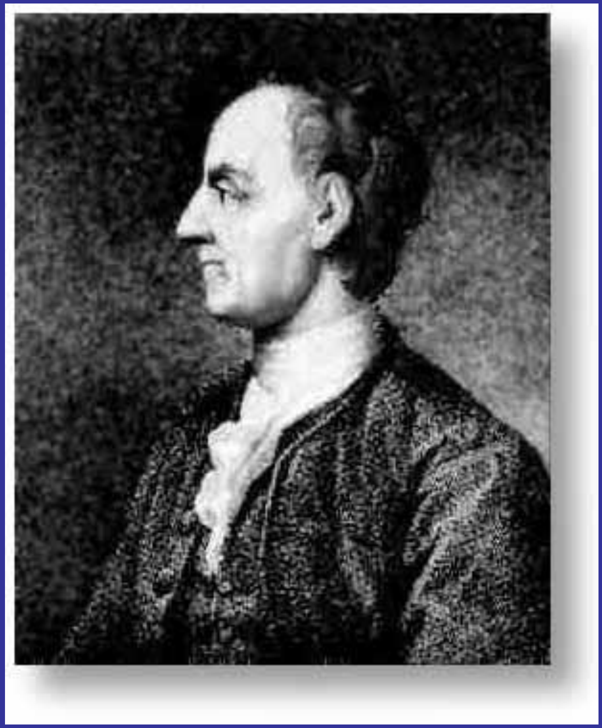
g_e = gravitational acceleration at the equator = 9.78032 ± 1 m/sec^2

f = polar flattening of the reference ellipsoid
$= (R_e - R_p)/R_e = (1/298.275) \pm 0.001$

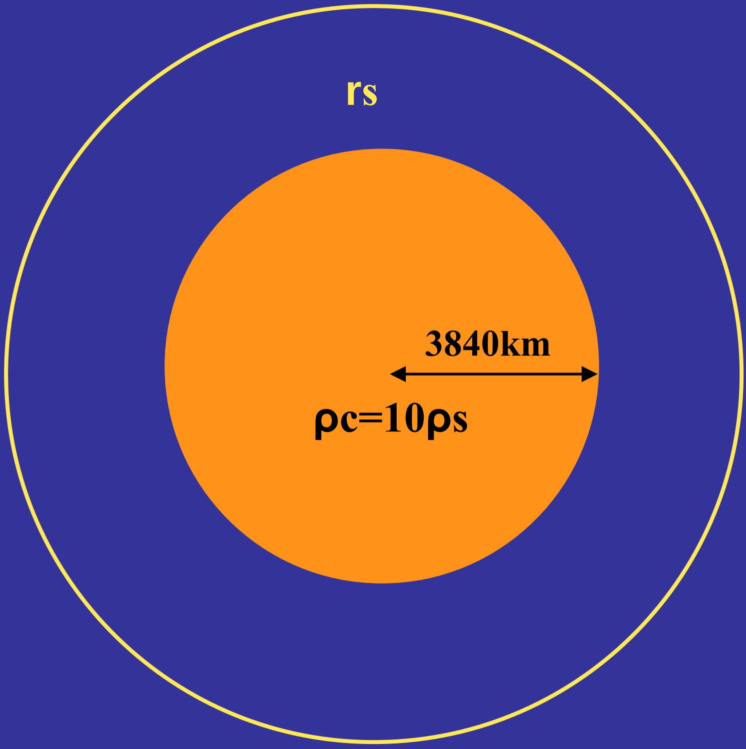
$\mathcal{O}$ = order of magnitude

$f_{he} = (5/2)\,(w^2 R_e/g_e)[1+\{5/2 - (15/4)(I_{33}/\mathcal{M}R^3)\}^2]^{-1} + \mathcal{O}(f^2)$

Notice that in this equation we use the moment of inertia with respect to the x_3 axis, which requires the integration of the mass ($\mathcal{M}$) of the earth along this axis. Therefore the hydrostatic flattening contains terms that give information about the distribution of mass within the earth. This was first used by the Swiss mathematician Leonhard Euler in 1749 to propose a layered density distribution within the earth.



Leonhard Euler
(1707-1783)



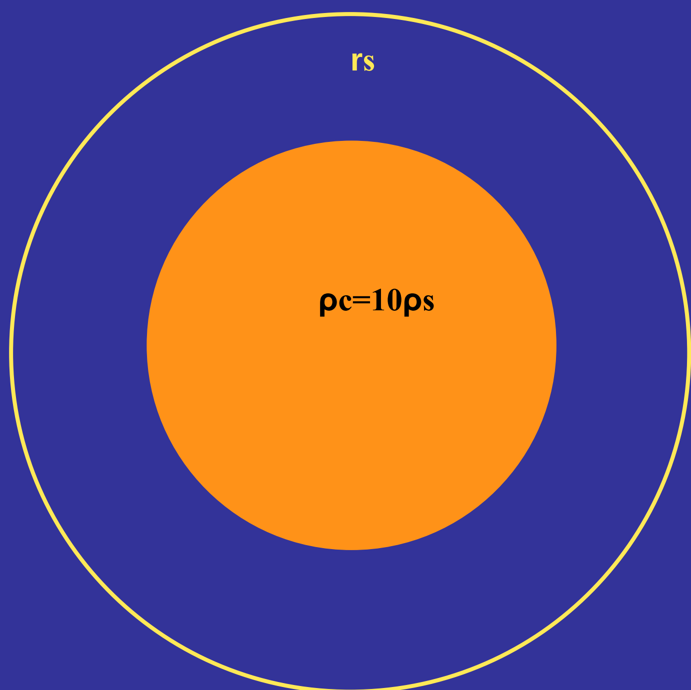
Leonhard Euler (1707-1783) pointed out in 1749 that in a homogeneous earth the quantity C-A/A would be equal to b-a/a,where C is the moment of inertia around the axis of rotation and A is the moment of inertia around an equatorial axis.

