Porosity and Permeability of Magmas

How porous and permeable are magmas?
How does gas escape from a magma?

Linking porosity and permeability of magma using empirical relationships

Core Quantitative Issue
Forces

Supporting Quantitative Issues
Porosity
Permeability
Iteration

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Edited by Judy Harden 10/29/07

Preview

This module presents calculations for porosity and permeability of bubbly magmas.

Slides 3-5 *give some background on the formation of porosity and permeability in magmas.*

Slide 6 *states the problem. Given many bubbles, such as 10^9 bubbles per cubic meter, how does porosity and permeability develop in magma?*

Slides 7-10 *analyze this problem. The solution involves the ideal gas law and resolving the forces acting on a rising bubble.*

Slides 11 and 12 *illustrate spreadsheets to calculate a solution to this problem.*

Slide 13 *summarizes the module and points to other problems that may be solved with iterative techniques.*

Slide 14 *gives the end-of-module assignments.*

Slides 15-17 *provide endnotes and additional references.*

What is the Porosity of Magma?

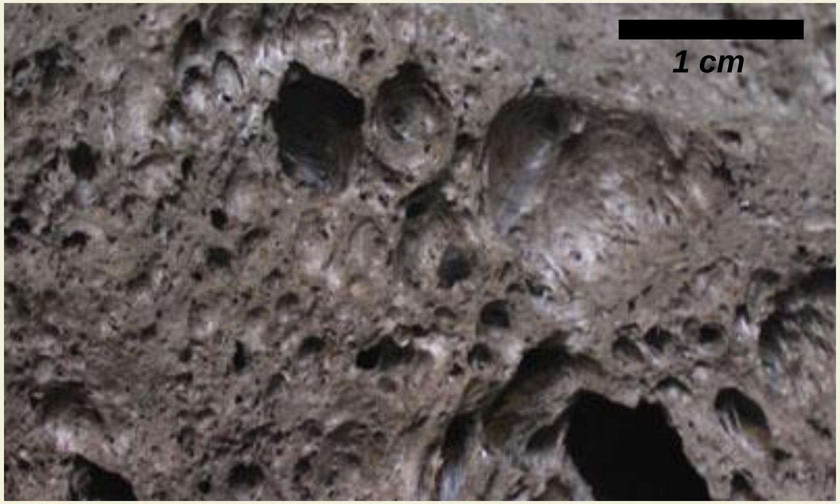
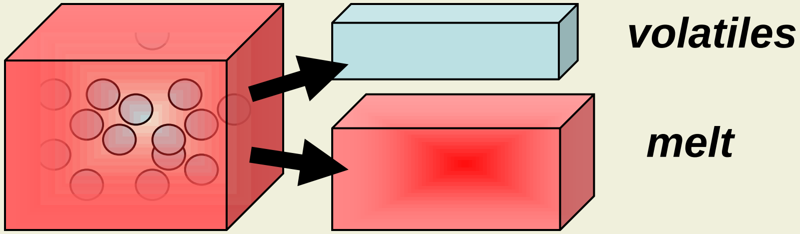


Photo by Peter LaFemina

Photograph of a pyroclast from Hekla volcano, Iceland. The bubbles in this pyroclast were just beginning to coalesce, increasing the permeability of the magma, when the pyroclast was erupted explosively from the volcano. In this case, the gas did not escape from the magma effectively, so the increased volume due to gas exsolution increased ascent velocity and the power of the explosive eruption. The vesicles seen in the pyroclast reflect bubble expansion at the moment of eruption. The porosity of this sample is over 60%.

The difference between explosive and passive degassing depends on the rate of ascent of magma, and often on the porosity and permeability of the magma. Once the magma becomes permeable, the volcano can literally "lose steam".

