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COMSOL Modeling of a Submarine Geothermal Chimney

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OUTLINE

- INTRODUCTION & MOTIVATION
- The Oil Peak: production vs. consumption.
- The need of diversified energy sources.

- DESCRIPTION OF A NATURAL PROCESS
- Energy transfer from the Earth's interior.
- Submarine Chimneys and thermal fluxes

- Using the FEM to estimate the transfer of thermal energy and Initial State of Submarine Reservoirs.

- CONCLUSIONS

MOTIVATION: The Oil Peak

- The world is consuming 86 M barrels of oil/day.

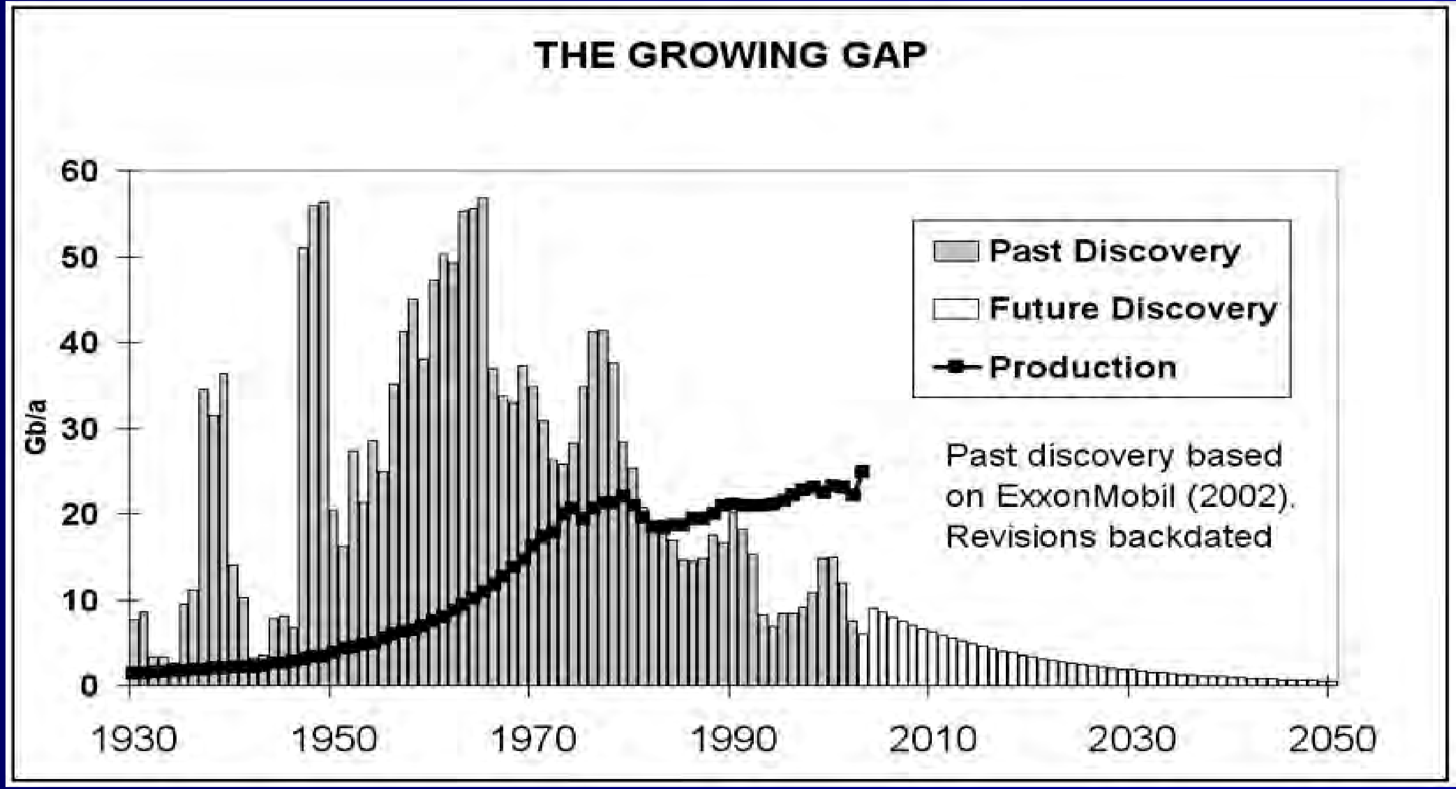
- Every year consumption grows by 1.5 MbOd.
  New oil province like Azerbaijan each year.
- Mexico’s production: 3.5 Mbod

- OPEC's Oil spare capacity: 10 Mbod in 1995.
- Today is only about 2 Mbod (2008).

- The world moved from a supply- led market to a demand- led one!

Motivation: The growing Gap

- There is no longer a safety margin to ensure price stability in the face of demand spikes and supply interruptions.



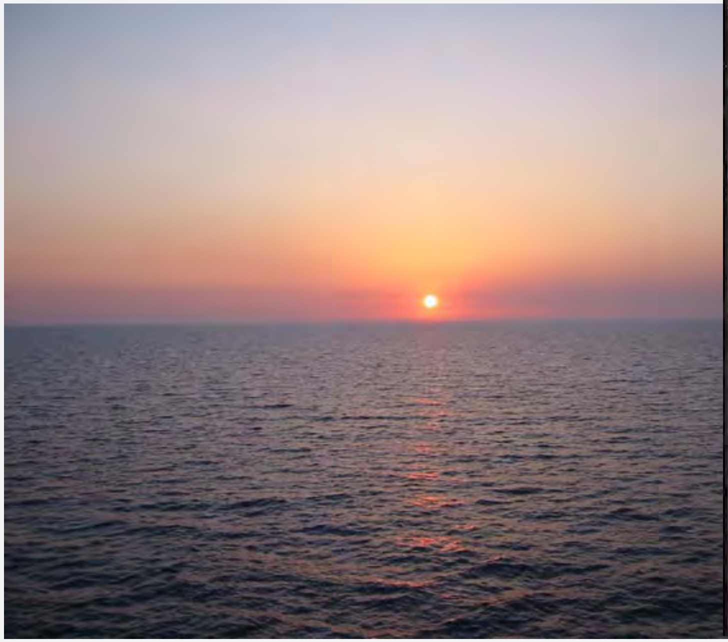
There is Demand for more Oil:

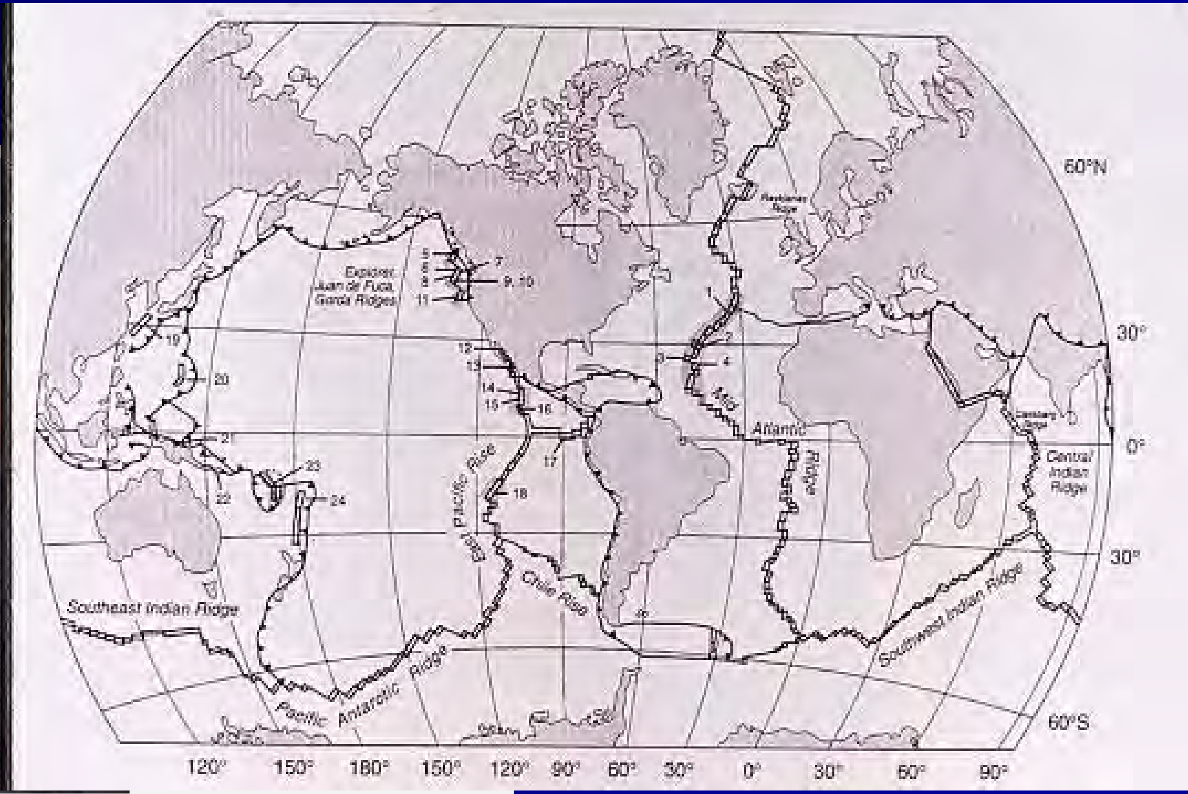
- **Today 50% of oil demand is for transportation.**
- Auto ownership in India and China is growing swiftly. By 2050 only these two countries could have 1.1 billion cars on the road.
- → Overwhelming increase in the need for automotive fuel:
- → **Limited Oil Supply + Increasing Demand = High Oil Prices**

The World Needs DIVERSIFIED ENERGY SOURCES

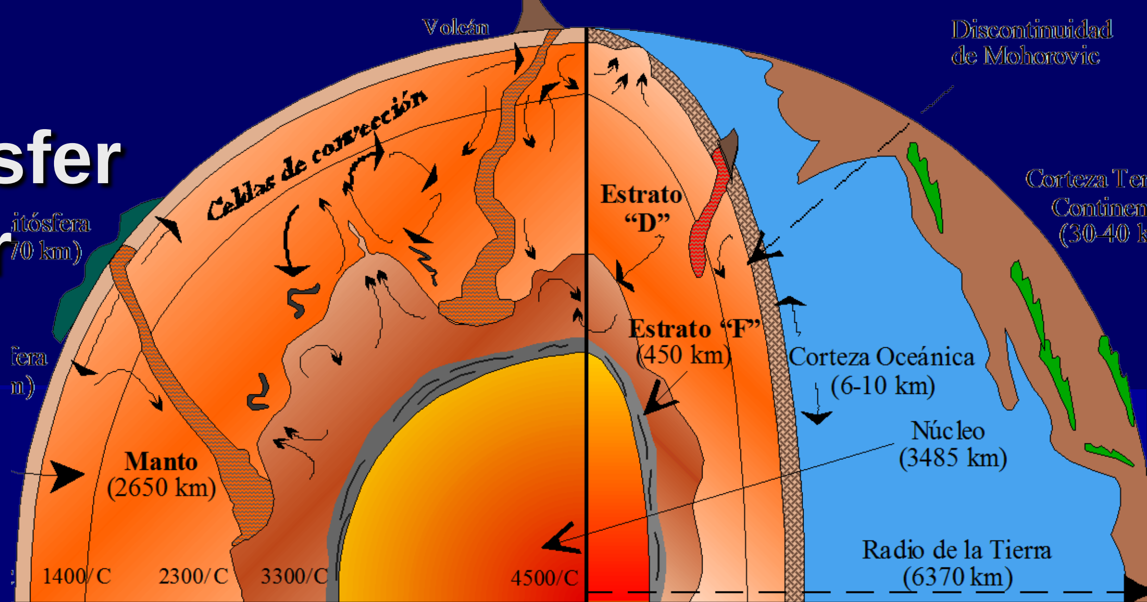
- **Energy transfer from the Earth’s interior.**
- **Submarine Chimneys and thermal fluxes**