(Moment of inertia is $\int r^2 r\, dv$, where r is the radius, r is density and v is volume)

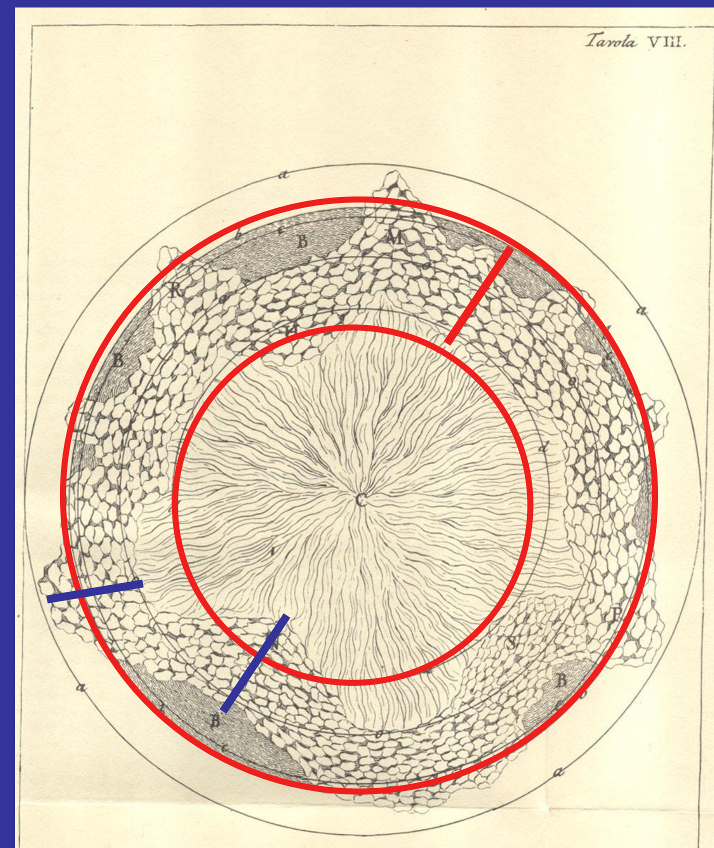
He found instead that C-A/A was 1/336, i.e. much smaller than 1/230. This is only possible if there is a “core” of sorts that has an appreciably higher density than the surronding shell.

Euler assumed a two-layer earth, with a “core” density 10 times the “shell” density and a core radius of 3840 km

Now let us compare Euler's earth with an almost exactly contemporary concept derived entirely on the basis of geological observations made on the surface of the earth:



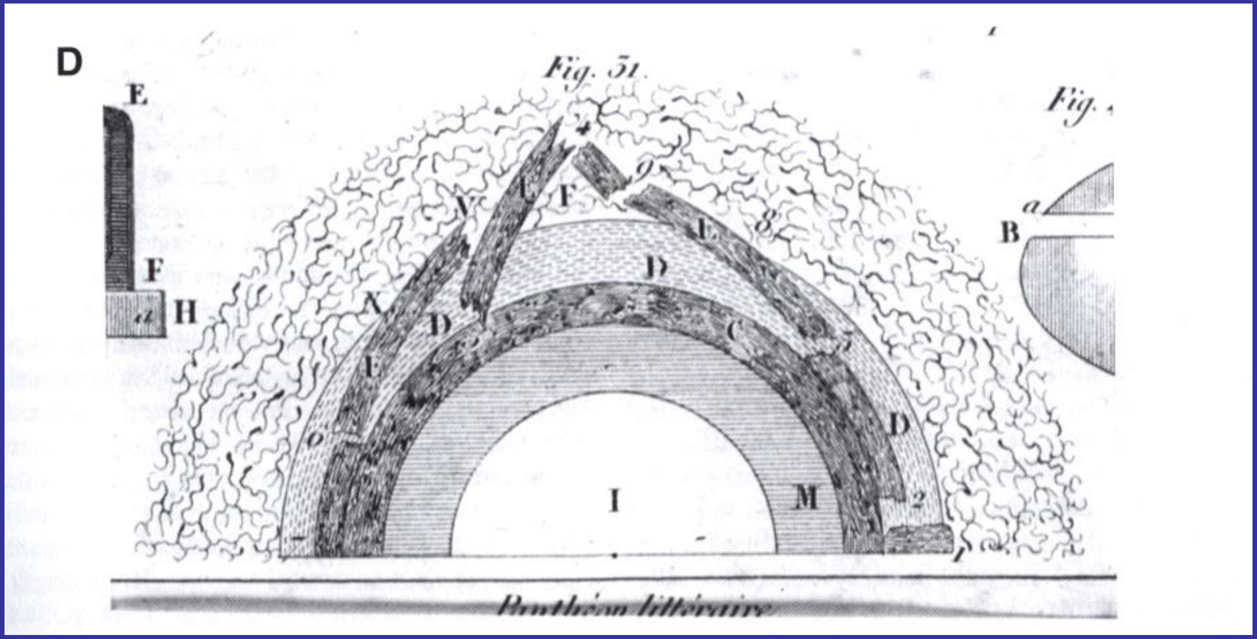
Euler's earth (1749)



Antonio Lazzaro Moro's earth (1740) with Euler's dimensions superimposed

The agreement between the thicknesses of Euler's "shell" and Moro's "crust" is entirely coincidental and both are wrong. There is no discontinuity known today at a depth of 2531 km.

Moro's "crust" was based both on what Moro had thought to be Empedocles' model and, via Thomas Burnet (1635?-1715) and John Woodward (1665-1728), on René Descartes' (1596-1650) layered earth.