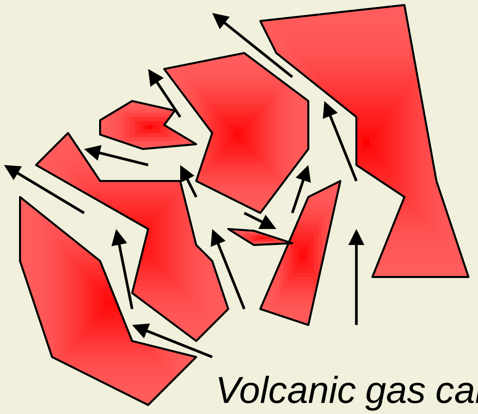
Studies of the porosity and permeability of volcanic rocks, therefore, provide important clues about the dynamics of magma ascent and eruption.



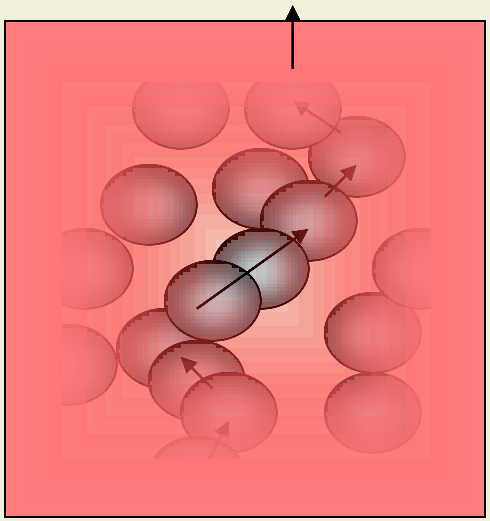
In this example, ~30% of the magma consists of volatiles in bubbles and ~70% as melt or solids (e.g., phenocrysts). The porosity is 30%.

To learn more about porosity go here: http://en.wikipedia.org/wiki/Porosity

How permeable is a vesicular magma?



Volcanic gas can escape through a sub-solidus cooling magma, made permeable by the formation of fractures.



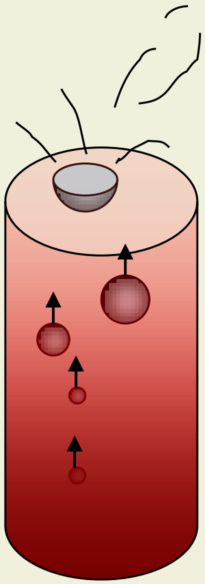
As bubble density increases in a molten magma, bubbles can coalesce and provide pathways for gas escape.

As bubbles rise in a magma, they expand via decompression and diffusion of volatiles from the magma into bubbles. That is, the porosity of the magma increases with decreasing pressure. Once bubbles begin to touch, they coalesce and form larger bubbles and may create an interconnected network of bubbles. Permeability describes the connectivity of pores and provides a measure of how easily fluids, such as volcanic gas, may flow through the rock, or through the bubbly magma. Gas escape, due to permeability, reduces the likelihood of explosive eruption.

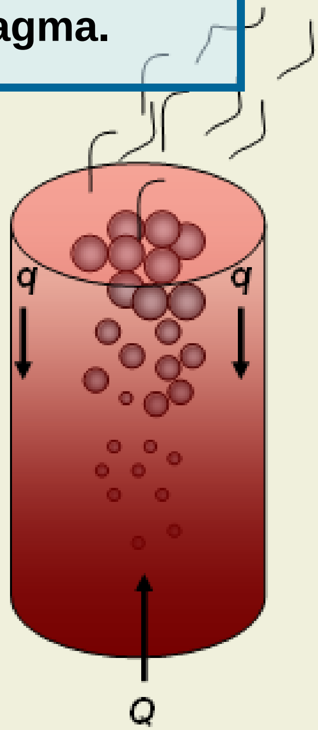
What are the units of permeability?

What are the possible mechanisms for passive degassing?

In passive degassing (i.e., gas flow from the volcano but very little or no eruption of magma), bubbles of gas must move toward the surface and escape. Consider two methods of accomplishing this without erupting large amounts of magma.



