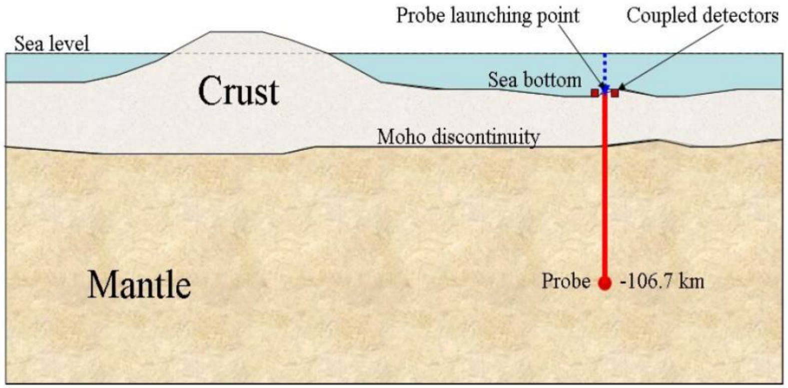
Self-sinking capsules to investigate Earth's interior



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Reaching the Mantle Frontier: Moho and Beyond,
September 9 – 11, 2010, The Carnegie Institution of Washington

Introduction

Our knowledge of the composition and structure of the Earth's interior through direct observation and sampling is limited to the uppermost 12 km.

The top 2 to 3 km of the crust have been sampled extensively at outcrop, by excavations, mines and boreholes.

From 3 to 12 km sampling is restricted to a handful of very deep boreholes.

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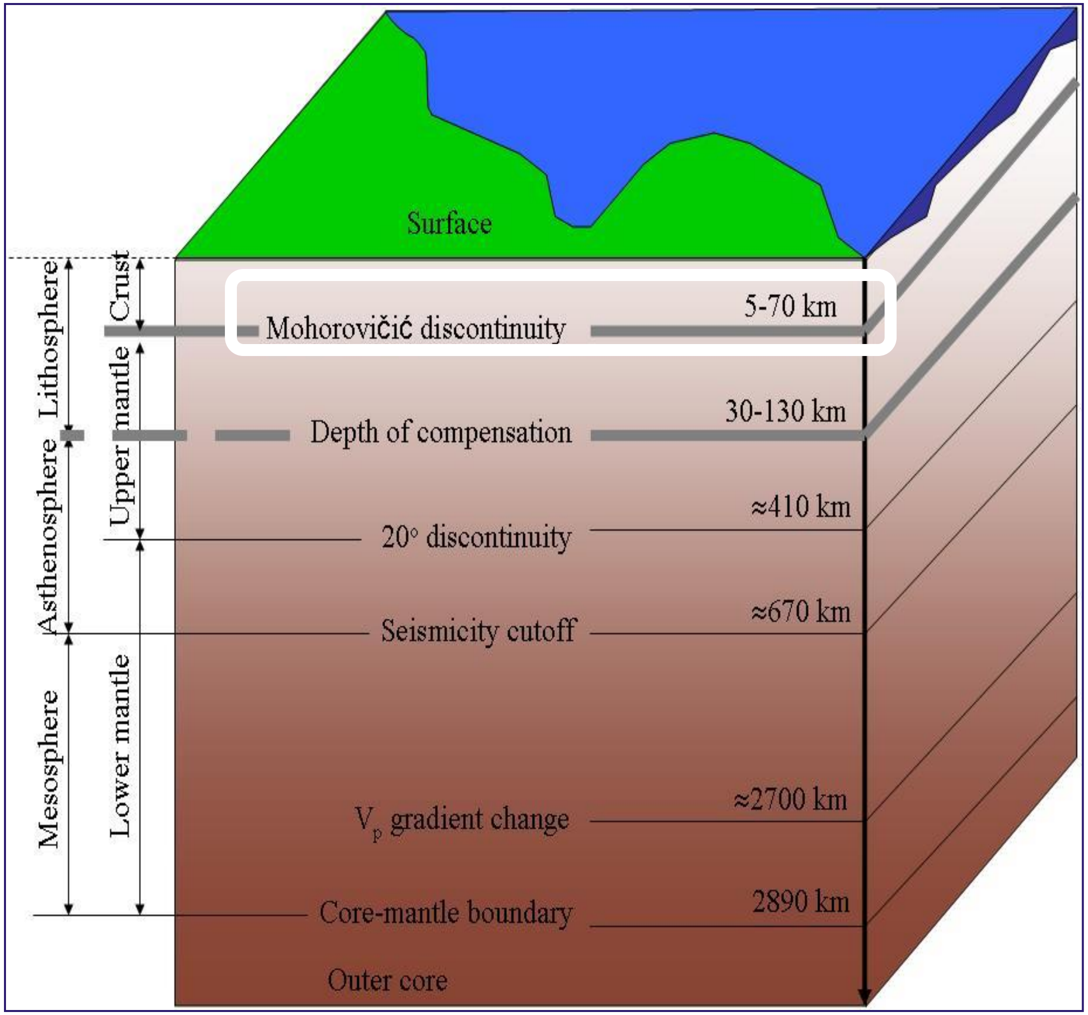
Chemically, the Earth can be divided into the crust, mantle (upper and lower), outer core, and inner core.

By material strength, the layering of the earth is categorized as lithosphere, asthenosphere, mesosphere, outer core, and the inner core.



Principal layers of the Earth (after Jordan 1979).

Probing the Earth's interior

Indirect Methods	Relevance to mantle
Extra-terrestrial materials	Chondrites, Moon
Asteroids	Sample return mission (*Hayabusa*)
Exhumed samples	Ophiolites, Xenoliths, Kimberlites, Exposures
Laboratory experiments	Mantle condition reproduction
Computer simulations	Evolution, convection, plate tectonics, plumes
Remote sensing	
Seismic waves	Mohorovičić discontinuity, mantle structure
Geoid/Gravity	Density
Geoelectromagnetism	Origin of magnetic records, electrical conductivity
Heat flow	Temperature distribution
Muon/geoneutrino	

Attempts to Reach the Pristine Mantle

A source of information for personal use in preparation for the International Workshop on "Reaching the Mantle Frontier; Moho and Beyond" September 9-11, 2010.

Records

Deepest drill hole: Kola SG-3 12,262 m (1970-1989)

Deepest scientific hole in ocean: 2,111 m Eastern equatorial Pacific (Legs 69, 70, 83, 111, 137, 140, 148 Hole 504B, DSDP/ODP, 1979-1993)

Deepest water depth drilled for science: 5,968.6 m Mariana Basin (Leg 129 Hole 802A, ODP, 1989-90)

Deepest oil well in ocean: 10,685 m (1,259 m water depth) Deepwater Horizon (BP)

Deepest water depth drilled for oil: 3,051 m Gulf of Mexico (Chevron)

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Attempts to Reach the Pristine Mantle

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Direct *in situ* deep sampling attempts

Through ocean floor

1) The Mohole Project	1958-1966
2) DSDP-ODP (504B, 1256D +....)	1968-1983/1985-2003
3) IODP Riser Drilling	2003-2013