Descartes' earth in his *Principes de Philosophie* (1644)

Joseph Fourier (1768-1830)

In 1822, Fourier's studies of the physics of heat flow and heat transfer have resulted in an equation establishing the temperature history of a body:

$d\mathrm{T}/dt = (k/\mathrm{r}\mathrm{C_p})\ (d^2\mathrm{T}/dx^2)$

Where T is temperature, t is time, $(k/\rho \mathrm{C_p})$ thermal diffusivity, with ρ being density and $\mathrm{C_p}$ specific heat.

In 1824 he applied his results to the earth. This showed that neither the solar nor the interstellar heat were capable of sustaining the geothermal gradient observed on earth, which Fourier showed to be 1˚C for every 32 metres.

To get a rough idea of how much solar heat can heat up the earth, consider that every year, a cm^2 of surface receives 225.000 calories of heat from the sun. If applied continuously, this is enough to raise the temperature of 225 tons of water by one degree centigrade! If we consider a container with a base of 1 m^2 and a height of 225 metres, we see that for a whole year, the solar energy, if applied continuously (i.e. if we don't count the nights and the cloudy days) is only sufficient to raise the temperature of the photic zone (including the *euphotic* and the *disphotic* zones) in the seas (which is about 200-250 metres deep) by one degree centigrade, if all the energy transferred were preserved! Therefore the energy transferred from the Sun contributes essentially nothing to the earth's internal heat budget.

Now let us return to Fourier's geothermal gradient:

If we take the surface temperature to be 0˚c, then at a depth of

32 m the temperature of the rocks reaches	1˚C
320 m	10˚C
3200 m	100˚C
32000 m = 32 km	1000˚C

At 32 km depth we have already passed the melting temperature of even dry granite, which is about 800˚C.

At 40 km, we reach a temperature of 1250 ˚C,which surpasses the melting point of basalt, which is 1200˚C.

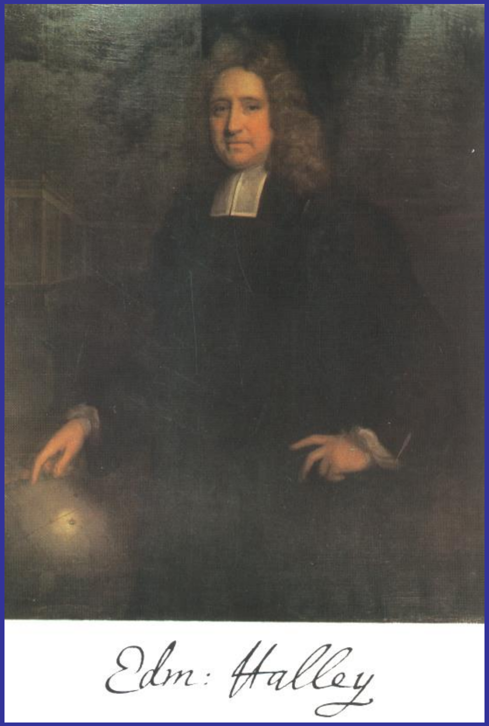
At about 53 km, we surpass 1700˚C,which is the hottest any known mineral can stand without melting.

Pierre-Louis-Antoine Cordier
(1777-1861)

On the basis of such considerations, the French mining engineer Cordier studied the geothermal gradient in 40 mines in France measuring about 300 temperatures. He concluded that the gradient was steeper than Fourier had thought, being 1˚C for every 15 to 25 metres. He extrapolated that and concluded that temperatures exceeding 100˚ of Wedgwood's pyrometer (>7200 ˚C), which Cordier thought would melt all lavas and most rocks, would be reached at a depth of less that 270 km in Carneaux, 150 km at Littry and 115 km at Decise.

In his epoch-making book “Essai sur la température de l’intérieur de la Terre” (*Mémoire de l’Académie des Sciences*,1827), republished in the same year in the *Mémoires du Muséum d’Histoire Naturelle*, v.15, pp. 161-244), Cordier argued that the earth’s crust was a product of solidification resulting from cooling and that its thickness was at most 55 leagues (100km), but probably much less.

He also argued, following Edmond Halley’s extraordinarily perceptive earlier view, that in the molten interior there may be an independently rotating iron core capable of causing the magnetic field of the earth!



The great British astronomer Edmond Halley (1656-1742)

Élie de Beaumont (1798-1874)

These arguments led, within the first half of the nineteenth century, to the conception of a crust underlain by a liquid interior of unknown thickness. One thought that if this crust were somehow loaded, it would subside into the underlying liquid interior. This was first expressed by the great French geologist Élie de Beaumont in 1828.

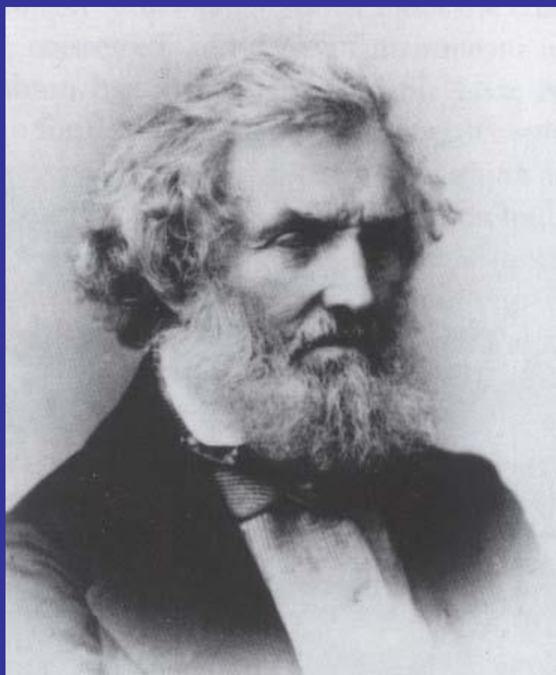
He thought that at a time when there was already life on earth, sufficient temperatures may have obtained at depths of 1000 m or so from the surface of the earth to keep most rocks at those depths in a liquid state. In other words, the thickness of the earth's crust at those times may have been only about a km. Now, Élie de Beaumont further believed that the accumulation of coal beds, corals and mussel-banks showed that most Palaeozoic seas had had a small depth. Yet the entire thickness of the Palaeozoic strata reaches several thousand m. The weight of even a small basin would thus have been enough to 'fold in' its basement. Every newly laid down bed would push the basin bottom closer to the red-hot interior. Élie de Beaumont thought that this would heat up the lower parts of the basin sufficiently to change the texture, even the structure, of the original sediments. The thicker the sediment package in a basin, the greater would be the effects of metamorphism.