Method 1: *Individual bubbles rise through the magma due to buoyancy force. As they rise, they grow primarily by decompression. When these bubbles reach the surface, they break, releasing gas and perhaps throwing volcanic bombs as the wall of the bubble bursts into the air. Such a mechanism requires a low viscosity magma and will not sustain high gas flux.*



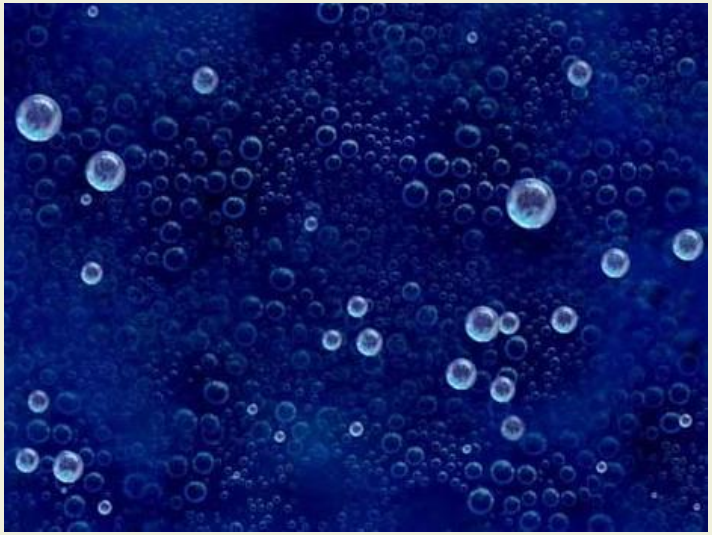
Method 2: *Bubbles ascend the conduit together with magma (**Q**). As bubbles rise, they grow by decompression. Bubble density (number of bubbles per cubic meter) is high enough for bubbles to touch and connect as they ascend and grow. This connection creates permeability and allows gas to escape. As the bubbles degas, they lose pressure and collapse, increasing the density of the magma and causing it to sink, perhaps at the margins of the conduit (**q**). Viscous magmas may degas in this manner, as long as mass flow is sustained from depth. Such a mechanism can sustain very high gas flux.*

In this module, you will explore Method 2 of passive degassing.

Problem 1

Given a regular distribution of uniformly sized bubbles, at what depth does an ascending bubbly magma become permeable?

In the Bubbles in Magma Module***, you considered a single bubble ascending from deep in a lava lake to the surface. Now consider a more realistic case in which there are many bubbles in a given volume of magma. At what depth does the magma become permeable so that the gas can escape from the bubbles and into the atmosphere?***



To Solve this problem you will need to:

1) **Make assumptions about the number of bubbles and their distribution in the magma.**
2) **Use the ideal gas law to estimate bubble volume [PV=nRT!].**
3) **Discover a solution "iteratively", solving repeatedly for porosity, pressure, and bubble volume.**

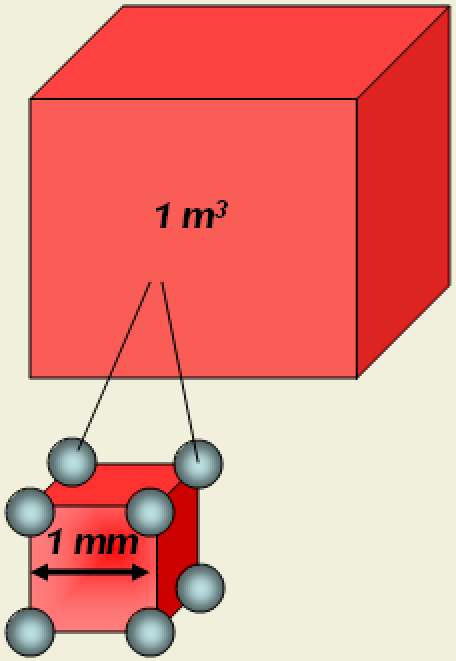
Learn more about bubbles and permeability

Review the ideal gas law: ***http://hyperphysics.phy-astr.gsu.edu/hbase/kinetic/idegas.html***

Designing a Plan, Part 1

Consider one cubic meter of magma.