On land

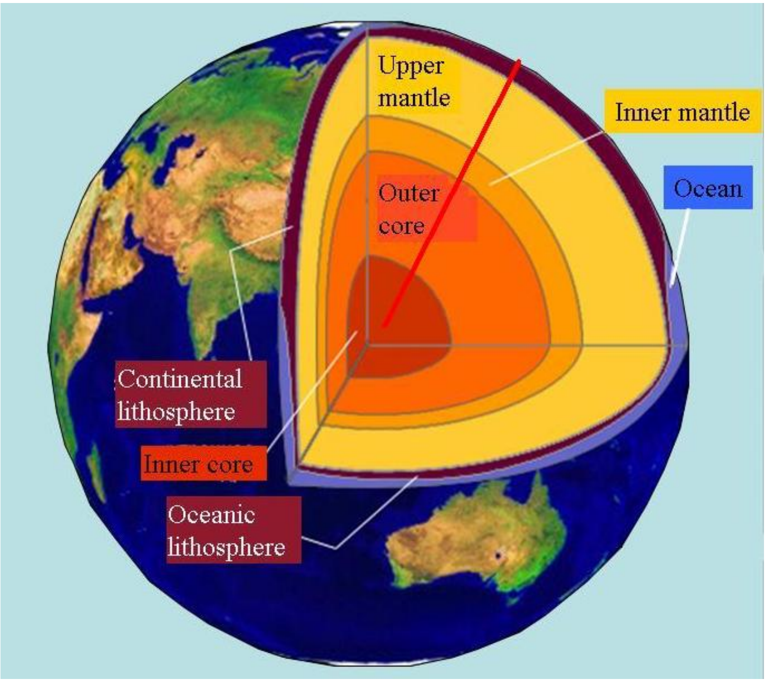
4) Soviet Kola Peninsula Drilling Project	1970-1989
5) Siljan Ring Project	1986-1987
6) KTB Deep Drilling Project	1990-1994
7) ICDP	1996-

Ideas

8) Self-sinking capsule ideas

Reaching Deep Earths Layers

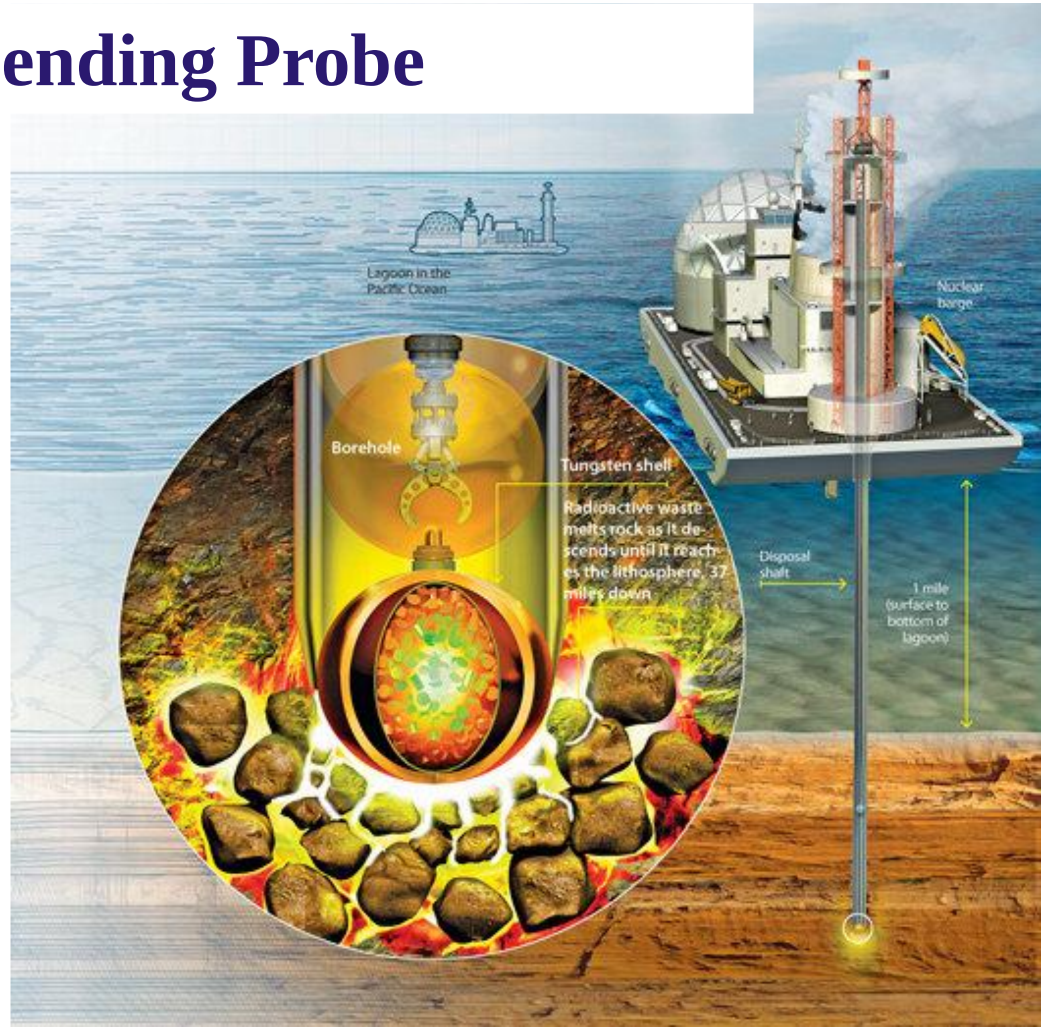
Stevenson (2003) proposed a "mission to the Earth's core" in which a small probe embedded in a huge mass of molten iron would descend along a crack propagating under the influence of gravity.



We have investigated the possibility of exploring the deeper reaches of the Earth's crust and upper mantle with a small, self-descending probe that melts the rocks and creates acoustic signals that could be detected at the surface, thus yielding information about the nature of the rocks through which the probe and the signals pass (Ojovan, Gibb, Poluektov and Emets 2005).

Self-Descending Probe

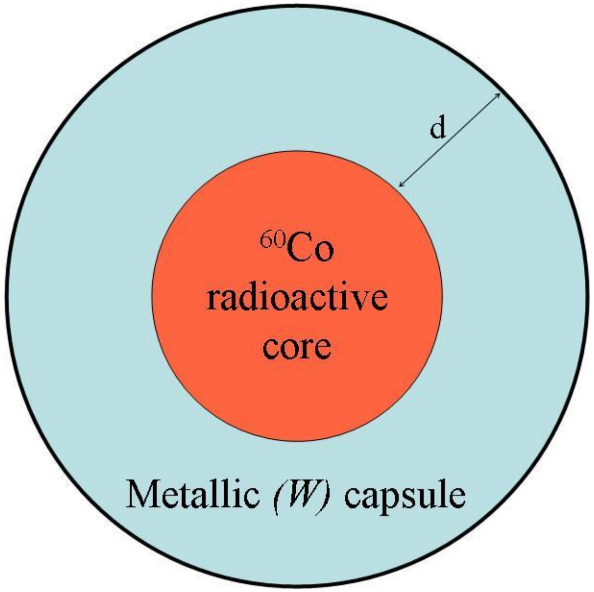
The self-descent of a spherical body by melting of the rock through which it passes has been considered in the contexts of nuclear reactor core melt down, the so-called "China syndrome" (Emerman and Turcotte 1983), and the deep self-burial schemes for nuclear wastes first proposed by Logan (Logan 1973; Kascheev *et al.* 1992; Byalko 1994).



The mechanism is simple. Heat from a source within the body partially melts the enclosing rock and the relatively low viscosity and density of the silicate melt allow it to be displaced upwards past the heavier body as it sinks (Emerman and Turcotte 1983). Eventually the melt cools and vitrifies or recrystallizes, sealing the route along which the body passed.

From a practical standpoint the probe needs to be small, dense, relatively inexpensive and spherically symmetrical to ensure an even distribution of temperature at its surface. In its simplest form it would consist of two concentric spheres with an outer diameter of less than, say, 1 m.

Ceramic materials, although suitably refractory, tend to be poor heat conductors and would overheat (Kosachevskiy and Sui 1999), thus limiting thermal loading of the probe and hence descent rates and ranges. The capsule should therefore be made of metal and we would propose tungsten (W). W melts at 3410ºC, has a specific gravity of 19.3, is relatively inexpensive and is predicted to have a low corrosion rate in silicate liquids at high temperatures and pressures and low oxygen fugacities.



The outer sphere, or capsule, needs to be made of mechanically strong, dense, refractory material. Its main functions are to protect the inner sphere (the heat source), conduct the heat efficiently to the outer surface of the probe and provide weight.