The great British astronomer Sir John Frederick Herschel (1792-1871)

British polymath and inventor Charles Babbage (1792-1871)

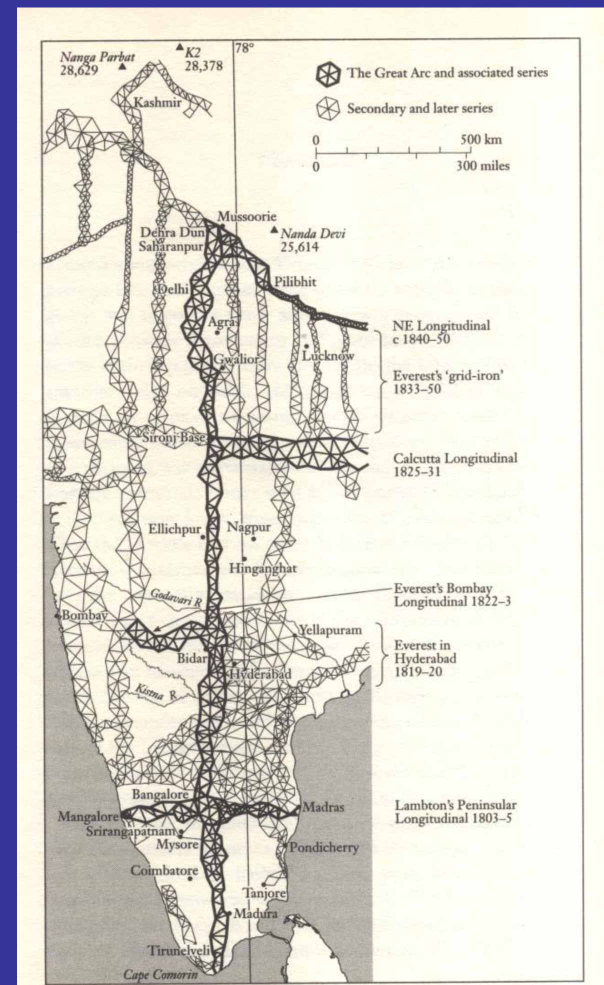
The views of both Charles Babbage and Sir John Herschel are found in appendices to the former's *Ninth Bridgewater Treatise* (Babbage, 1838, notes F through I, pp. 204-247) and are concerned primarily with the means of generating uplifts and depressions through the internal heat of the earth. Both contend that the lines of equal temperature must mimic the topography grossly, subaerial or subaqueous. While erosion depresses (with respect to the centre of the earth) the geotherm below a given point near the original surface, deposition raises it. This may cause metamorphism or even melting under thick sedimentary piles and might liberate water vapour and other gases, causing volcanic eruptions. Herschel, in his letter to Lyell (in Babbage, 1838, pp. 225-236), pointed out, that since a fluid substratum must exist beneath the crust, sedimentation would load any basin floor and depress the crust underneath into the substratum. By contrast, erosion would occasion uplift.

Independent evidence that the crust must "float" on a denser substratum came from the plumb line observations during the geodetic work of the Great Trigonometrical Survey of India at the time headed by Colonel Sir George Everest, one of the greatest geodesists of all times.



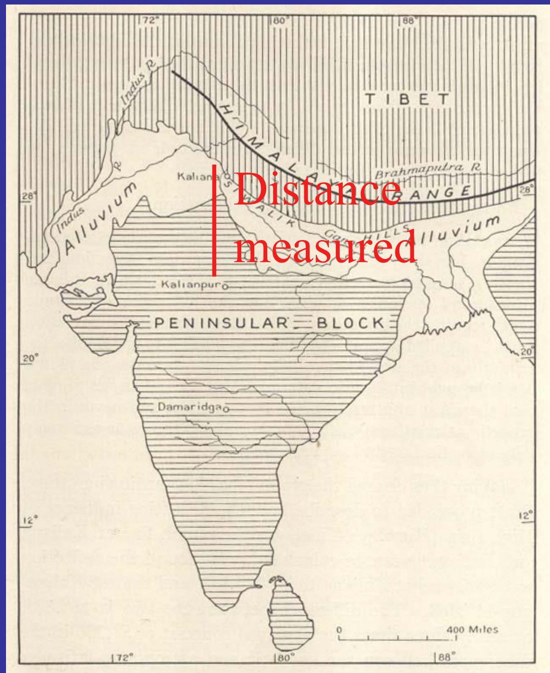
Sir George Everest (1790-1866)