In a regular, mono-dispersed pattern, bubbles of equal volume are spaced at equal intervals to fill this cubic meter. In reality, magmas are poly-dispersive. That is, randomly spaced bubbles have a size distribution that reflects the complexities of bubble nucleation in the magma and the pressure history of the cubic meter of magma as it ascends.



If we assume:

1) *A regular, mono-dispersed bubble distribution,*
2) *Ideal gas law behavior of the bubbles,*

then it is short work to estimate the porosity of the 1 m^3 of magma for different hydrostatic pressures.

Prove to yourself that there will be 10^9 bubbles per cubic meter for the above regular, mono-dispersed bubble distribution. What is the porosity of this magma, if the radius of each bubble is 0.2 mm? Answer: about 3.3%

Designing a Plan, Part 2

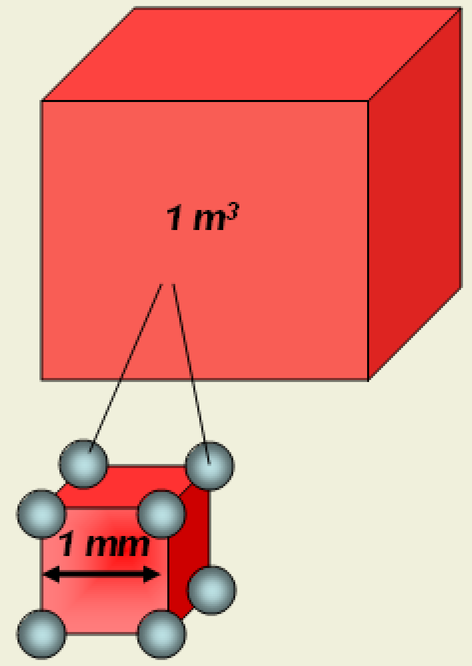
Although the magma is porous when bubbles of any size are present, it is not permeable until the bubbles connect to form a network that allows gas to escape from the magma.

This happens in the ideal regular, mono-dispersed bubble distribution when the radius of each bubble grows to one-half the distance separating the bubbles.

Experiments suggest that actual magmas become permeable at lower porosities than forecast by the regular, mono-dispersed bubble distribution. With random bubble nucleation sites and a variety of bubble-size distributions, Blower (2001) developed the relation for porosity 30-80 percent:

$$k = ar^2\left[\phi - \phi_{cr}\right]^b, \phi \geq \phi_{cr}$$

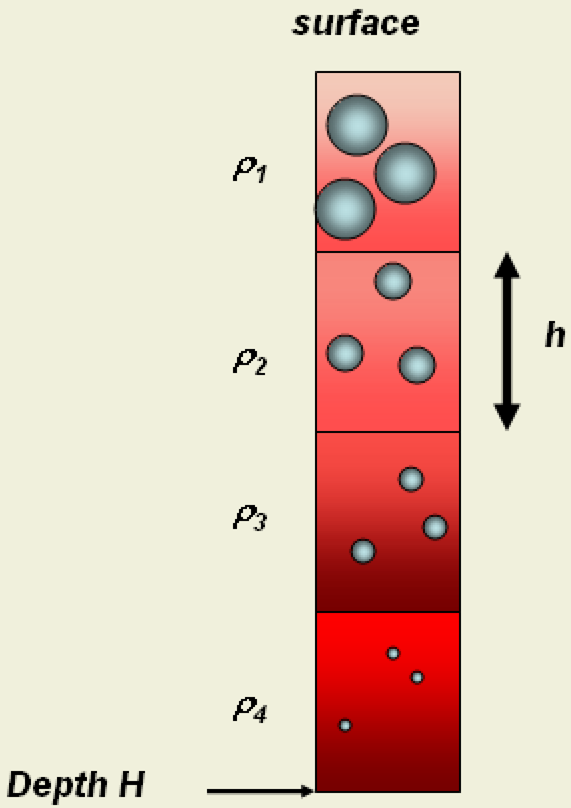
where k is permeability (m^2), a and b are constants, r is the bubble radius (m), ϕ is porosity, ϕ_{cr} is the critical porosity, below which permeability is zero. Constants a, b, and ϕ_{cr} are found by regression of rock laboratory measurements. Blower found that a= 8.27 x 10^{-6}, b = 2.10, and ϕ_{cr} = 0.3 fit some laboratory measurements well.