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For the inner sphere, or heat source, we would propose ^{60}Co metal with a total initial activity of at least 3.85×10^{18}Bq (104 MCi).

Table 1. Radiogenic heat parameters of radionuclides

Radionuclide	Half-life, $T_{1/2}$, y	Specific activity*, A, Ci/g	Q factor, mW/Ci	Specific heat release, Q_m, kW/kg
^{60}Co	5.27	1130	15.4	17.4
^{90}Sr	28.5	136	1.16	0.158
^{134}Cs	2.06	1294	10.19	13.2
^{137}Cs	30.17	86.9	6.96	0.61

*1 Ci=3.7 10^{10} Bq (disintegrations per second).

^{60}Co is chosen because it has a high specific heat generation, yields a solid daughter decay product (^{60}Ni) and is readily available from the spent sealed radioactive sources (SRS) widely used in industry, medicine and research. Deep self-burial of SRS has been proposed as a means of safely disposing of them (Ojovan and Gibb 2005).

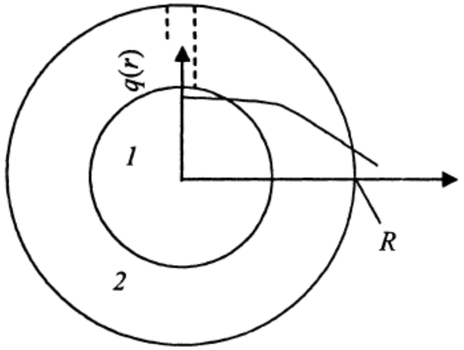

Fig. 1. Form of a self-sinking capsule: *1*) active material; *2*) capsule; *q*(*r*) – distribution of heat sources in the capsule.

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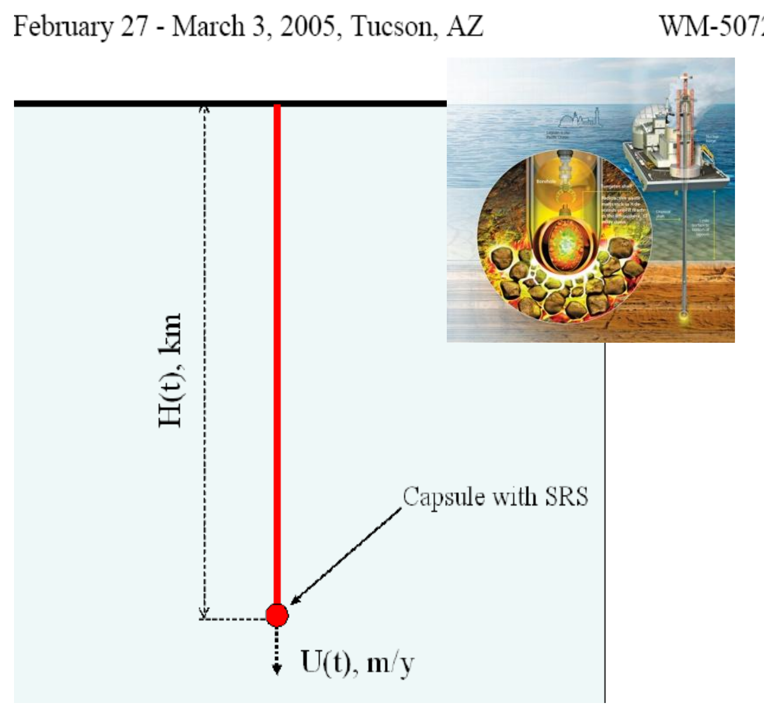
The probe would have to be launched from a reasonably close-fitting, large-diameter borehole or small shaft. Depending on the local near-surface geology this could be anything between a few tens and a few hundreds of metres deep.

Initial heating and melting of the rocks would probably be accompanied by some surface emission of steam as groundwater evaporated but this would soon cease as the probe attained greater depths with higher hydrostatic and lithospheric pressures and the passage became sealed by vitrified or recrystallized rock.



Transport of the completed probe to the launch site would require (radiation) shielding and refrigeration. As an alternative, only the heat source requires special transport arrangements and it could be loaded into the capsule, which is then welded closed, on site immediately prior to launch.

Descent Rates

The descent rates and ultimate depth range are largely functions of the initial design parameters of the probe.

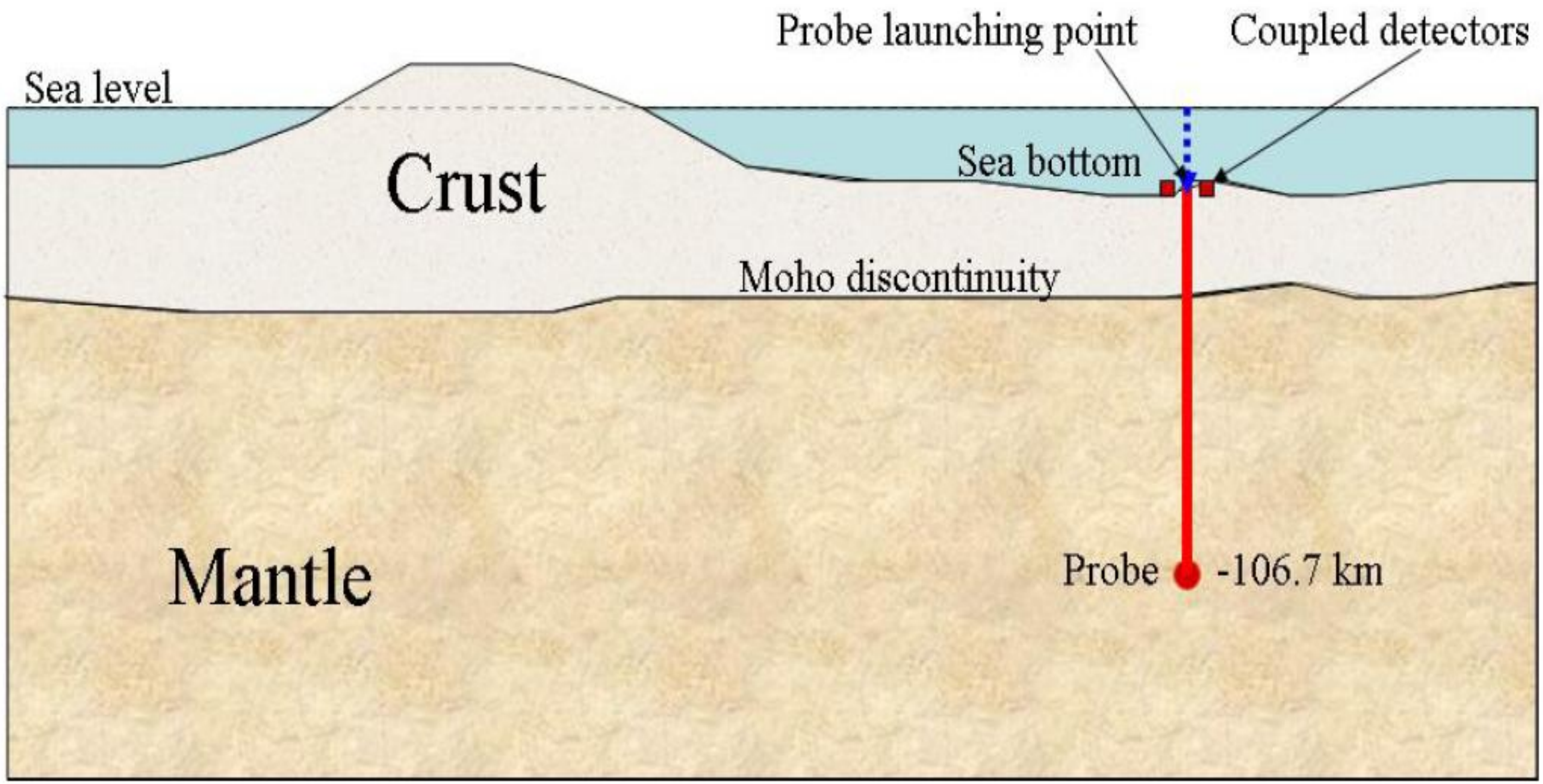


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Table 2. Parameters used in modelling descent through oceanic lithosphere