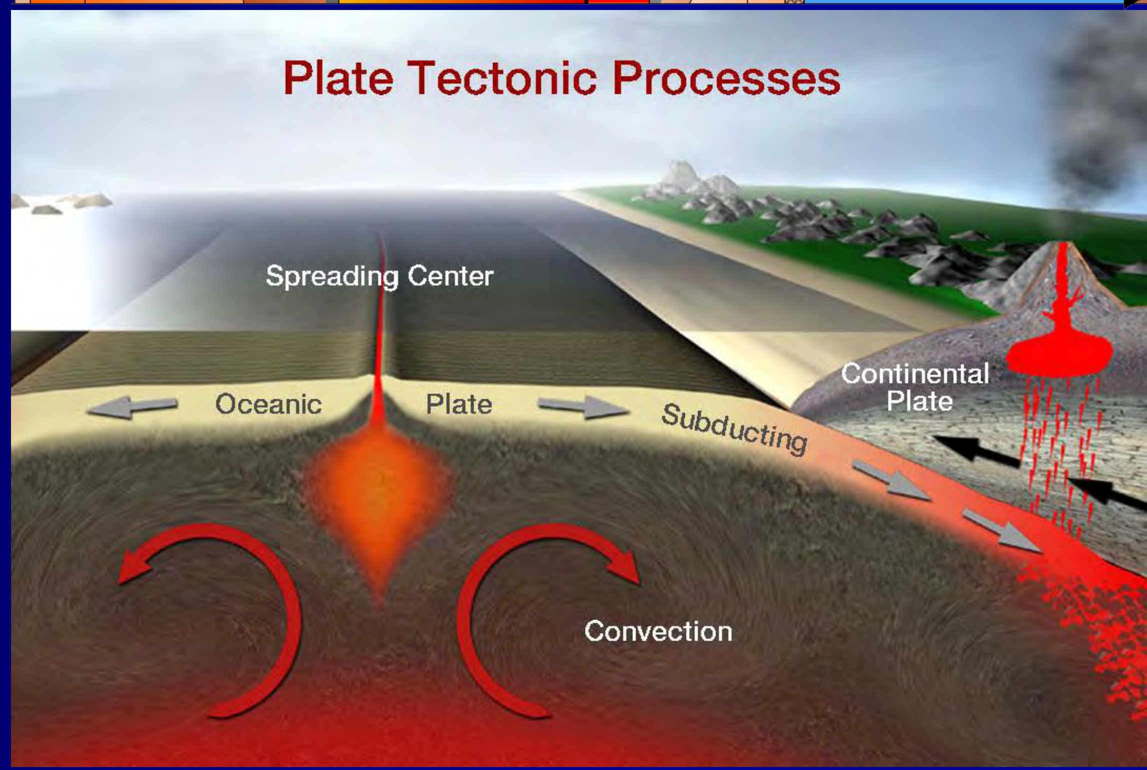
The oceans contain thermal energy because of the magmatic activity in the oceanic crust. They are a very important primary energy source.





Mass & energy transfer from Earth's interior is controlled by hydrothermal circulation at the deep ridges of the oceans.



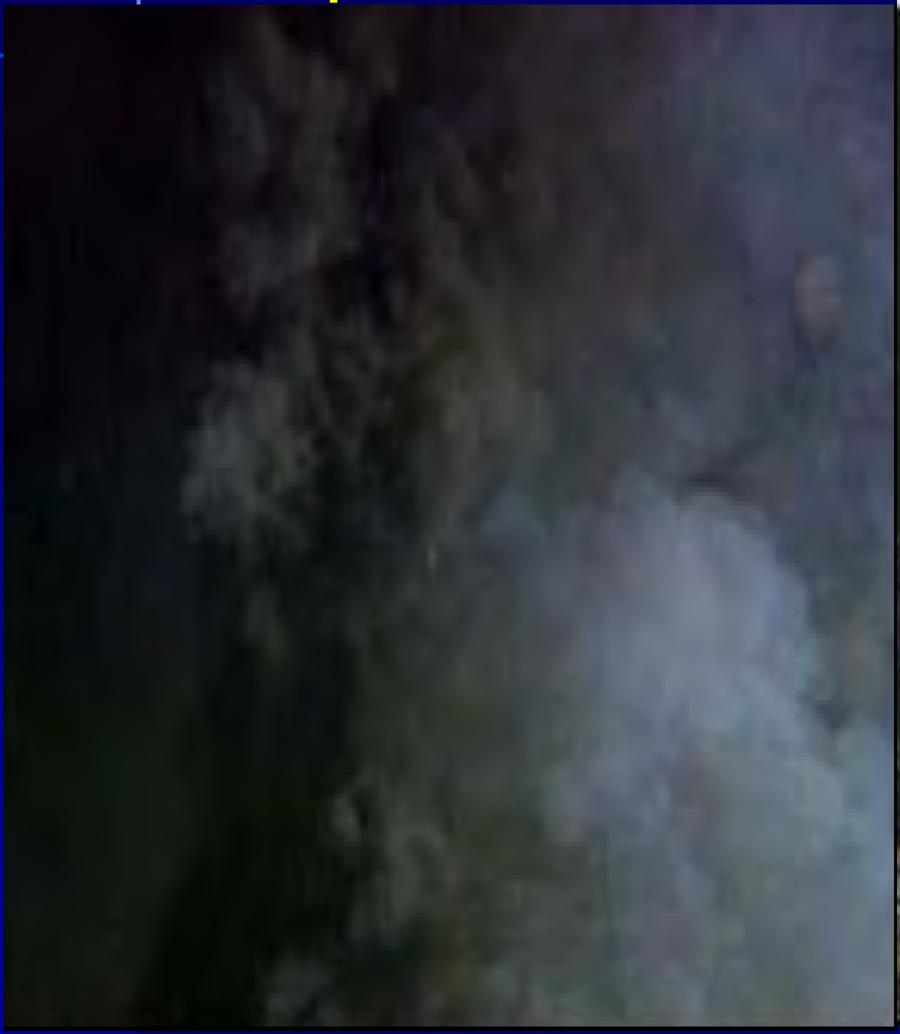


A Prototype of CS

- Submarine geothermics influence the composition of the oceanic crust and the chemistry of the oceans.
- Transfer of gases extends the influence of hydrothermal activity from the oceans to the atmosphere.
- The fluid circulating in seafloor hydrothermal systems is chemically altered at elevated temperature and pressure.
- The heated seawater containing H_2S is ejected upward through hydrothermal vents forming chimneys.

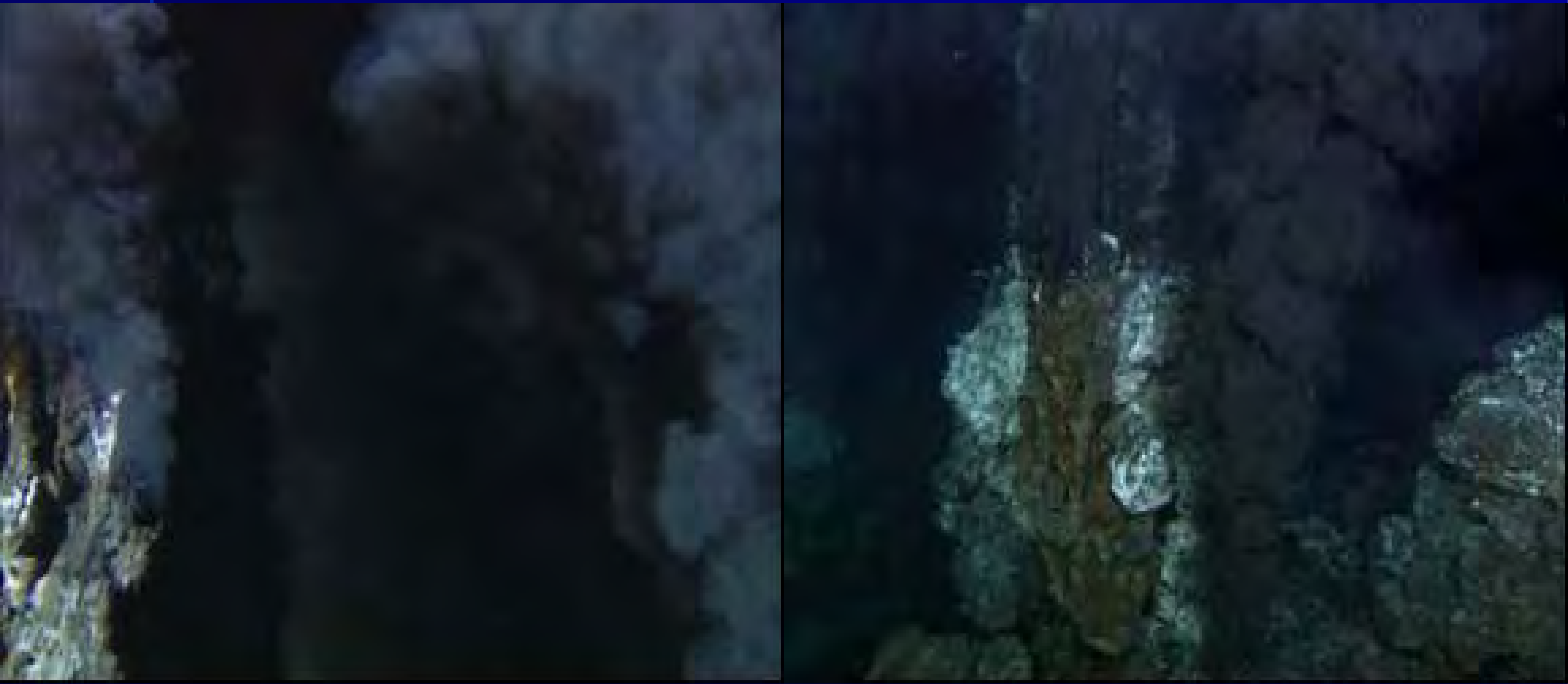
Formation of Submarine Chimneys

- First steps:



Formation of Submarine Chimneys

- Black smoker chimney walls are initially emplaced because of mineral dissolution mixed with seawater and precipitation within wall's pore spaces.



Formation of Submarine Chimneys

- There is deposition of Cu-Fe sulfide along the inside of the flow conduit. Height of a chimney: 5 – 60 meters!

A Prototype of CS

- This mechanism produces hydrothermal vent fields which support diverse and unique biological communities starting from microbial populations.
- Chemosynthetic bacteria use the H_2S as a metabolic source of energy forming food for other animals.
- These organisms are living at depths where there is no sunlight for photosynthesis.
- The understanding of mass and energy flows among all these complex subsystems requires integrated models that include their interactions.

Chemosynthetic bacteria use existent H_2S as a metabolic source of energy to form links of food for worms and other strange animals.

Tube Worms, fishes & many other bizarre creatures exist:




The most strange animals are found close to submarine chimneys:

Mathematical model of thermal flows.