What is the porosity of this magma with regular, mono-dispersed bubble distribution (1 mm between the centers of each bubble pair) when the magma first becomes permeable?

Designing a Plan, Part 3

The last part of the problem involves the density of the magma. If there are a lot of bubbles, then the bubbles change the density of the magma. This should be taken into account in the estimate of porosity. For example, in the diagram showing decompressing bubbles, density increases with increasing depth (e.g., $\rho_1 < \rho_2 < \rho_3 < \rho_4$).



For the diagram, pressure at depth H is given by:

$$P = [\rho_1 + \rho_2 + \rho_3 + \rho_4]gh$$

alternatively written:

$$P = gh\sum_{i=1}^{4}\rho_i$$

where g is gravity, h is the thickness over which some constant density is assumed.

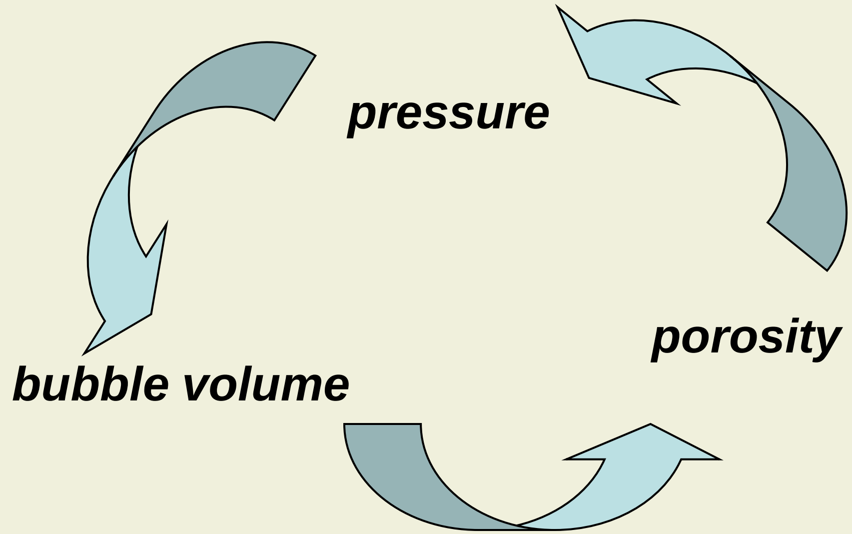
In Excel:

	B	C	D	E
2				
3	depth	density	h	pressure
4	(m)	(kg m^{-3})	(m)	(Pa)
5	1	1200	1	11760
6	2	1800	1	29400
7	3	2000	1	49000
8	4	2100	1	69580
9	5	2150	1	90650

The formula is:
E6=E5+(C6*9.8)*D6

Designing a Plan, Part 4

The problem now seems circular! The pressure depends on porosity of the overlying layers; but porosity, in turn, depends on pressure because pressure controls bubble growth by decompression. The way to solve this problem lies in iteration. Iteration is the repetition of a series of commands until the answer converges on a stable solution.



Start

Specify the range of depths (say 0.5-5 m at 0.5 m intervals).

Calculate hydrostatic pressure using the density of bubble-free magma.

Calculate the volume of an individual bubble (Ideal gas law).

Given the number of nucleation sites and bubble volume, calculate the porosity.

From the porosity, recalculate the pressure and volume.

Is the answer stable? (iterate 1000 times)

No

Yes

Finish

In Excel, you can make a spreadsheet "iterate" by using "circular references". That is, the answer in each cell depends on the answer in the other.