Depth D (km)	Rock type	Pressure P (kbar)	Temperature (Ambient), (°C)	Density ρ (kg/m^3)	Thermal conductivity λ (W/m, °K)	Heat capacity C_p (J/kg, °K)	Heat of fusion L (J/kg)	Thermal diffusivity K (m^2/s)	Solidus T_S (°C)	Liquidus T_L (°C)
0	Basalt	0.001	25	2900	1.590[b]	782[c]	307730[b]	$7.013\ 10^{-7}$	1079	1358
7	Basalt	1.930	128	2900	1.590[b]	895[c]	307730[b]	$6.126\ 10^{-7}$	1114	1370
7	Peridotite	1.930	128	3234[a]	3.389[b]	895[c]	383734[b]	$1.171\ 10^{-6}$	1134	1721
30	Peridotite	8.250	464	3234[a]	3.138[b]	982[c]	420669[b]	$9.881\ 10^{-8}$	1200	1772
100	Peridotite	27.500	1256	3234[a]	2.720[b]	~1067[c]	509324[b]		1453	1901
145	Peridotite	40.000	1544	3234[a]	3.222[b]	???	566893[b]		1628	1958

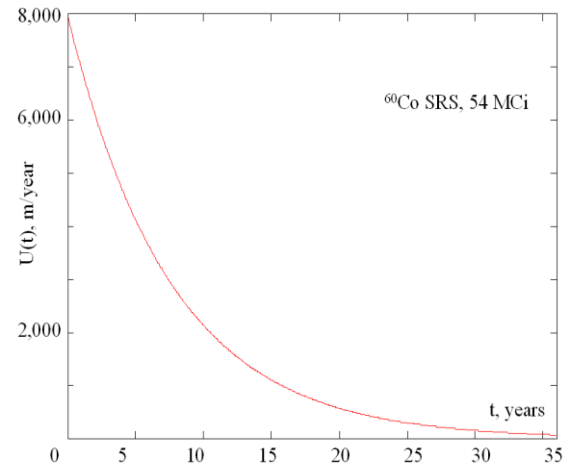
a = data from (Clark Jr. 1966);
b = data from (Yoder 1976);
c = data corrected for ambient temperature from Fig.4a of (Vorsteen & Schellschmidt 2003);
T_S & T_L from various sources (anhydrous melting).

Table 3. Descent of probe through oceanic lithosphere

Depth range (km)	Rock type	Threshold power q_{th} (W/m^3)	Initial velocity U_0 (m/y)	Descent time (y)
0 – 7	Basalt	24566	16934	0.43
7 – 30	Peridotite	56804	11296	2.80
30 – 100	Peridotite	34322	9955	22.40
100 -106.7	Peridotite	18878	999	39.10

The initial descent through the basaltic layer is remarkably rapid.

At just under 2 m/hour this is comparable with conventional rotary drilling of scientific boreholes.



The probe would reach the Mohorovicic discontinuity in 5.1 months.

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Table 4. Parameters used in modelling descent through continental lithosphere

Depth	Rock type	Pressure	Temperature	Density	Thermal conductivity	Heat capacity	Heat of fusion	Thermal diffusivity	Solidus	Liquidus
D (km)		P (kbar)	Ambient, (°C)	ρ (kg/m^3)	λ (W/m, °K)	C_p (J/kg, °K)	L (J/kg)	K (m^2/s)	T_S (°C)	T_L (°C)
0	Granite[h]	0.001	25	2600	3.400[d]	782[c]	290000[f]	1.672 10^{-6}	959	1089
10	Granite[h]	2.750	100	2600	2.900[d]	870[c]	290000[f]	1.282 10^{-6}	977	1118
10	Schist[i]	2.750	100	2610	3.405[d]	868[c]	290000[f]	1.503 10^{-6}	977[f]	1118[f]
17	Schist[i]	4.650	183	2610	2.995[d]	926[c]	290000[f]	1.239 10^{-6}	995[f]	1140[f]
17	Metapelite[j]	4.650	183	2700	2.557[d]	926[c]	290000[f]	1.023 10^{-6}	995[f]	1140[f]
22	Metapelite[j]	6.000	242	2700	2.370[d]	955[c]	290000[f]	9.191 10^{-7}	1002[f]	1150[f]
22	Amphibolite[k]	6.000	242	2999[a]	2.698[d]	955[c]	307730[b]	9.420 10^{-7}	750[b]	1117[b]
27	Amphibolite[k]	7.400	300	2999[a]	2.082[d]	970[c]	307730[b]	7.156 10^{-8}	705[b]	1102[b]
27	Mafic granulite	7.400	300	2930[a]	1.992[b]	970[c]	385428[b]	7.010 10^{-8}	1162[e]	1426[e]
30	Mafic granulite	8.250	325	2930[a]	1.992[b]	982[c]	689592[b]	6.925 10^{-7}	1180[e]	1437[e]
30	Peridotite	8.250	325	3234[a]	3.138[b]	982[c]	420669[b]	9.881 10^{-8}	1180[e]	1884[e]
100	Peridotite	27.500	888	3234[a]	2.720[b]	~1067[c]	509324[b]		1402[e]	1963[e]
145	Peridotite	40.000	1168	3234[a]	3.222[b]	???	566893[b]		1561[e]	2016[e]

a = data from (Clark Jr. 1966); b = data from (Yoder 1976); c = data corrected for ambient temperature from Fig.4a of (Vorsteen & Schellschmidt 2003); d = values corrected for ambient temperature using equations 4 & 5 of (Vorsteen & Schellschmidt 2003); e = values from (Wyllie 1971); f = best available estimate.

h = Niznekansky granite (Petrov et. al. 2005); i = Bi-Musc-Kspar schist 14 of (Vorsteen & Schellschmidt 2003); j = Gnt-Bi-Musc orthogneiss 13 of (Vorsteen & Schellschmidt 2003); k = Gnt-Amph-Bi paragneiss 16 of (Vorsteen & Schellschmidt 2003). T_S & T_L from various sources (anhydrous melting except for amphibolite).

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Table 5. Descent of probe through continental lithosphere

Depth range (km)	Rock type	Threshold power q_{th} (W/m^3)	Initial velocity U_0 (m/y)	Descent time (y)
0 – 10	Granite	39350	22787	0.45
10 – 17	Schist	37920	20919	0.79
17 – 22	Metapelite	27567	19477	1.06
22 - 27	Amphibolite	24048	17737	1.34
27 - 30	Mafic granulite	26749	14772	1.55
30 -100	Peridotite	46290	9472	28.6
100 – 101.5	Peridotite	34279	312	34.6

The results of the modelling indicate that the initial sinking through the granitic upper crust is over 30% faster than through the oceanic basaltic layer.

The probe would reach the mantle in just over a year and a half.

Thereafter it would attain a depth of 101.5 km before stopping after 34.6 years.

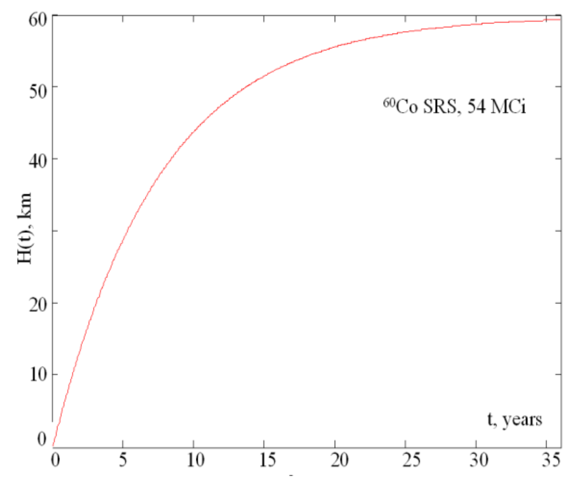


Table II. Self-burial parameters for spent SRS capsules.