The triangulation along the "Great Arc" of meridian in India



THE GREAT ARC AND ASSOCIATED SERIES

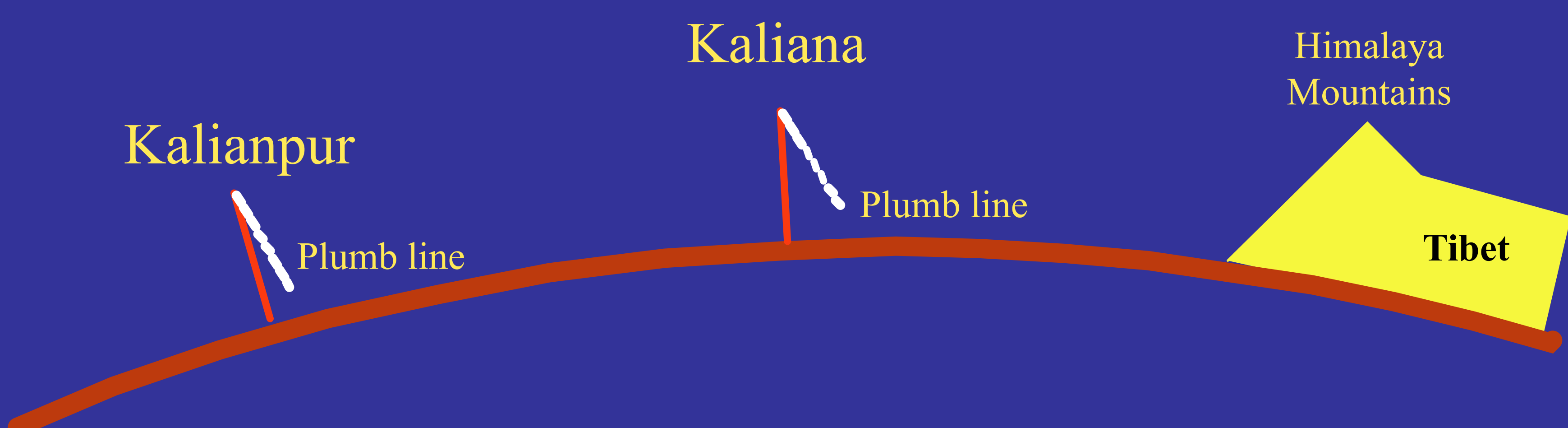
A plumb line is a simple device used to establish the vertical on the surface of the earth. If the earth were a perfect ellipsoid, the plumbline would everywhere show the true vertical to the surface. If, however, there are topographic irregularities, they would add additional material with power to attract and the plumbline would deviate towards them from the vertical (to the geoid).



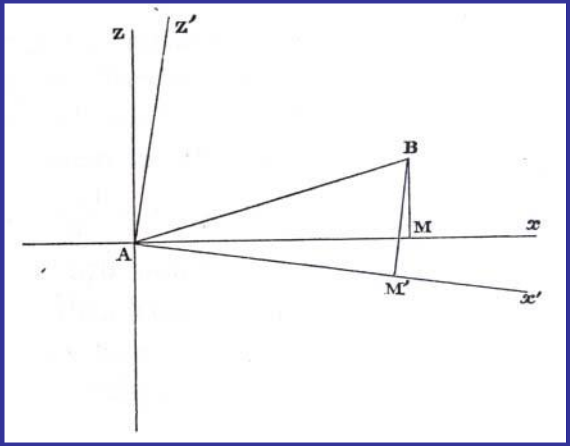
Distance between Kaliana and Kalianpur by triangulation = 5°23’42”.294

Same distance by astronomical fixing = 5°23’37”.058

There is thus an “error” of 5”.236, which is about 154 m (over a distance of 603.75 km!) reported by Everest in 1847



Colonel Everest thought that the error lay in establishing the vertical at every triangulation station between Kaliana and Kalianpur and he distributed the error of 5”.236 among the triangles. However, in 1855 Archdeacon John Henry Pratt (1809-1871) showed that this could not be, because the error in triangulation is dependent on the second order of the value of the deviation of the plumb line:



Pratt’s figure to show that the error in triangulation is dependent on the second order of the deviation of the plumbline

The error due to deviation is AM-AM’ =

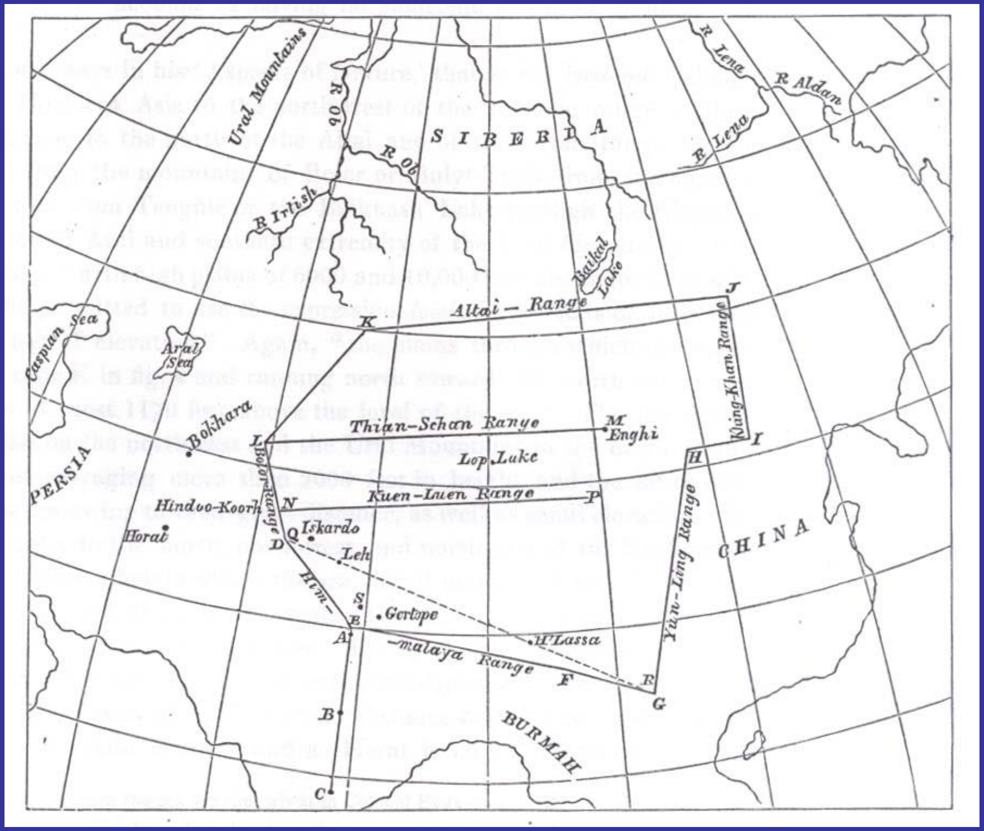
$$AM[1-\{\cos(<BAM+<zAz')\}/\cos<BAM]=$$