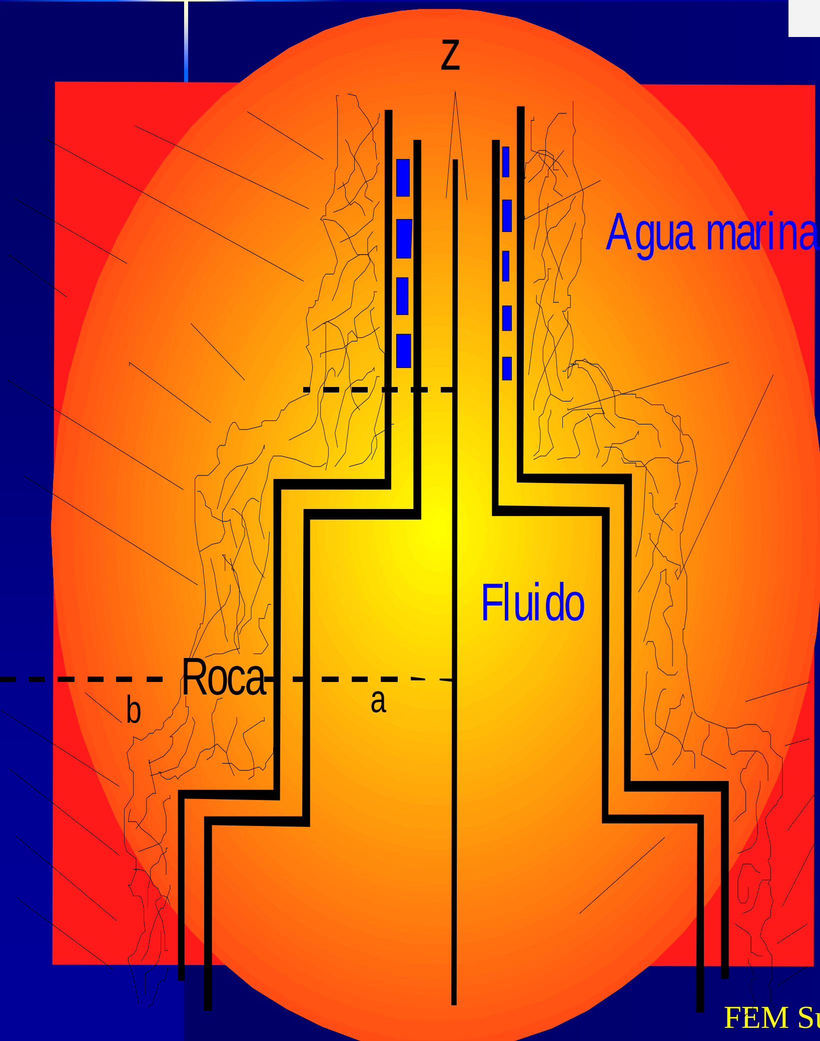
- **radial-vertical flow:**

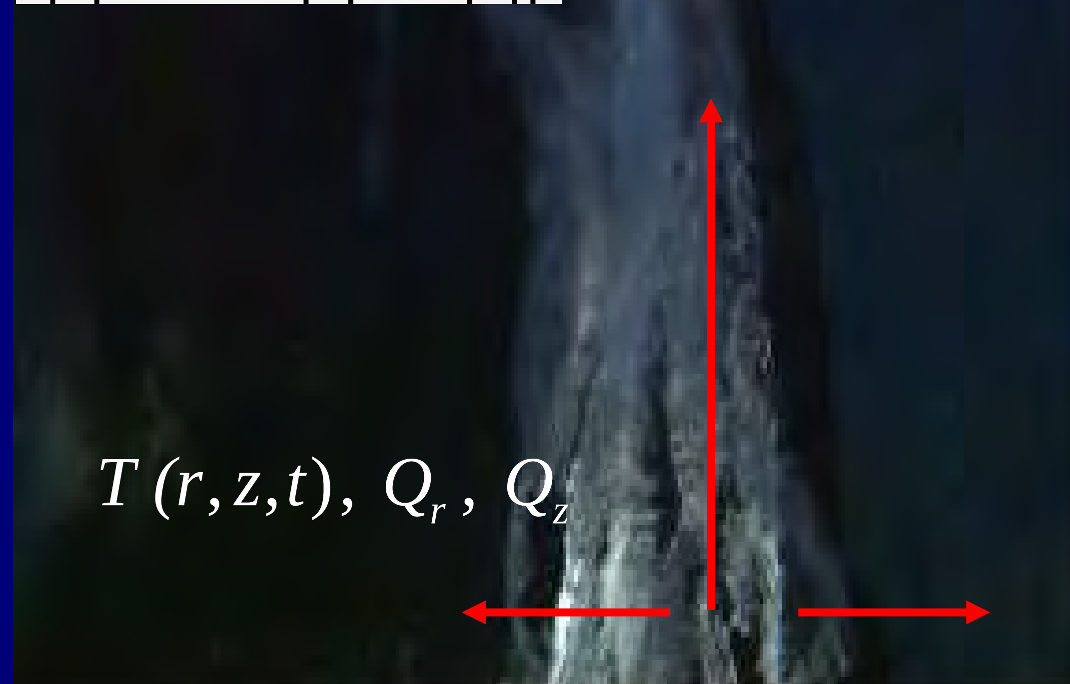
$$\nabla^2 T = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t}, \text{ in } \Omega$$

$$T(r, z, 0) = T_i(r, z)$$

$$T(r_a, z, t) = T_a(z)$$

$$T(r_b, z, t) = T_b(z)$$





Temperature at the chimney:

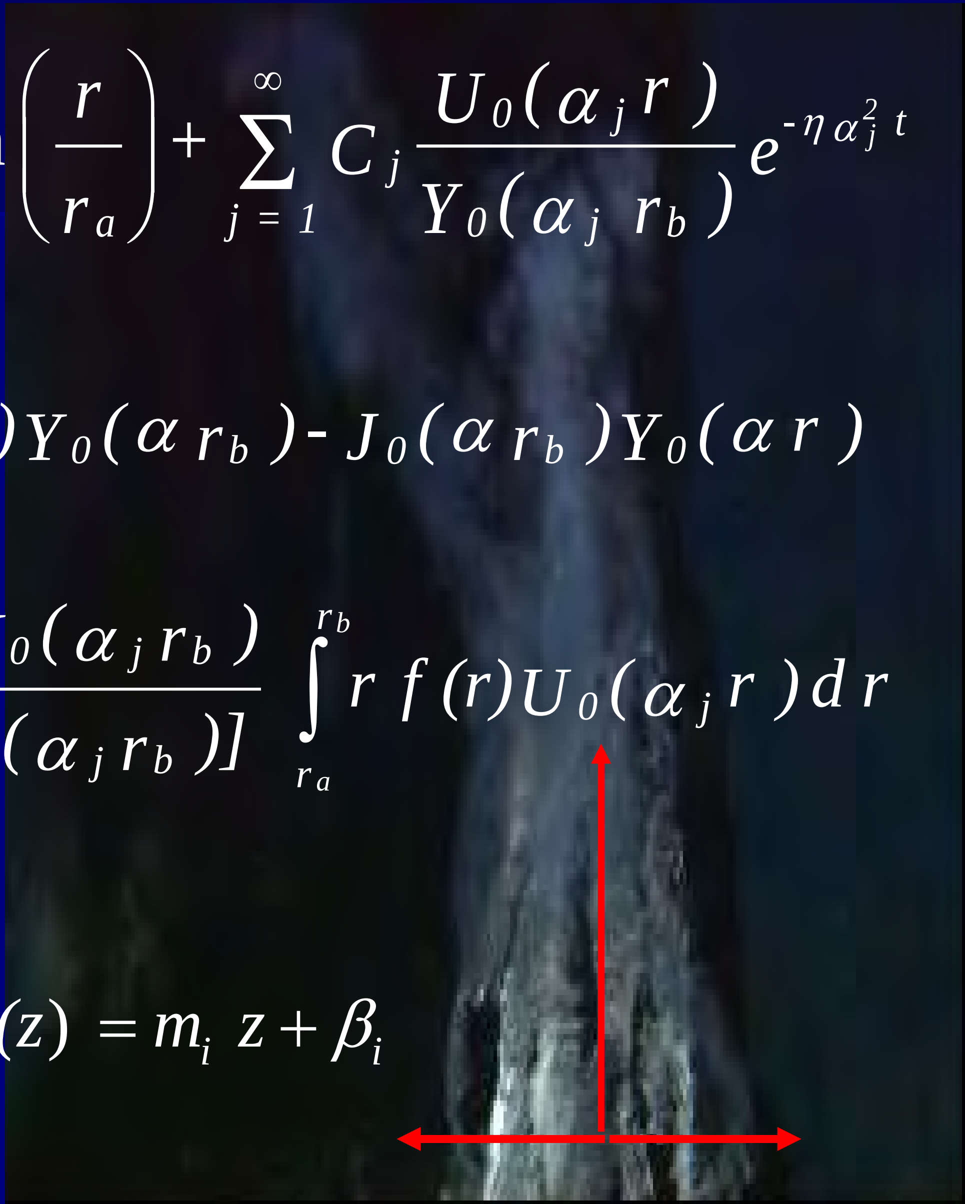
$$T(r,z,t) = T_a + \frac{T_b(z) - T_a(z)}{\mathrm{Ln}(r_b / r_a)} \,\mathrm{Ln}\left(\frac{r}{r_a}\right) + \sum_{j=1}^{\infty} C_j \frac{U_0(\alpha_j r)}{Y_0(\alpha_j r_b)} e^{-\eta \alpha_j^2 t}$$

- **where:** $U_0(\alpha r) = J_0(\alpha r) Y_0(\alpha r_b) - J_0(\alpha r_b) Y_0(\alpha r)$

$$C_j = \frac{\pi^2 \alpha_j^2 J_0^2(\alpha_j r_a) Y_0(\alpha_j r_b)}{2\left[J_0^2(\alpha_j r_a) - J_0^2(\alpha_j r_b)\right]} \int_{r_a}^{r_b} r\, f(r) U_0(\alpha_j r)\, dr$$

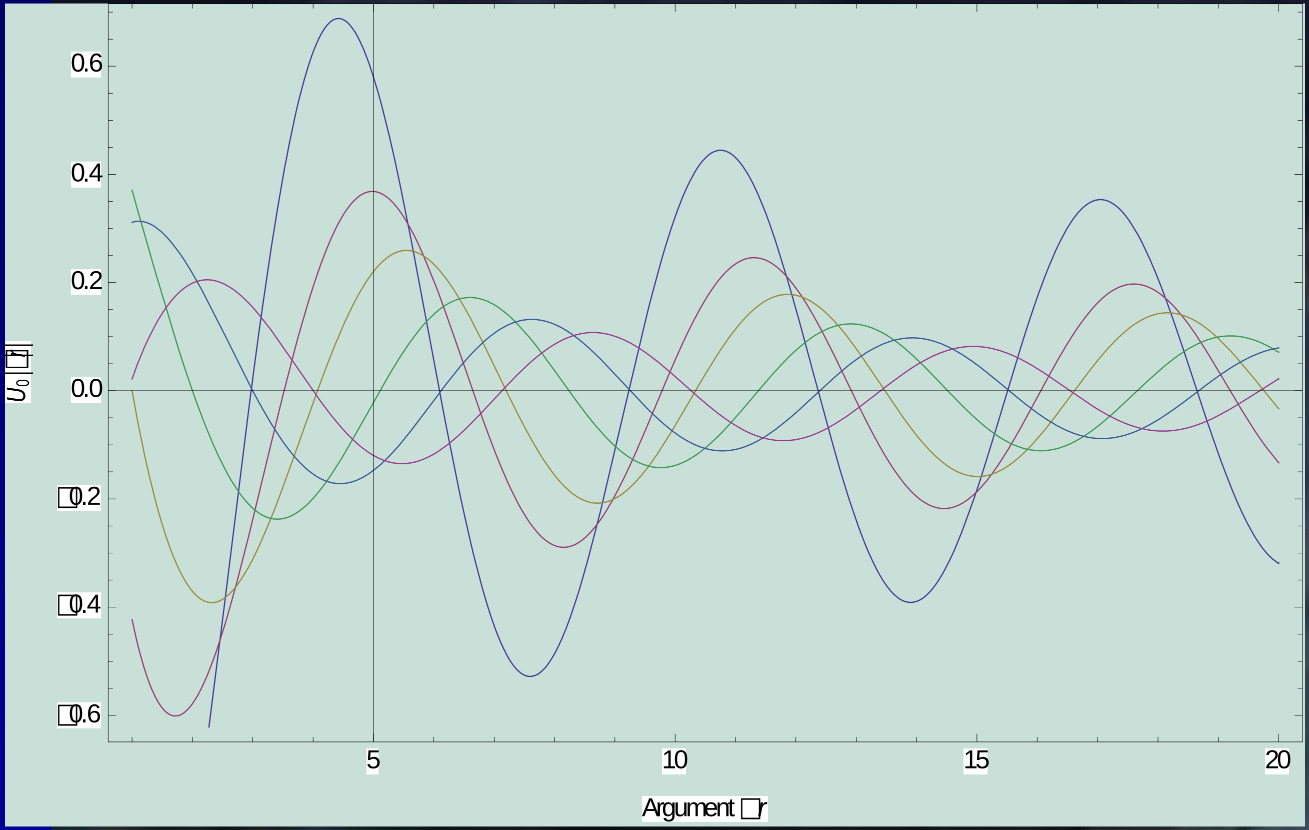
- $T_i = f(r)$ **is the initial condition.**

$$T_a(z),\ T_b(z) = m_i z + \beta_i$$



Cross product Bessel functions:

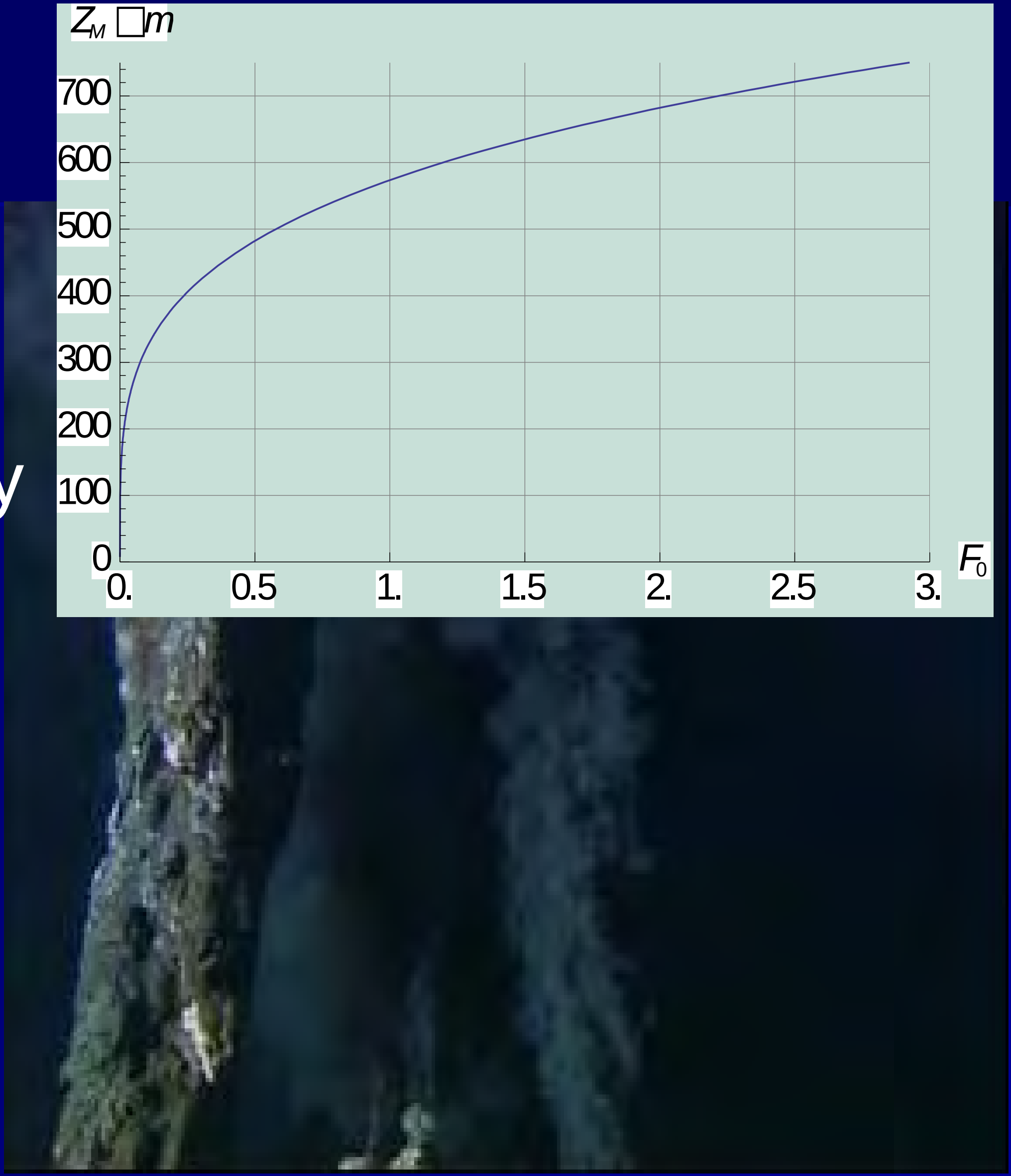
- Real roots of $\mathbf{U}_0$:



Natural chimneys discharge water at 350°C, 2600-3000 m depth.

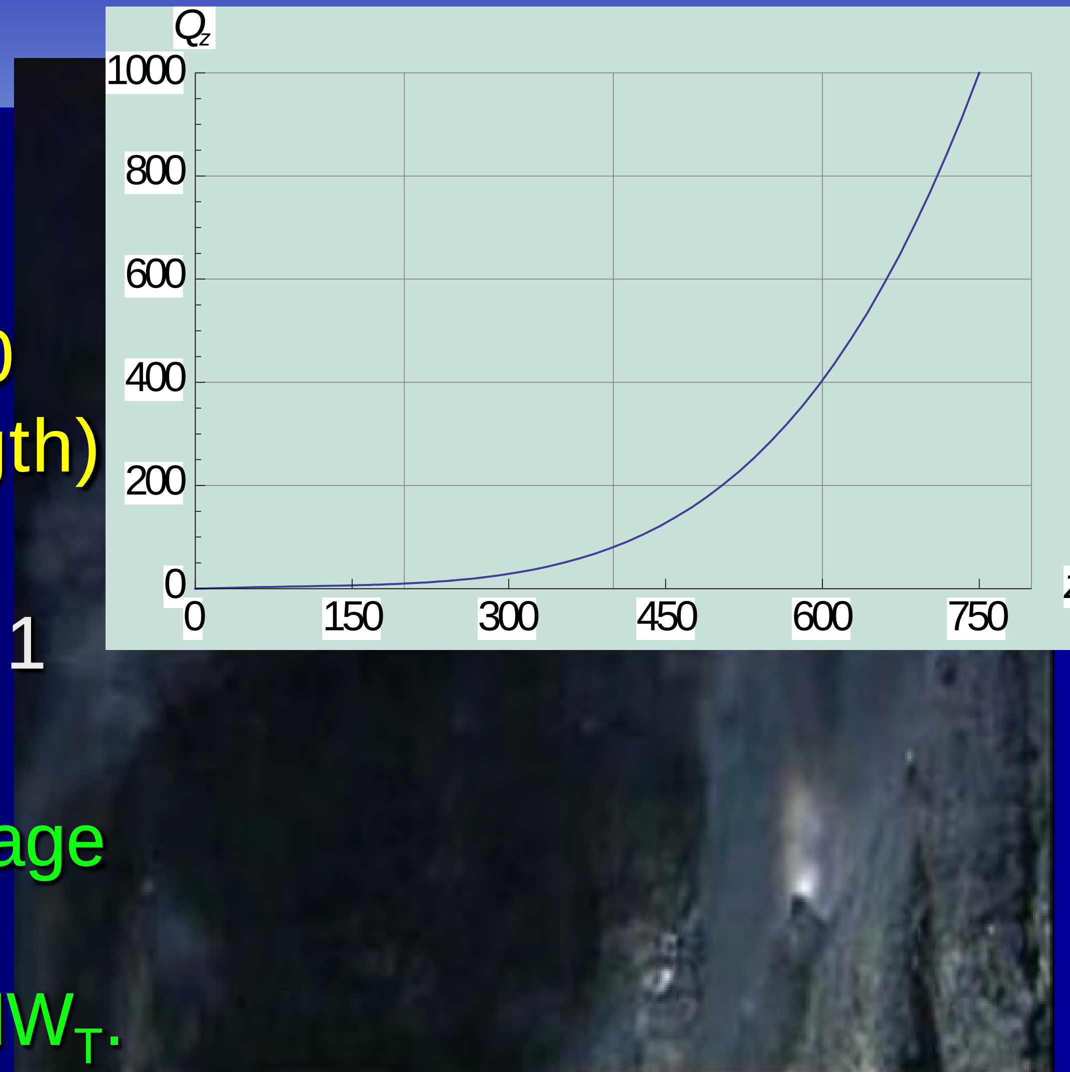
- The height of plumes is a function of the heat flux discharged by the chimney.

- A height of 370 m will correspond to a heat flux of about 60 MW_T.



The discharges remove about 30% of the heat lost from oceanic crust. Average value □1.5 W_T/m^2.

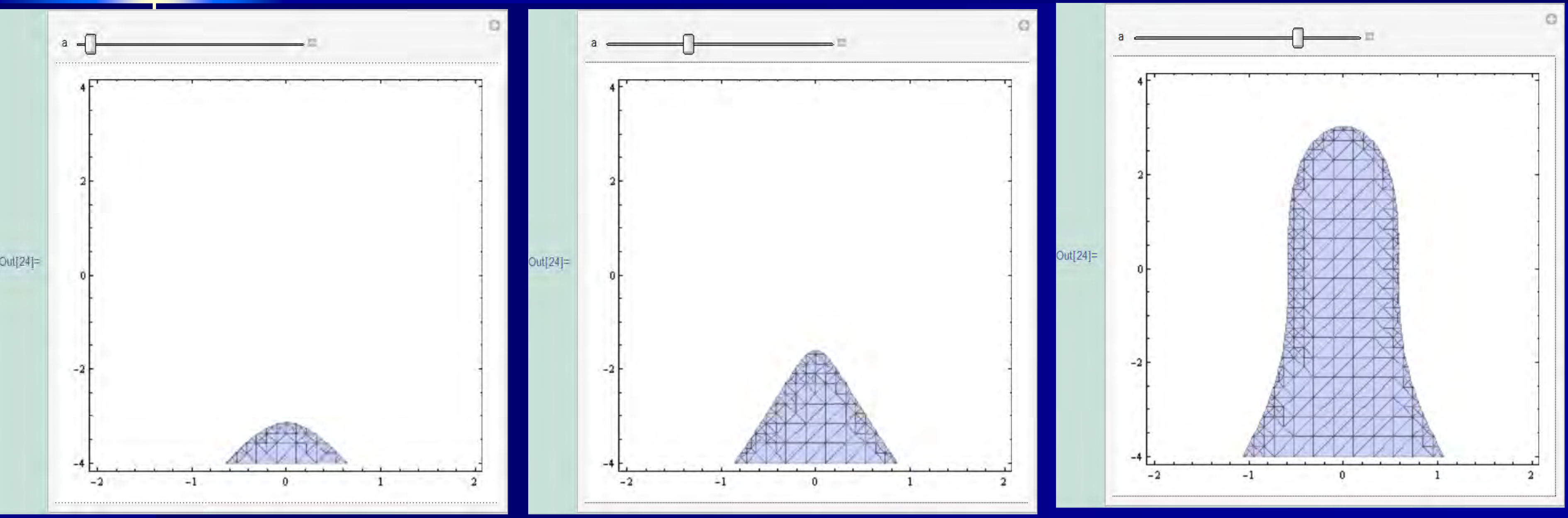
- For the ridges the heat discharged is between 2 and 100 MW_T/Km (unit length)
- Measured thermal fluxes range from 1 to 93 $MW_{T.}$
- The accepted average value for a single orifice is about 8 MW_T.



COMSOL SIMULATION OF A SUBMARINE CHIMNEY

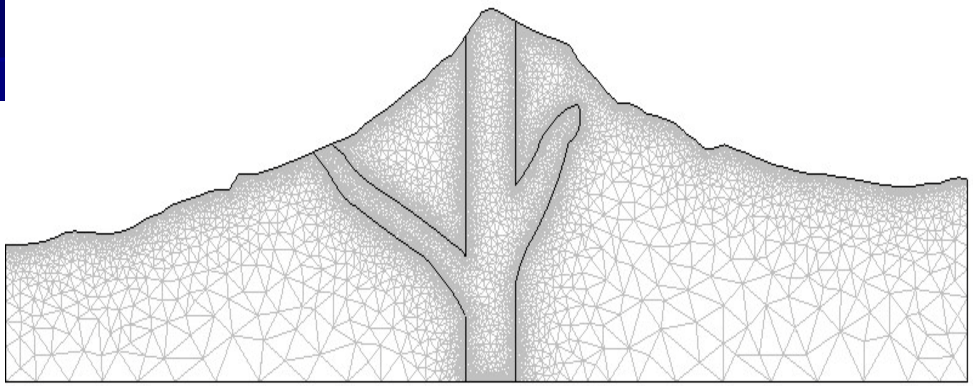
Meshing a growing chimney.