Capsule radius R, m	Radionuclide	Initial activity, PBq (MCi)	Number of 2PBq SRS	Approximate volume occupied by SRS in capsule, L	Initial specific heat power q(0), kW/m^3	Total heat power Q, kW	Initial descent velocity U(0), m/y	Time of continuous descent τ, years	Maximum depth of penetration H(τ), km
0.50	^{60}Co	200 (5.4)	~100	~1-2	162	85	790	18.5	6
0.50	^{60}Co	2000 (54)	~1000	~10-20	1620	850	7900	36	60

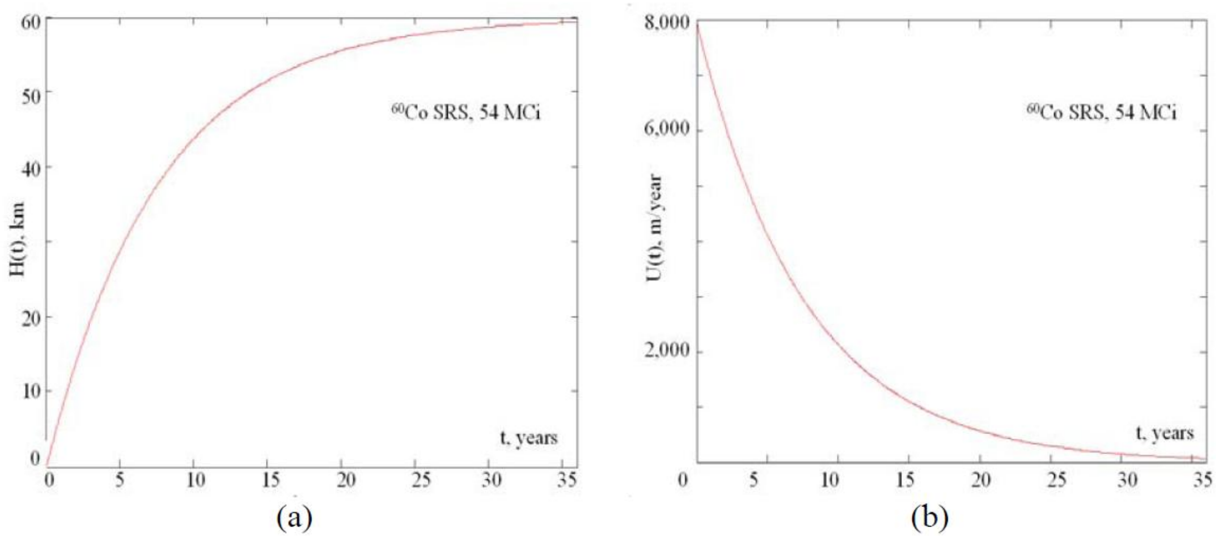
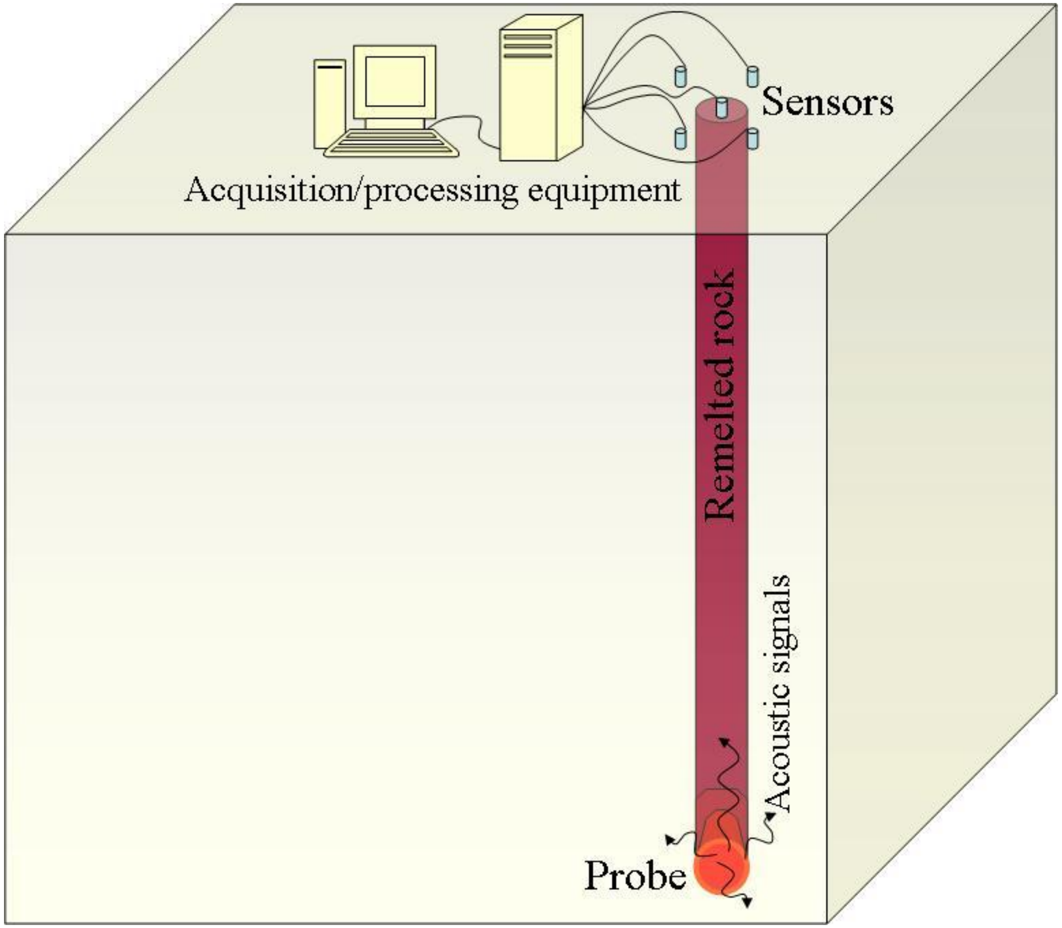


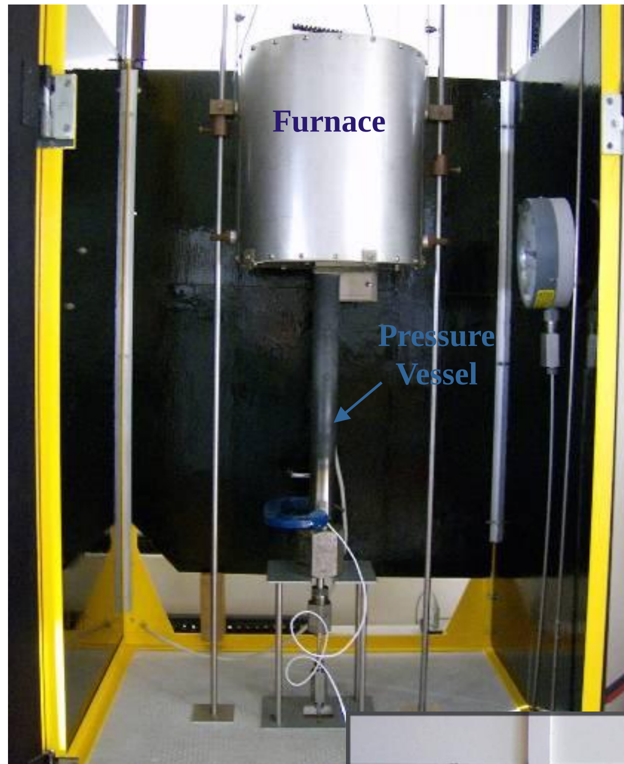
Fig. 3. Penetration depth (km) of a self-descending 50-cm radius tungsten capsule heated by ^{60}Co SRS (a) and the rate of self-burial (b).