$$AM(\tan <BAM \cdot \sin <zAz'+ 1- \cos zAz')=$$

$$BM <zAz'+1/2\ AM\ (<zAz')^2$$

Thus the geodetic error is a function of the square of the deviation angle. But the astronomical error is directly dependent on the difference between the two plumbline directions.

Pratt calculated the attraction of the entire mountainous mass, which he called the “enclosed region,” north of the measuring stations.



Pratt’s “Enclosed Region”

He found that the calculated difference between the stations was 15”.885 or nearly three times the observed difference of 5”. 236. This meant that Pratt had assumed that the mountainous mass within the enclosed region had too much of an attraction. For his calculation he had assumed a density of 2.75 g/cm^3 for the average density of the Enclosed region. To account for the “too much attraction” he tried to reduce it, but he found that even if he reduced it to the absurd value of 2.25 g/cm^3, the enclosed region still had too much attraction to account for the anomaly.

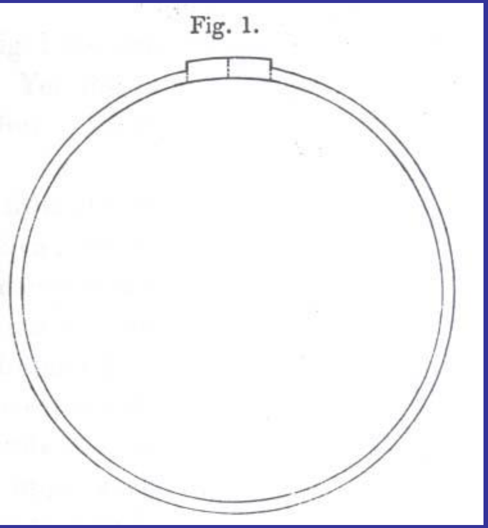
In his 1855 paper, Pratt could not resolve the anomaly. He resorted to changing the curvature of the surface, but this was clearly an *ad hoc* solution.

The solution of the problem came from the Astronomer Royal George Airy.

The Astronomer Royal
George B. Airy
(1801-1892)

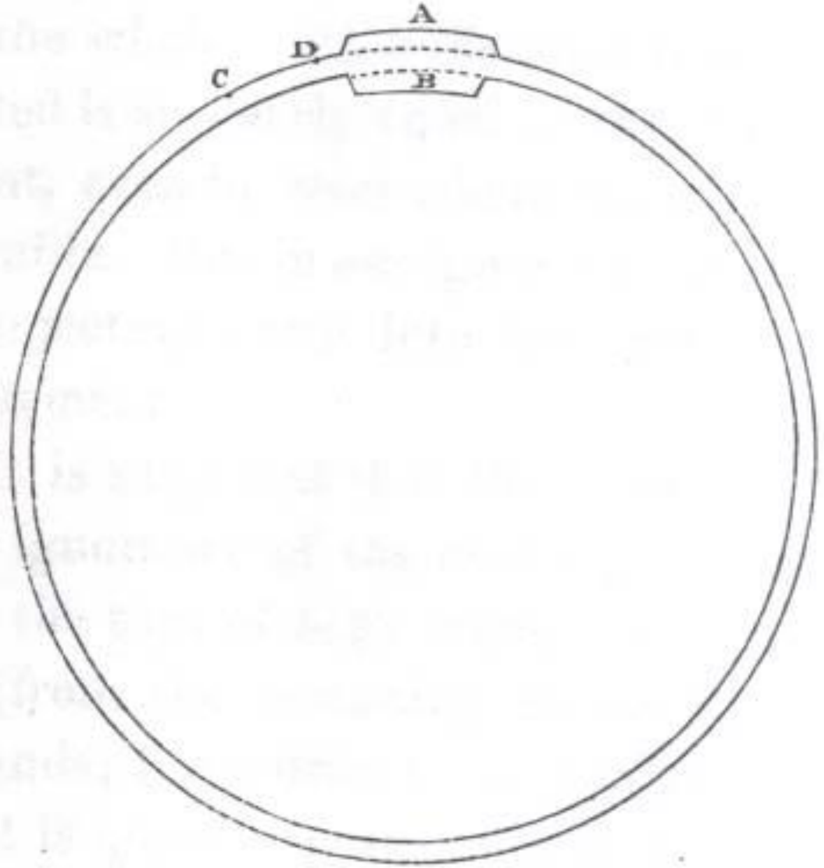
Airy pointed out that Pratt's assumption of considering the enclosed region as an additional load on the outer shell of the earth was unreasonable, because the shell could not be strong enough to support it.

If the enclosed region had a geometry as shown here, the cohesion across the vertical lines indicated would be such as to hang a rock column twenty miles long, if



the shell was only 16 km thick. If the shell were assumed 160 km thick, the cohesion necessary would have been one to hang a rock column 322 m long, which Airy thought was still excessive.