- The geometry Modeling is very simple:

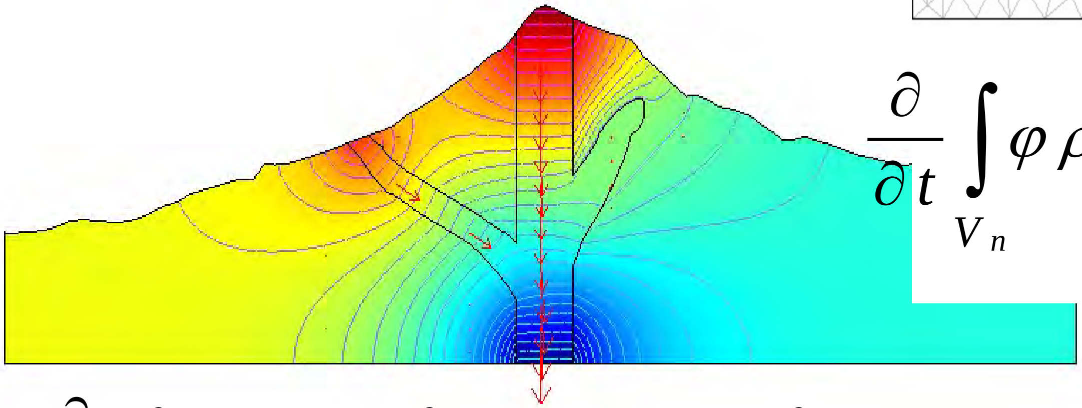


Plot Region: $5x^2 + \frac{1}{16}y^3 < a \in [-2,3]$

A volcanic system using COMSOL:



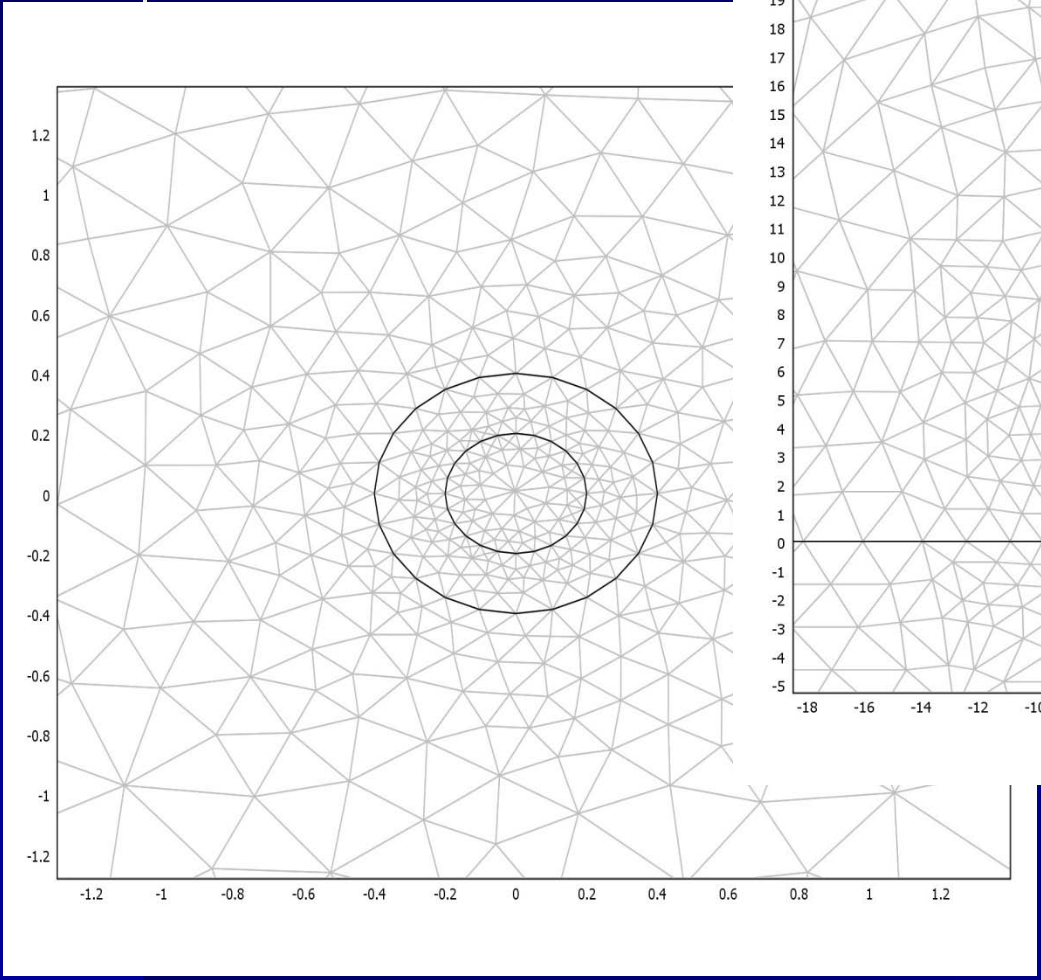
$$\frac{\partial}{\partial t}\int_{V_n} \varphi\,\rho_k\,dV + \int_{V_n} \vec{\nabla}\cdot\vec{F}_k\,dV = \int_{V_n} q_k\,dV$$

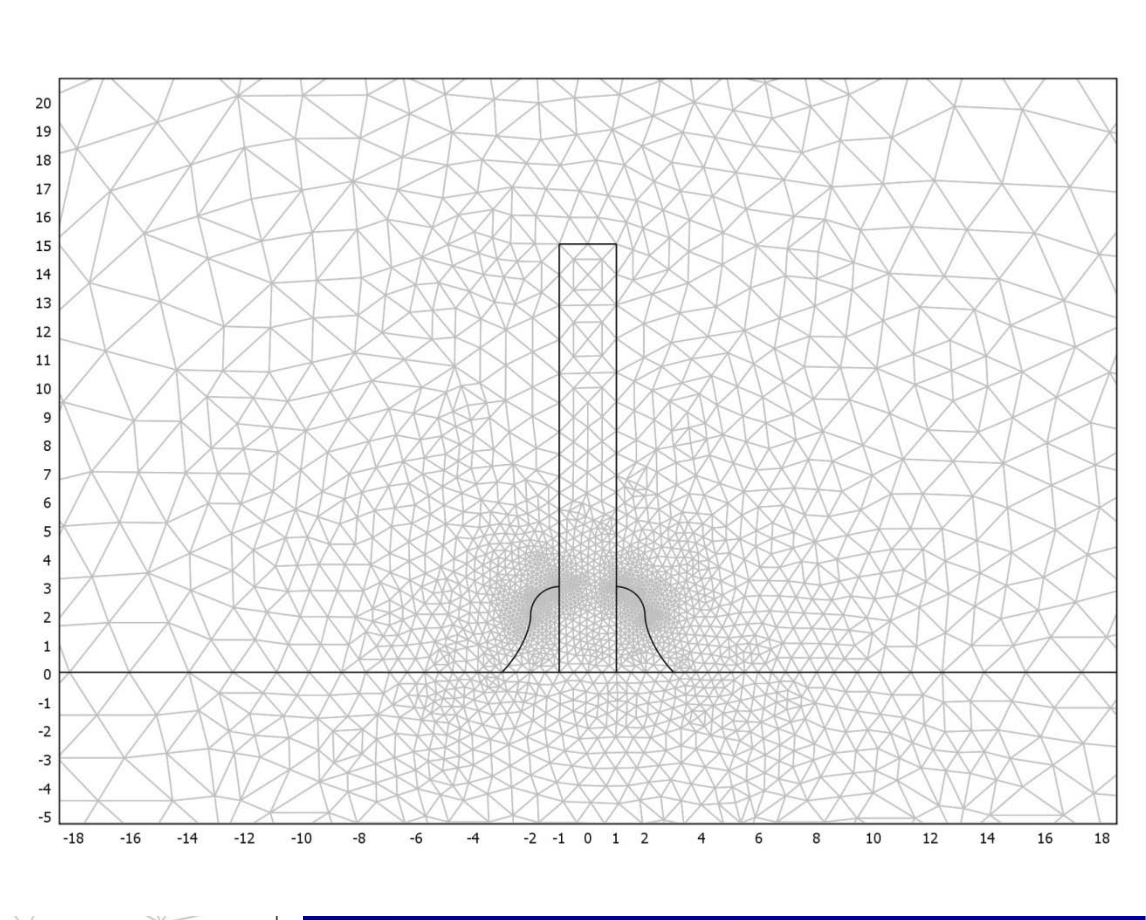


$$\frac{\partial}{\partial t}\int_{V_n} U_T\,dV + \int_{V_n} \vec{\nabla}\cdot\vec{F}_E\,dV = \int_{V_n} q_U\,dV$$

$$U_T = \varphi\rho_f e_f + (1-\varphi)\,\rho_r e_r$$

Two FEM discretizations:





Initial State: reservoir parameters

- Boundary conditions are: constant *T* for seawater at its lateral boundaries and at the bottom and top of the submarine reservoir.

Table 1. Thermodynamics of the Submarine Reservoir.

function	Seawater	Hot Water
Pressure	220 bar	220 bar
Temperature	4 °C	350 °C
Fuid flow rate	70 cm/s	250 cm/s
Heat Flux	0.34 W_T/m^2	1.50 W_T/m^2

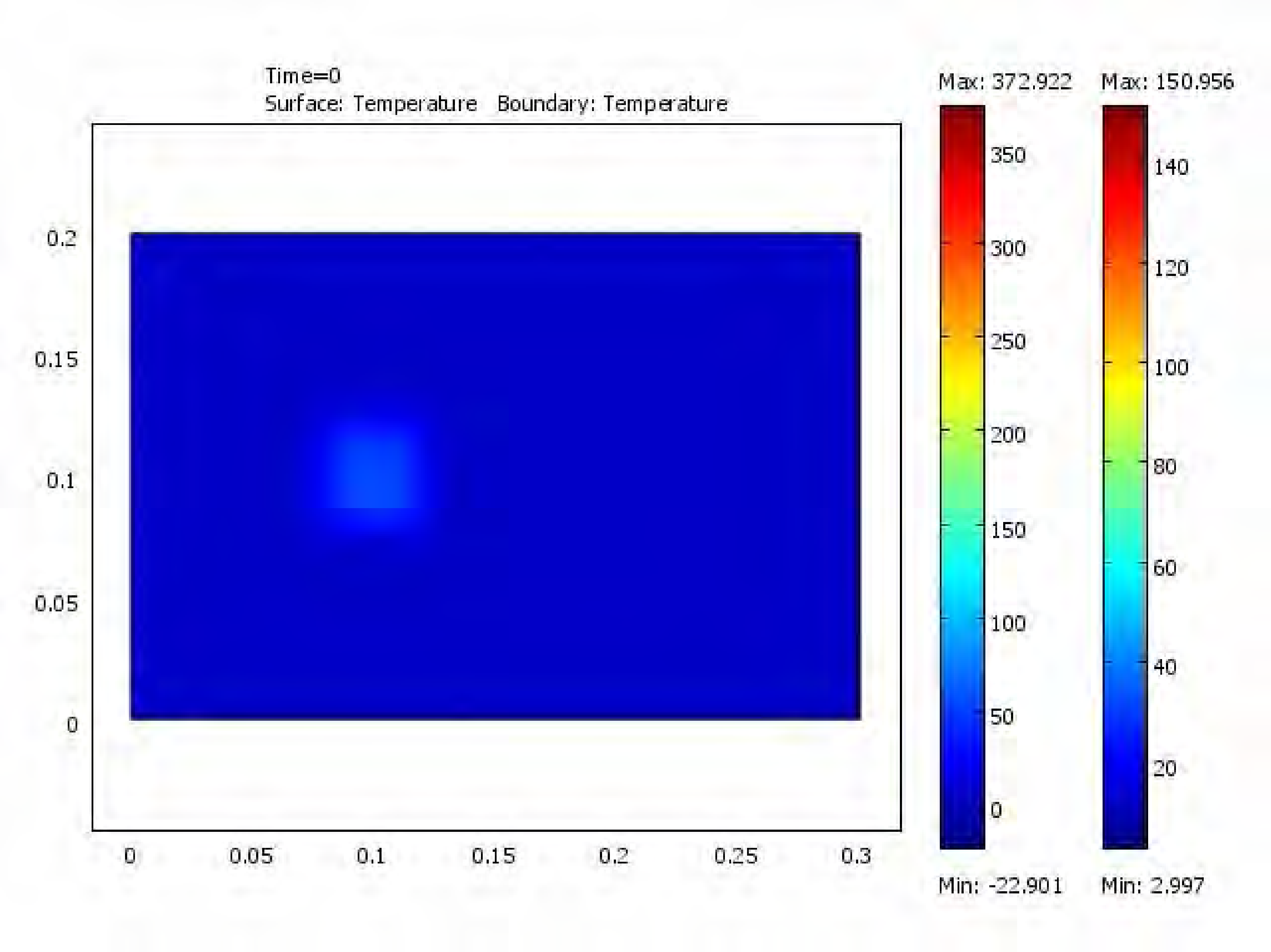
Initial State: Domain parameters

- Boundary conditions are: constant *T* for seawater at its lateral boundaries and at the bottom and top of the submarine reservoir.