In a spreadsheet, the calculation looks like:

	B	C	D	E	F	G
2	***Calculate the magma porosity and bubble volume in a bubbly magma***					
3		***as a function of pressure.***				
4	***Physical constants***					
5	gravity	9.8	m s^{-2}			
6	gas constant	8.314472	J K^{-1} mol^{-1}			
7						
8	***Magma Properties***					
9	melt density	2500	kg m^{-3}			
10	magma temperature	1300	K			
11	nucleation sites	2.50E+07	m^{-3}			
12						
13	***Water vapor***					
14	H_2O	2.00E-07	g			
15	molecular mass H_2O	18.025	g mol^{-1}			
16	moles H_2O	1.11E-08	mol			
17						
18	***Calculation***			***Iterative Calculation***		
19	depth	pressure	initial volume	magma porosity	pressure	bubble volume
20	(m)	(Pa)	(m^3)	(%)	(Pa)	(m^3)
21	0.5	12250	9.7903E-09	0.42760	7012	1.71E-08
22	1	24500	4.8952E-09	0.17517	17116	7.01E-09
23	1.5	36750	3.2634E-09	0.10686	28057	4.27E-09
24	2	49000	2.4476E-09	0.07615	39374	3.05E-09
25	2.5	61250	1.9581E-09	0.05890	50903	2.36E-09
26	3	73500	1.6317E-09	0.04792	62566	1.92E-09
27	3.5	85750	1.3986E-09	0.04034	74321	1.61E-09
28	4	98000	1.2238E-09	0.03481	86145	1.39E-09
29	4.5	110250	1.0878E-09	0.03059	98020	1.22E-09
30	5	122500	9.7903E-10	0.02727	109936	1.09E-09

A cell containing given information

A cell containing a physical constant

A cell containing a normal formula without circular reference

A cell containing an iterative formula – one that contains a circular reference

Using information from the previous slides, decide what to enter in each cell containing a formula.

Go to the next slide for help with the iterative formulas, before trying to complete this spreadsheet!

Details about the iteration:

	B	C	D	E	F	G
2	***Calculate the magma porosity and bubble volume in a bubbly magma***					
3		***as a function of pressure.***				
4	***Physical constants***					
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6	gas constant	8.314472	J K^{-1} mol^{-1}			
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8	***Magma Properties***					
9	melt density	2500	kg m^{-3}			
10	magma temperature	1300	K			
11	nucleation sites	2.50E+07	m^{-3}			
12						
13	***Water vapor***					
14	H_2O	2.00E-07	g			
15	molecular mass H_2O	18.025	g mol^{-1}			
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17						
18	***Calculation***			***Iterative Calculation***		
19	depth	pressure	initial volume	magma porosity	pressure	bubble volume
20	(m)	(Pa)	(m^3)	(%)	(Pa)	(m^3)
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30	5	122500	9.7903E-10	0.02727	109936	1.09E-09

In this spreadsheet:

the formula in cell E21 uses the result in cell G21.

the formula in cell F21 uses the result in cell E21.

the formula in G21 uses the result in cell F21.

Note from the above that this is a circular reference.

To run the spreadsheet with a circular reference, go to Tools: Options: Calculations

Check the iteration box! Select Maximum iterations =1000 and Maximum Change = 0.001

Learn more about the Excel iteration set-up

What you have done

You have investigated the change in porosity and permeability of magma as a function of pressure.

Porosity and permeability are important petrophysical characteristics of rocks. In management of oil and water resources, porosity and permeability of reservoir rocks controls the rate of fluid extraction. In volcanology, porosity and permeability of magma determine the ease with which volcanic gases escape from rising magmas. This in turn controls the rate of volcano degassing and the energy of volcanic eruptions.