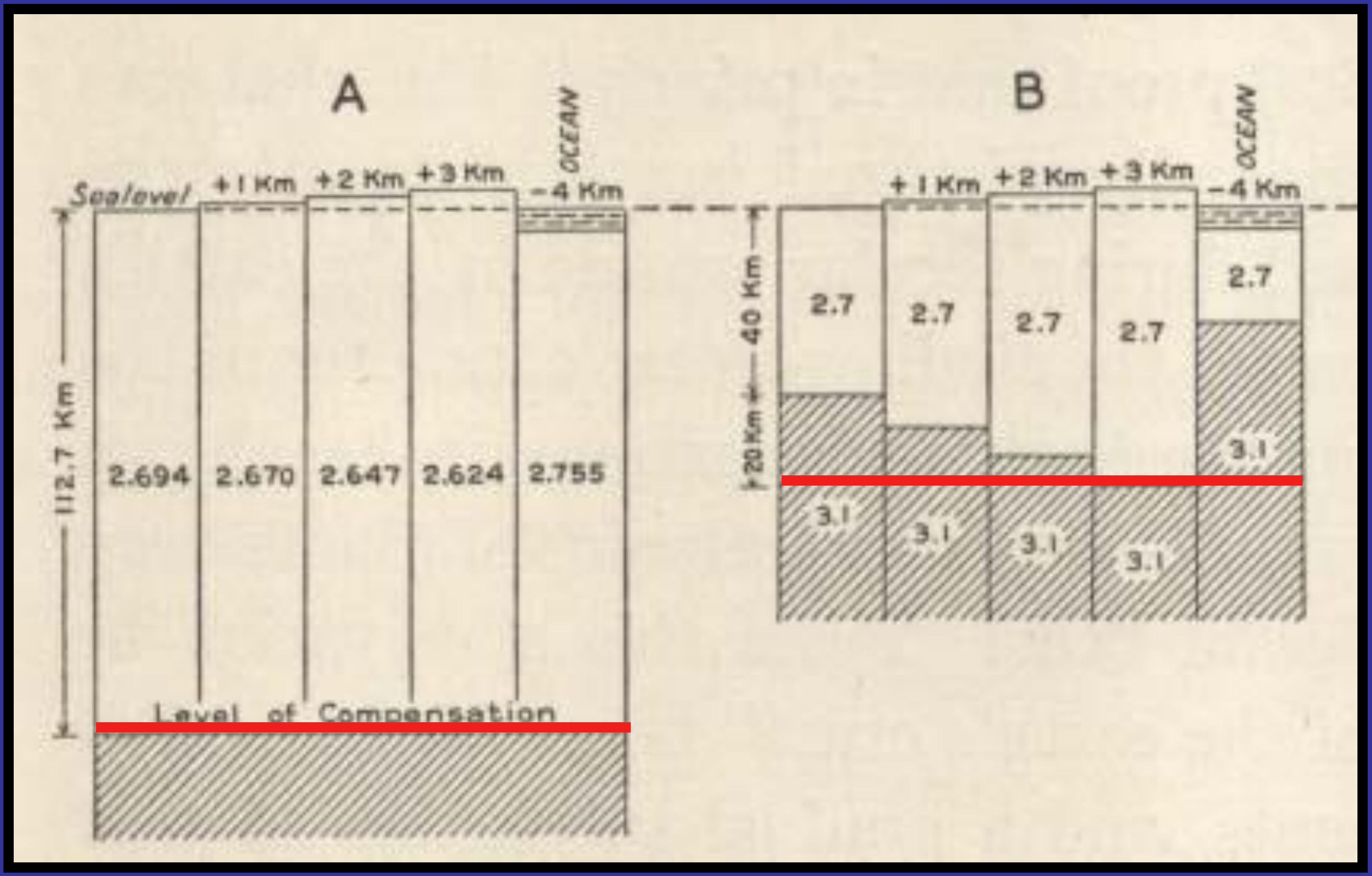
Fig. 2.



Airy instead suggested to "float" the enclosed region on a denser substratum. He then wrote "In all cases, the real disturbances [of the plumb line] will be less than that found by computing the effect of the mountains, on the law of gravitation. Near to the elevated country, the part which is to be subtracted from the computed effect is a small proportion of the whole. At a distance from the elevated country, the part which is to be subtracted is so neary equal to the whole, that the remainder may be neglected as insignificant, even in cases where the attraction of the elevated country itself would be considerable. But in our ignorance of the depth at which the downward immersion of the projecting crust into the lava takes place, we cannot give greater precision to the statement." (Airy, 1855, p. 104)

In an 1859 paper, Pratt objected to Airy's idea because 1) he believed Hopkins' idea that the curst was 1280 to 1600 km thick; 2) he thought it absurd to have a liquid more dense than a solid of the same material; and 3) he saw that Airy's idea would lead to a variable topography of the lower boundary of the crust and the crust would have to be thin under depressions and thick under elevations. He did not believe any sort of cooling could produce such a crust.

He instead suggested that the differences in elevation may result from the attenuation of the mass below them (so as to lower their density) and all columns supporting different heights would be found to be equally heavy at an imaginary level at depth.



Pratt type crustal geometry to account for topography and gravity

Airy type crustal geometry to account for topography and gravity

All columns above the red line have the same weight

By the middle of the nineteenth century different kinds of evidence had converged to indicate that the earth indeed had a concentrically layered internal geometry and that as one descended, both temperature and pressure increased. It was also thought by many that the density increase was not gradual, but discontinuous.

Additional evidence for this latter view came from meteorites!