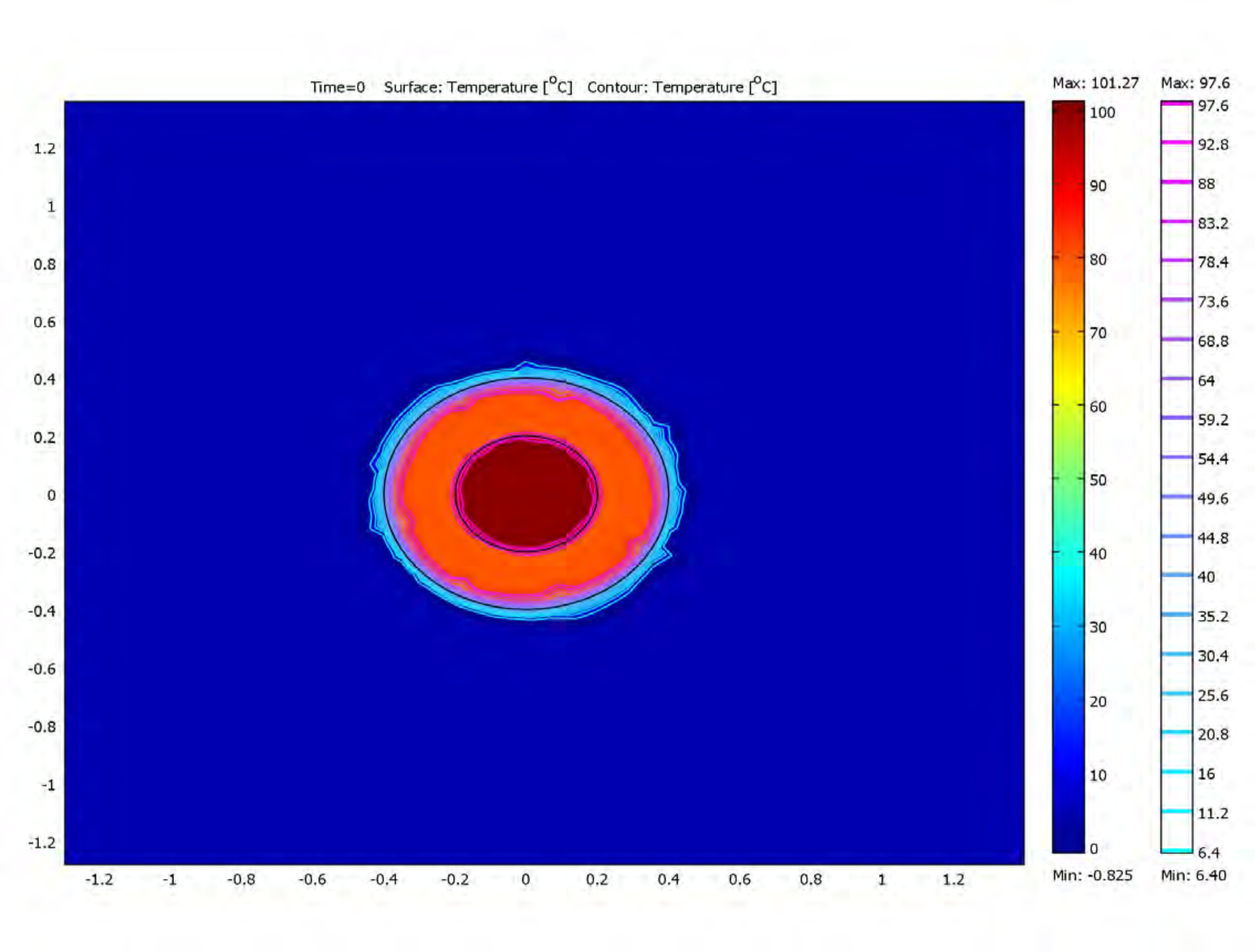
Table 2. Parameters of the Submarine Reservoir.

function	Seawater	Hot Water	Chimney
K	0.580	0.4708	76.2
□	1011.0	611.7	7870.0
C_p	4120.0	7543.0	440.0
T	4°C	350°C	300°C

Initial State: pure conduction

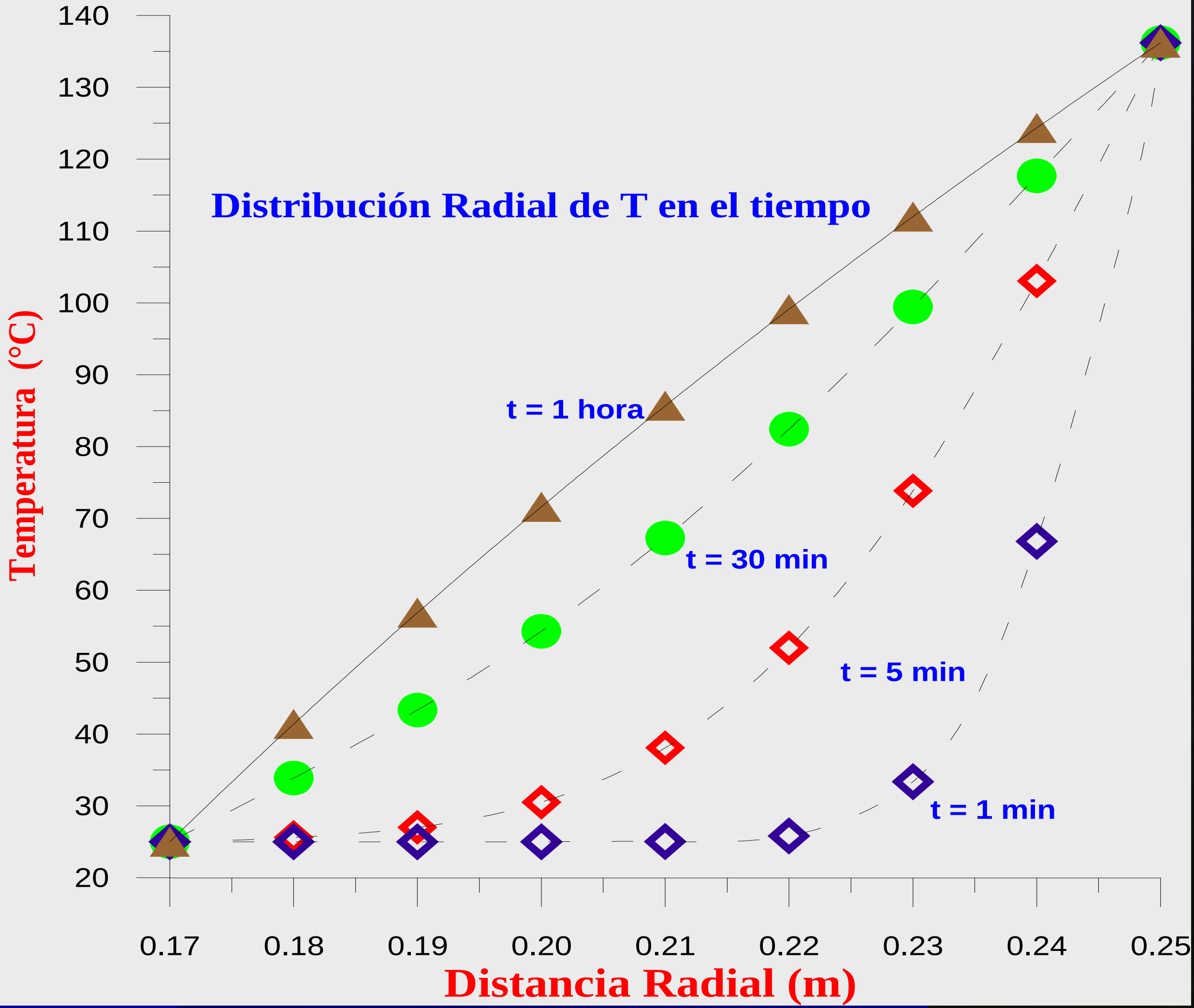


Initial State:

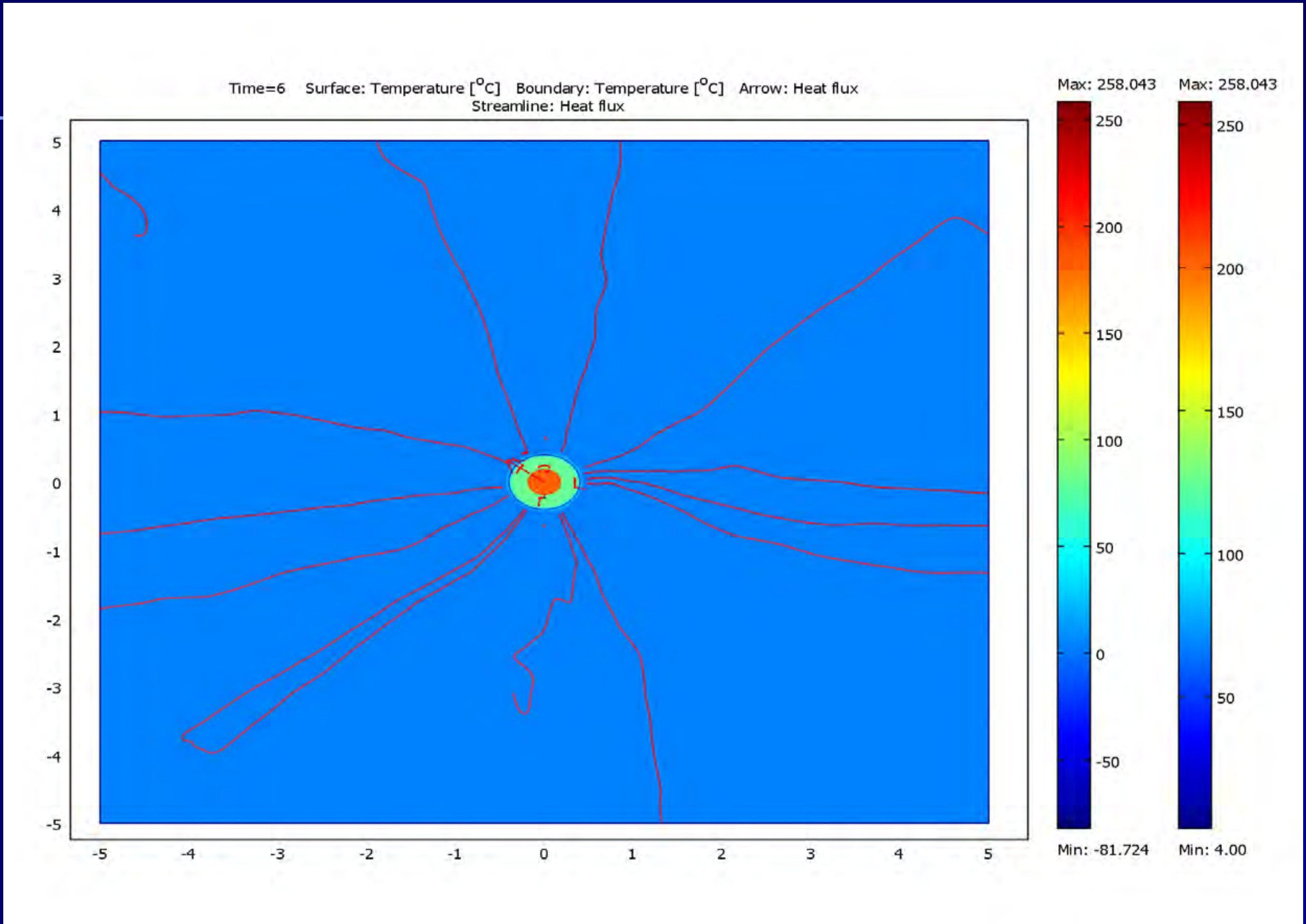


Radial Heat Conduction:

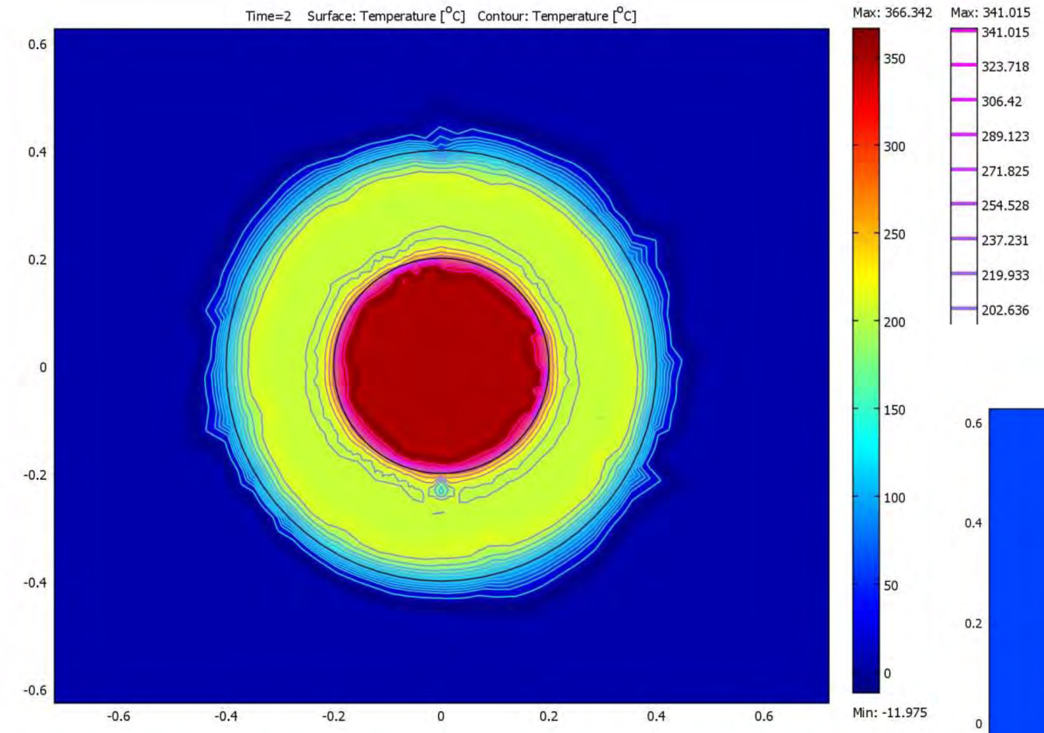
- Radial temperature Distribution :

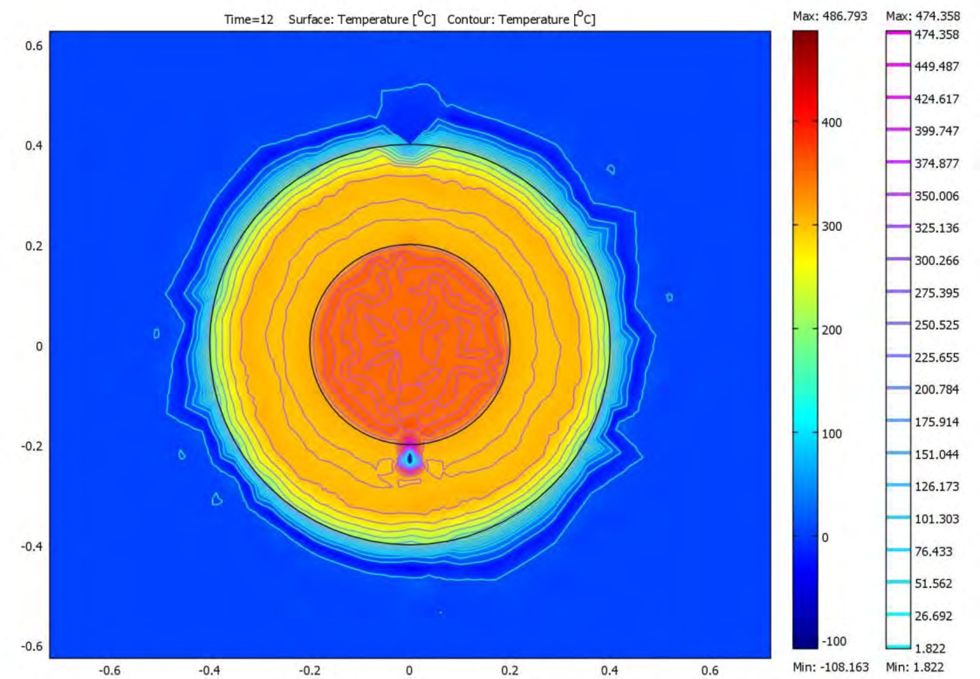


Initial State: radial disturbance:

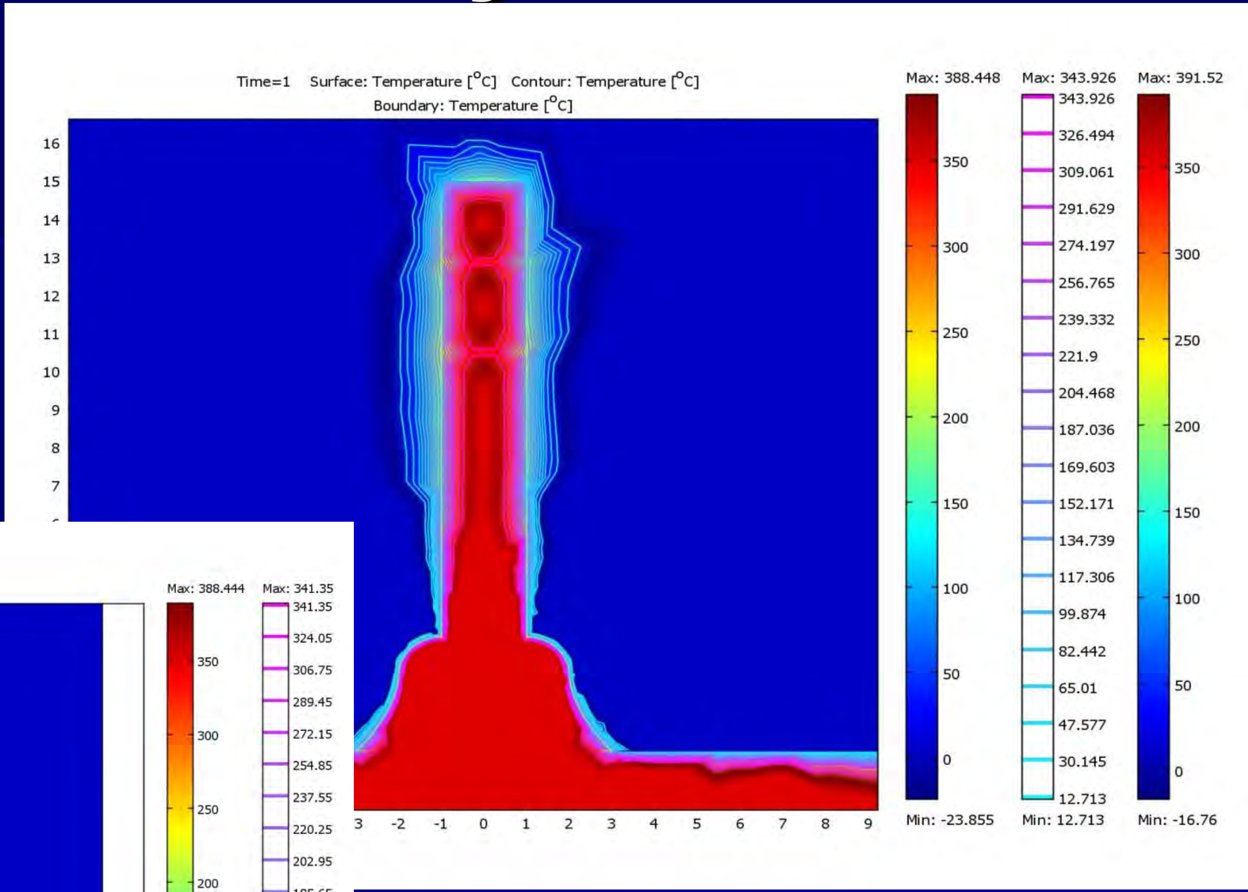


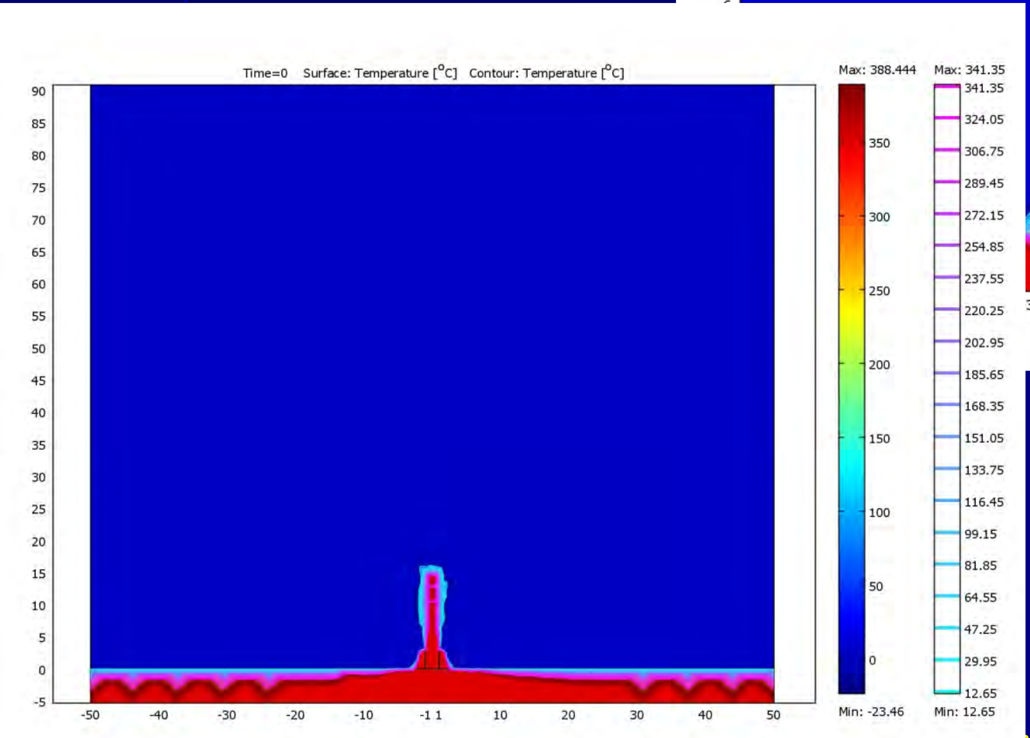
T inside the walls :