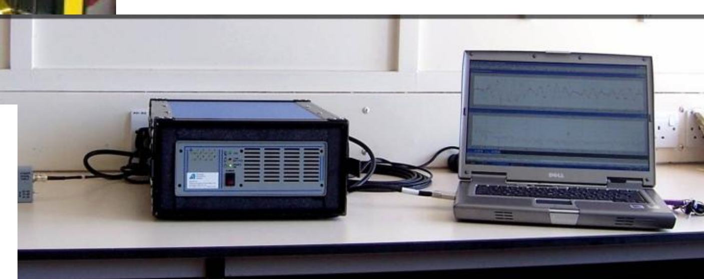
Acoustic Tracking

A few suitably positioned detectors continually monitoring the signals reaching the Earth's surface from the probe would provide data on the position and motion of the probe as well as the properties of the rocks through which it was sinking and through which the acoustic signals passed



Acoustic emission monitoring on melting-crystallization of granite





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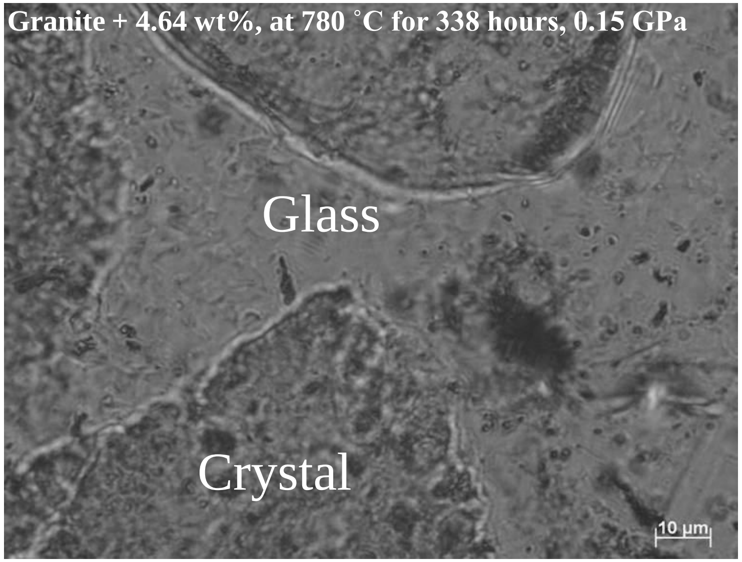
Characterisation of Partial Melting and Solidification of Granite E93/7 by the Acoustic Emission Technique

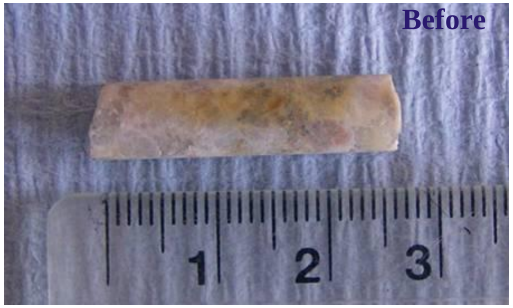
Lyubka M. Spasova, Fergus G.F. Gibb and Michael I. Ojovan

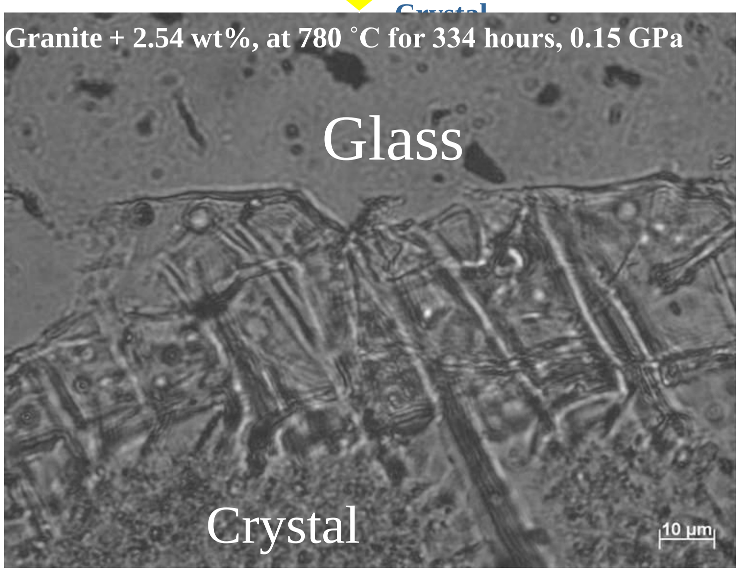
Melting and Solidification/Recrystallisation of Granite