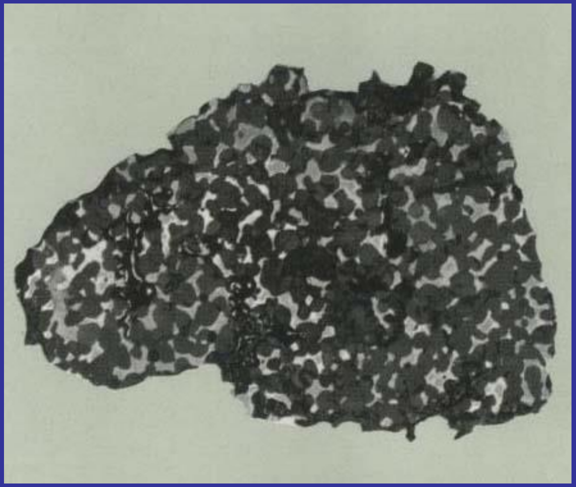
Auguste Daubrée
(1814-1896)

In a series of papers between 1866 and 1885, the great French geologist Auguste Daubrée classified the meteorites into four great classes of

1) Meteorites composed almost entirely of iron alloyed with nickel and some other metals

Iron meteorite with Widmannstätten figures composed of kamacite (ρ=7.3-7.9) and taenite (ρ=7.8-8.2) lamellae

2) Meteorites with silicate grains in an iron matrix (e.g. Pallasites)



Olivine grains (ρ=3.27-4.37) in an iron mass

3) Meteorites consisting of silicates with some grains of iron (achondrites). These are the most common meteorites. Their compositions range from basaltic to ultramafic.

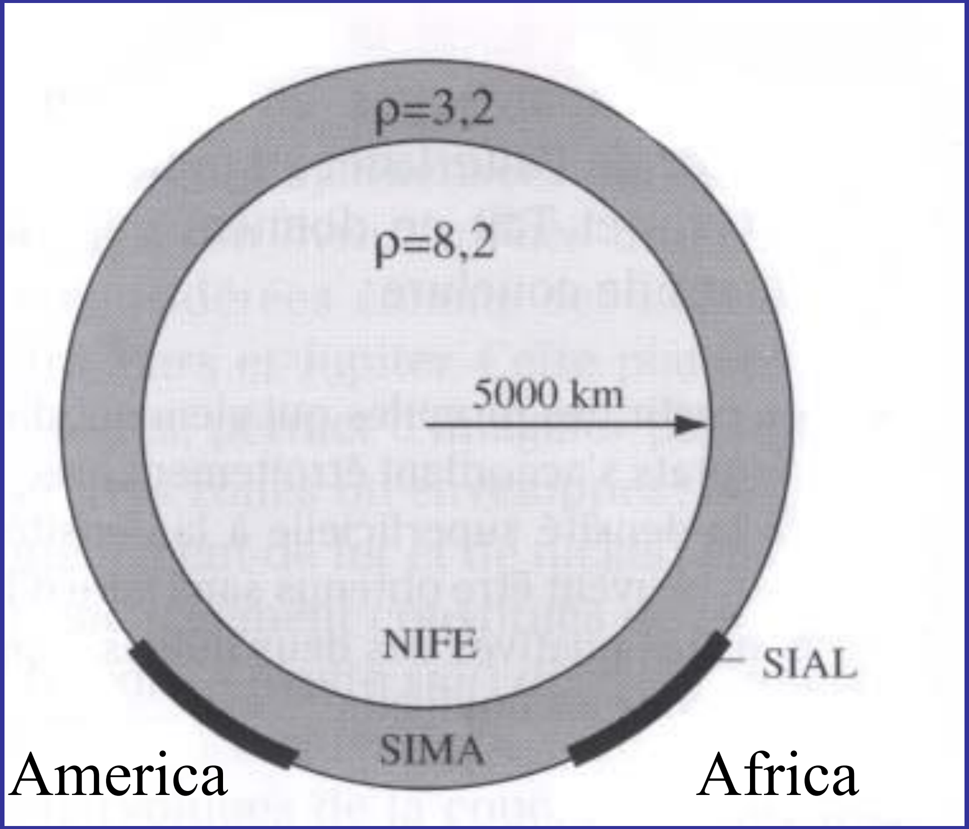
The Rosebud stony meteorite consisting of an olivine (ρ=3.27-4.37) - hypersthene (ρ=3.4-3.5) ultramafic rock (from King, 1976)

4) Meteorites with no iron at all and some of them with carbonaceous chondrites (e.g. the Allende meteorite)

In those days tektites were also thought to be of meteoric origin (we now know them to be just glass ejecta from the earth that form when meteorites hit the surface and melt it). Their silicic composition and low density (anywhere between 2.3-2.8) suggested to Daubrée that meteorites had a natural density sequence. He thought they probably came from a now-disrupted planet.

A fragment of the Allende meteorite

Finally, in 1909, Eduard Suess, an Austrian geologist and possibly the greatest geologist who ever lived, proposed, in the fourth volume of his great classic *Das Antlitz der Erde* (=The Face of the Earth) the following internal geometry of the earth on the basis of all the available evidence then:



Suess' earth (equatorial cross-section)

Eduard Suess
(1831-1914)

Among the evidence used were:

1) Shape of the earth
2) Geology of the surface
3) Geophysical considerations on the movements of the earth and their implications for the internal density distribution
4) Meteorites

For his geophysical basis Suess used the great Göttingen geophysicist Emil Wiechert's model of 1897. Wiechert's model was wrong mainly because he neglected the influence of pressure on density. He simply used the density of the iron meteorites, whereas we today think that the density of the core may be more that 12 g/cm^3!

Emil Wiechert
(1861-1928)

To summarize: When the twentieth century opened, we still had only a very vague idea of the internal structure of the globe. It was in the first three decades of the twentieth century that the picture was greatly clarified owing to the developments in seismology.

Seismology is the science of earthquakes (and similar phenomena). Today we can perhaps define it as the science of elastic waves in rocky planets (as we now also do seismology on the Moon!)

How has seismology helped us to understand the interior of the earth?