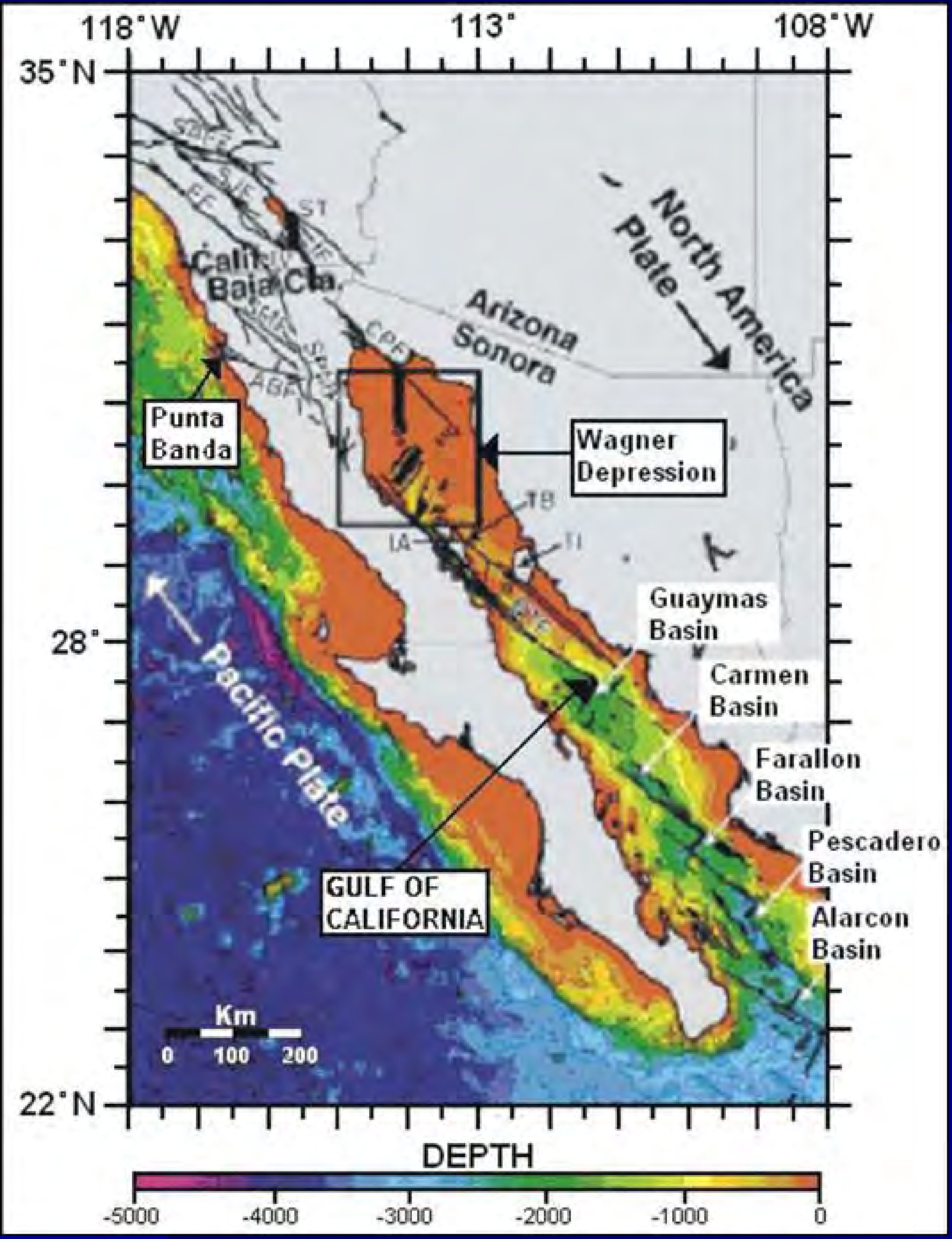
Initial State in the cylinder:





Plumes are created by thermal - chemical fluid input from submarine hot spring systems into the deep ocean.

- There is an enormous range of temporal and spatial scales involved in the characteristics of these plumes.
- Plume with vortices emerging from a black smoker at 342°C.



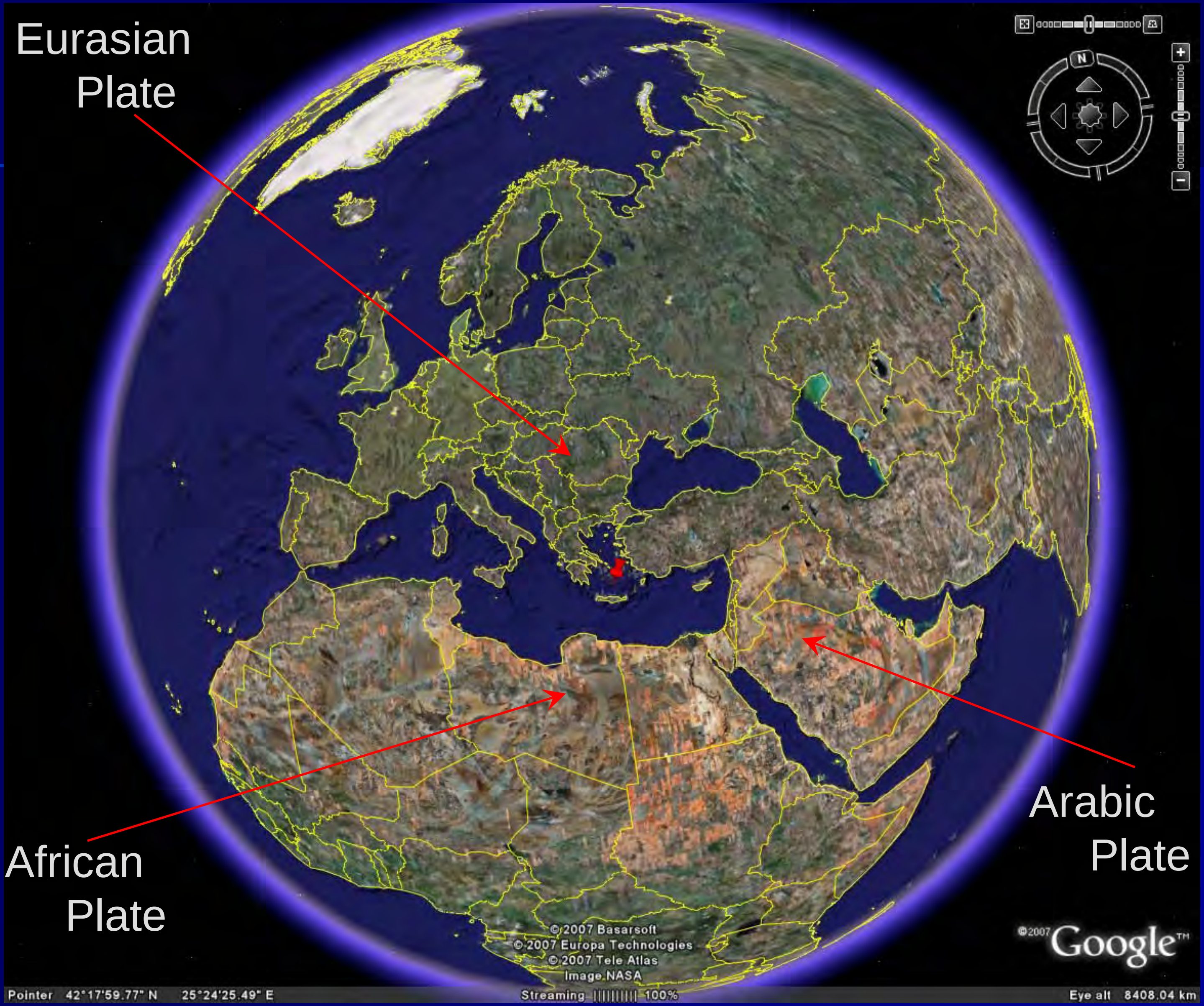
Submarine geothermal energy in the Gulf of California and Punta Banda.

Geothermal Energy in Two Submarine Systems in Mexico:

$$C_E = \frac{1.0 \times 10^{-6}}{31,557,600\, t_A} \qquad G_E = f_E \cdot C_E \, \Delta \, E_{Total} \quad (MW_e)$$

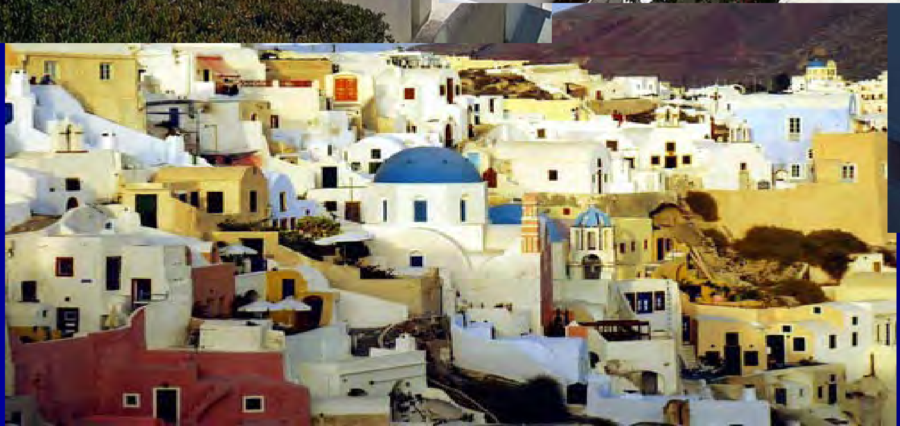
Zone	P (bar) T (°C)	Energy density M J/m^3	Available Energy 10^{15} J	Geothermal Potential MW_T/Km^3
Punta Banda	51, 220	574	232	245
Gulf of California	220, 360	906	832	880

Tectonical location of Greece:

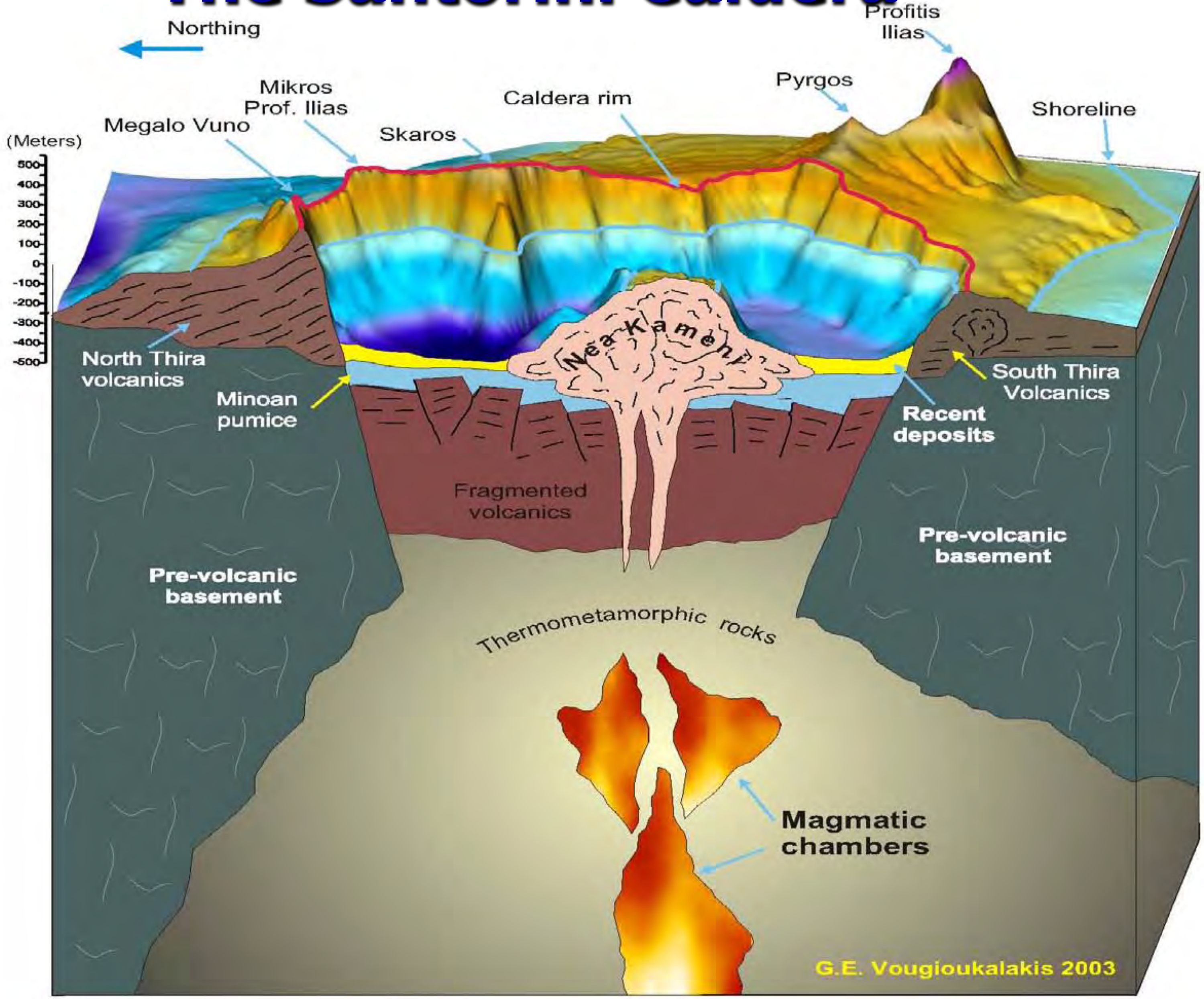


2) Formation of the Santorini island Complex:

Santorini: 2008



The Santorini Caldera



Submarine Geothermal Energy in Santorini:

$$G_E = \frac{f_E \cdot \rho c_p V \Delta T}{t_C} \quad (MW_e)$$

Rock Volume	P, T	**Energy density** (MJ/m³)	**Recovery factor**	**Geothermal Potential** (MW_e)
100 km^3	50 bar 160°C	411	2 %	869

Conclusions

- The energy of the Earth is a resource, virtually infinite and equitable distributed all around the Oceans.

- ✓ **Submarine resources contain an infinite energy potential**

- As a primary energy source, submarine systems are an immense hope for the future.