In this module, you were required to perform iteration on your spreadsheet in order to solve for the actual volume and pressure of the bubbly magma as a function of depth. Iteration was necessary because the volume of bubbles, and hence the density of the magma, varies with depth in the lava lake or volcanic conduit. Iteration is a commonly used computational technique to solve a wide variety of complex problems in the geosciences. Elsewhere in volcanology, iteration is used to solve for pressure conditions in a volcano conduit during eruptions. In hydrogeology, iteration is used to solve groundwater flow problems, especially when properties of the water (e.g., salinity) change over the problem space.

Some useful starting points for learning more about porosity and permeability in magmas:

Cashman, K.V. and Mangan, M.T. ,1994, Physical aspects of magmatic degassing II. Constraints on vesiculation processes from textural studies of eruptive products. Reviews in Mineralogy, 30: 447-478. [a starting point for understanding bubbles in rocks]

Blower, J.D., 2001, Factors controlling permeability-porosity relationships in magma. Bulletin of Volcanology 63: 497-504. [accessible development of a best-fit statistical model of permeability based on analysis of pyroclasts].

End-of-Module Assignments

1. Make sure you turn in your spreadsheet showing the worked example.

2. Modify the spreadsheet to calculate permeability using the equation on Slide 9. Also, show the change in pressure, porosity, and bubble volume at 0.25 m intervals from 5 m depth to 0.5 m depth. At what depth does the magma become permeable?

3. Calculate the change in permeability of magma at 0.5 m depth caused by changing the number of bubble nucleation sites smoothly between 1 x 10^7 m^{-3} and 2.5 x 10^7 m^{-3}, with 2 x 10^{-7} g water vapor per bubble (melt density = 2500 kg m^{-3}, temperature = 1300 K). Use the Blower (2001) model of permeability. Describe how and why permeability changes with the number of nucleation sites.

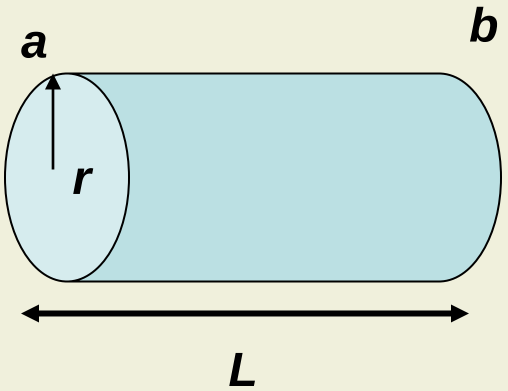
4. Sulfur dioxide (SO_2) flux from Stromboli volcano has been measured to be around 4.6 kg s^{-1}. Sulfur (S) in melt inclusions (bits of trapped primitive magma in crystals) is about 0.23 wt%; in contrast, S in pyroclastic bombs thrown from Stromboli is about 0.03 wt%. The difference is the amount degassed in bubbles, and degassed into the atmosphere by the volcano as long as sufficient permeability is reached. If the bubble-free magma density is 2500 kg m^{-3}, approximately how much sulfur degases from 1 m^3 of magma (give answer in kilograms)? How much SO_2 degases from 1 m^3 of magma (give answer in kilograms)? Then, what flux of magma is required to sustain an SO_2 flux of 4.6 kg s^{-1}? What is your estimate of how much magma reaches the surface and degases at Stromboli every day? Based on these calculations and information in this module, develop a conceptual model for this degassing. Describe your model in words and draw appropriate illustrations of the major aspects of the model. Please thank H. Mader for this question if you happen to meet her!

Units of Permeability

The unit of permeability is the Darcy. In practice, permeability is reported in mD, milliDarcy, where 1 mD = 10^{-12} m^2.

Permeability is a coefficient in Darcy's law, which can be expressed in terms of the volume flux of a liquid through a tube packed with permeable material as:

$$Q = -\frac{k\pi r^2}{\eta}\left[\frac{Pb - Pa}{L}\right]$$



where Q is the volume flux (m^3 s^{-1}), r is a cross sectional area (m^2), η is the liquid viscosity (Pa s), and [Pb-Pa]/L is the pressure gradient (Pa m^{-1}) that drives the flow.