Granite Powder



Solid Granite





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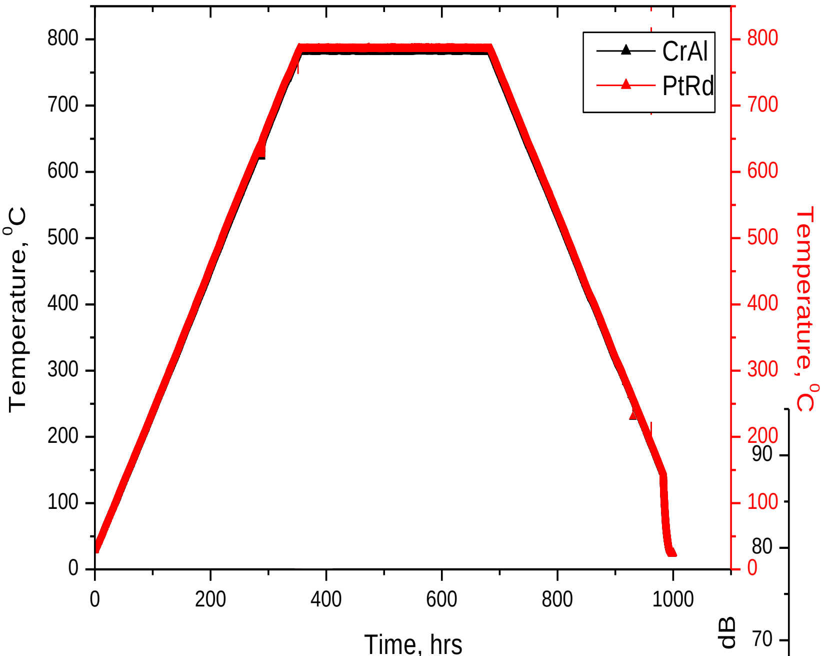
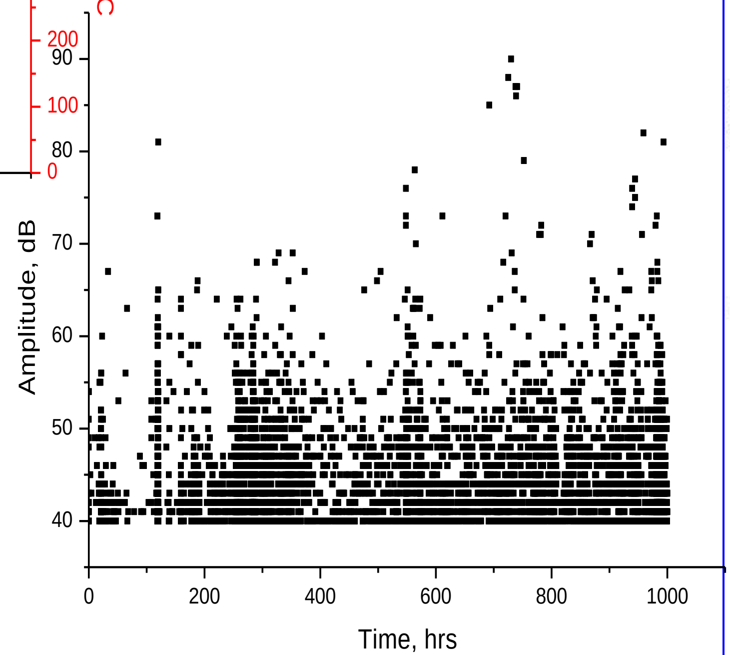
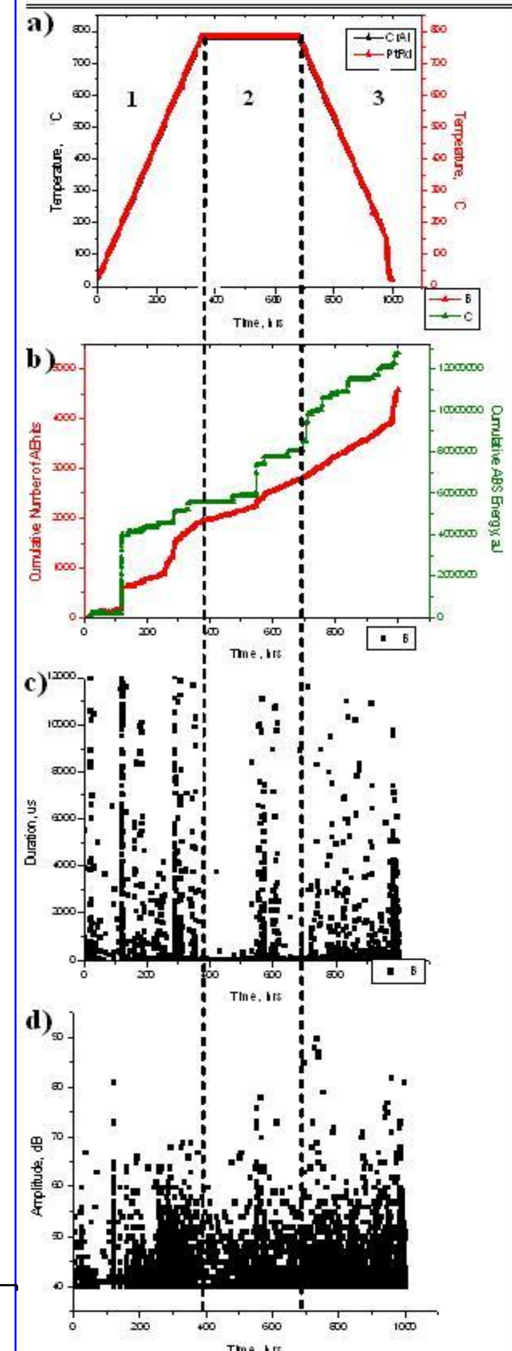
Solid Heating	Stage of Constant Temperature at	Cooling	Total Number of AE Hits
0 - 351.5 hours 1,838 hits	351.5 - 685.5 hours 778 hits	685.5 - 982 hours 1,234 hits	3850







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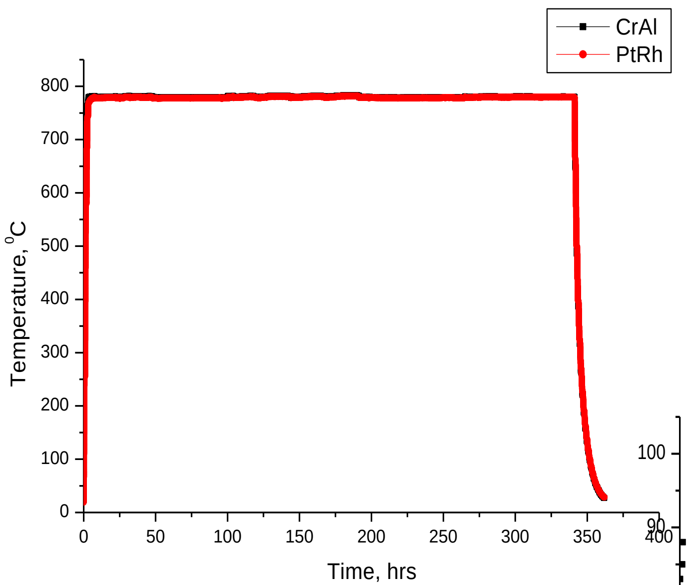
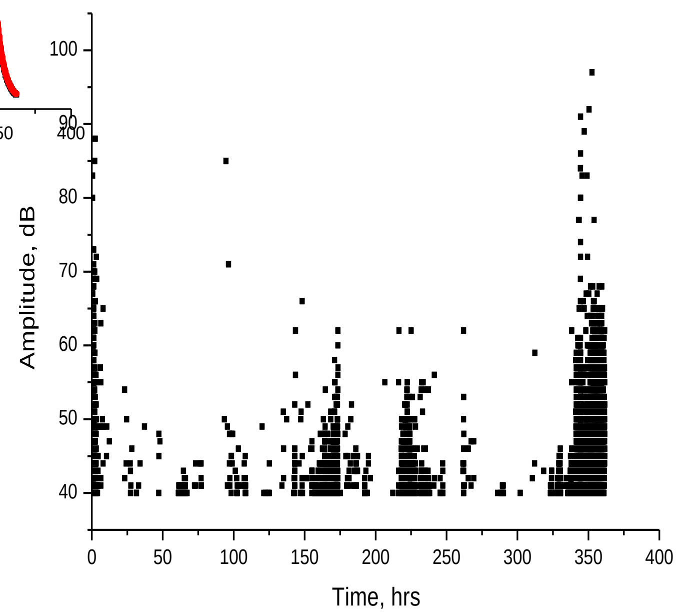
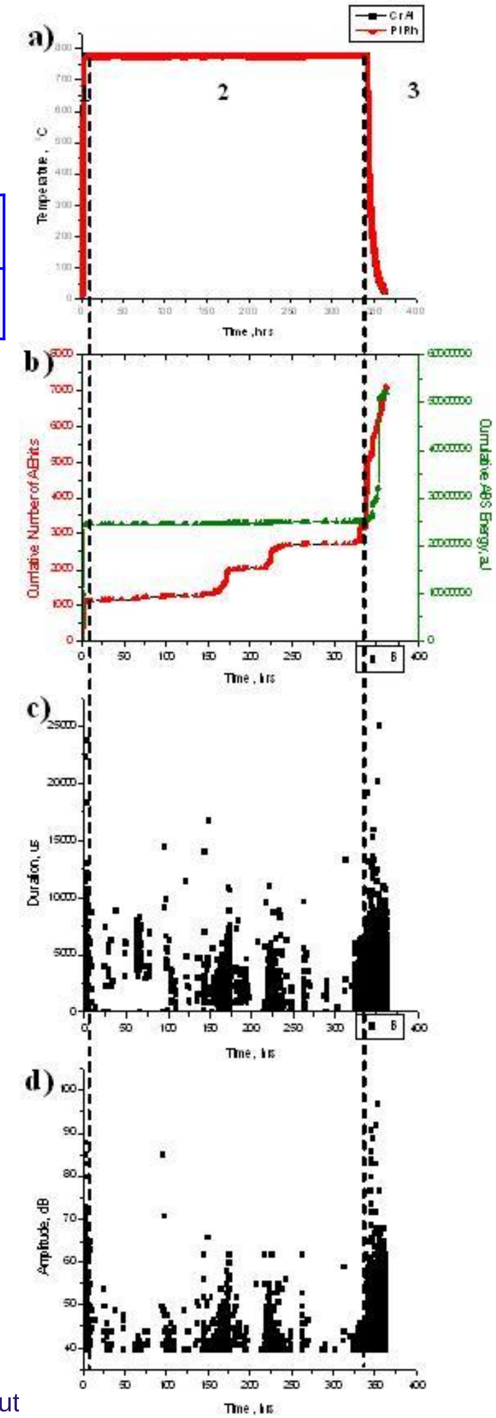
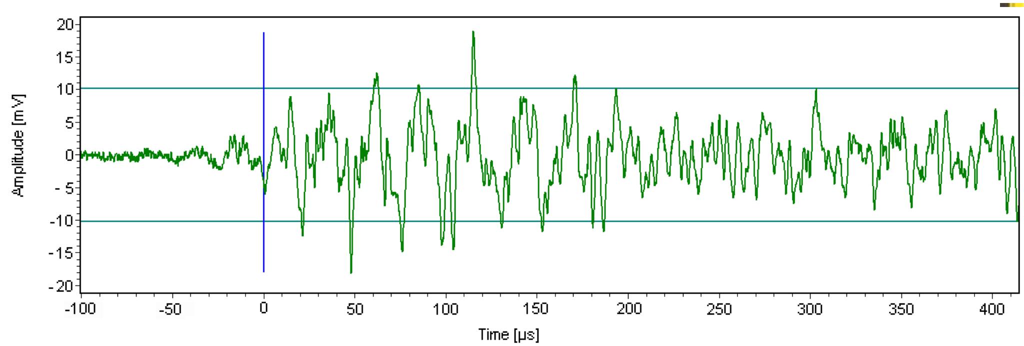
Powder Heating	Stage of Constant Temperature at 780°C	Cooling	Total Number of AE Hits
0 - 4 hours 1,111 hits	4 - 341.5 hours 3,964 hits	341.5 - 362 hours 2,058 hits	7,133

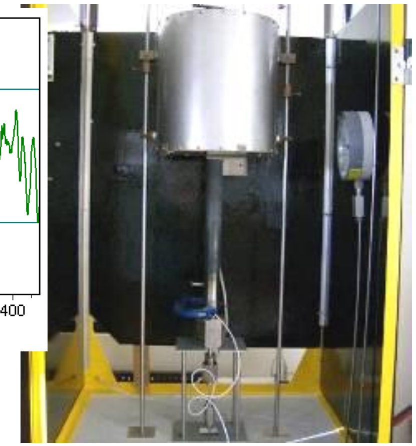


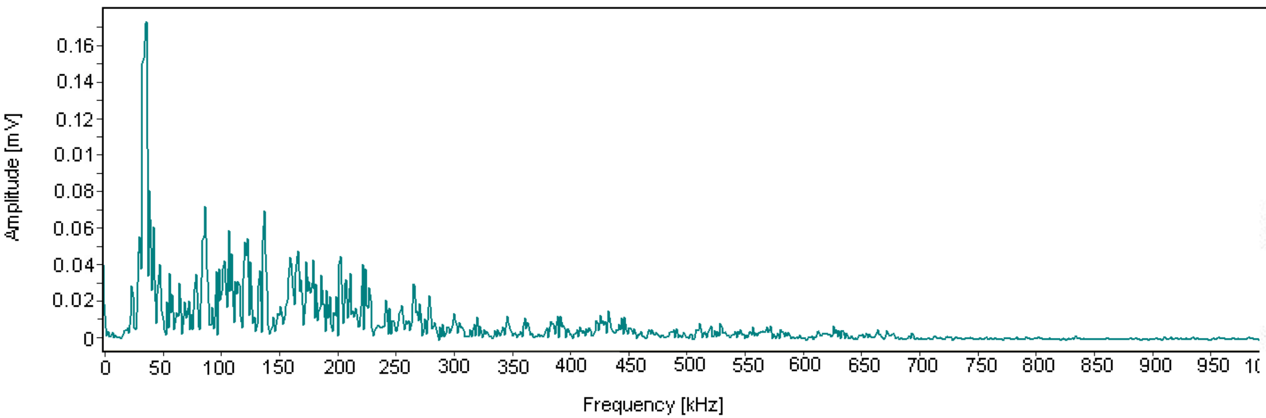


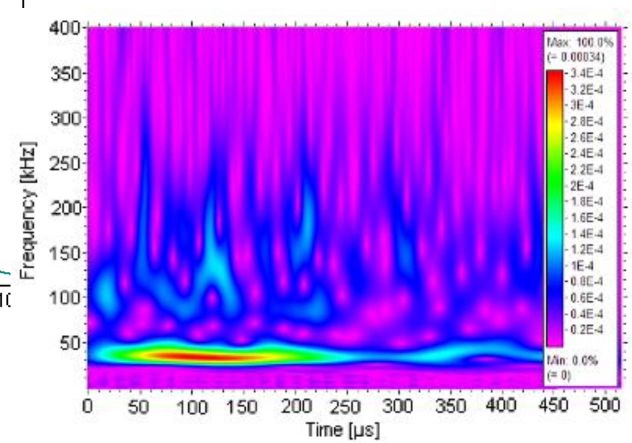


Melting of natural granite at 780ºC and 0.15 GPa is associated with acoustic signals.









The signals associated with the granite melting-crystallization were distinguished from the equipment noise on the basis of their primary frequencies of **39 kHz** and in the range between 101 and 300 kHz, particularly at 249, 244, 283, 205 and 112 kHz.

The melting of the solid granite is associated with characteristic acoustic signals of durations from a few µs to 30 ms and amplitudes from 40 to 78 dB.
On cooling, the processes of recrystallisation/solidification is associated by signals characterised by high primary frequency signals (between 501 and 800 kHz) with relatively low amplitudes between 40 and 55 dB and short durations (mainly <100 µs).

An issue for the remote detection of those AE signals is the attenuation over the large distance that they have to be transmitted. The amplitudes of the signals recorded from the granite samples in our experiments did not exceed 80 dB at a distance of <40 cm from the source.

Appropriate experimental assessment of the options for transmission of the generated AE signals, e.g., using waveguides and signal attenuation has to be conducted. For this purpose, the first step would be to use larger samples, which was not possible with the equipment available.

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Conclusions

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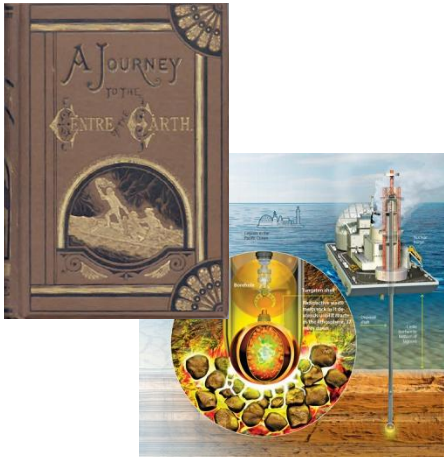
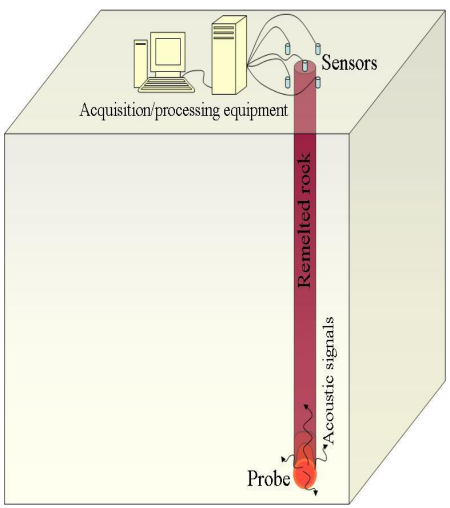


Small, spherical, heat-emitting probe could reach depths well in excess of 100 km below the surface of both oceanic and continental crust. Initial penetration of the crust would be very rapid and worthwhile depths in the mantle could be reached in ~35 years.



The acoustic signals generated during the melting and subsequent recrystallisation of the rocks through which the probe descends could be detected at the Earth’s surface. These signals could provide valuable information about the physical properties of the rocks and uniquely define the mineralogical and chemical compositions and other properties of the rocks.