Prove to yourself using the above equation that the units of permeability are m^2.

More about Darcy's Law:
http://en.wikipedia.org/wiki/Darcy's_law

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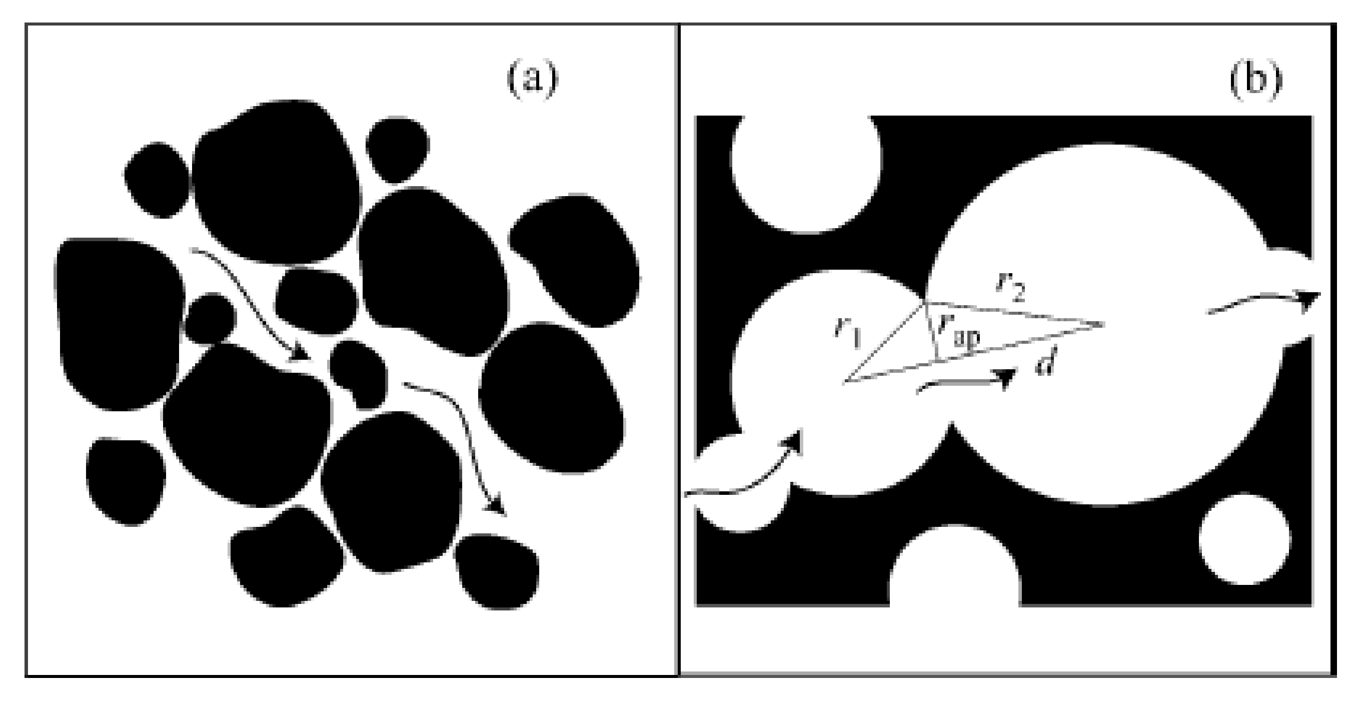
Differences in permeability in granular and vesicular rocks



In granular rocks, such as sandstones or pyroclastic deposits, permeability is related to the shape and connectivity of spaces between individual grains (a). In vesicular magmas and rocks that cool from these magmas, such as lava flows, permeability is related to the connectivity of bubbles (b). Blower (2001, Bulletin of Volcanology, 63: 497-504) showed that the width of the aperture, r_{ap}, controls the resistance to flow in linked sets of bubbles. Note that r_{ap} is related to the radius of the bubbles and the distance between them, using geometry rules. Diagram from Blower (2001).

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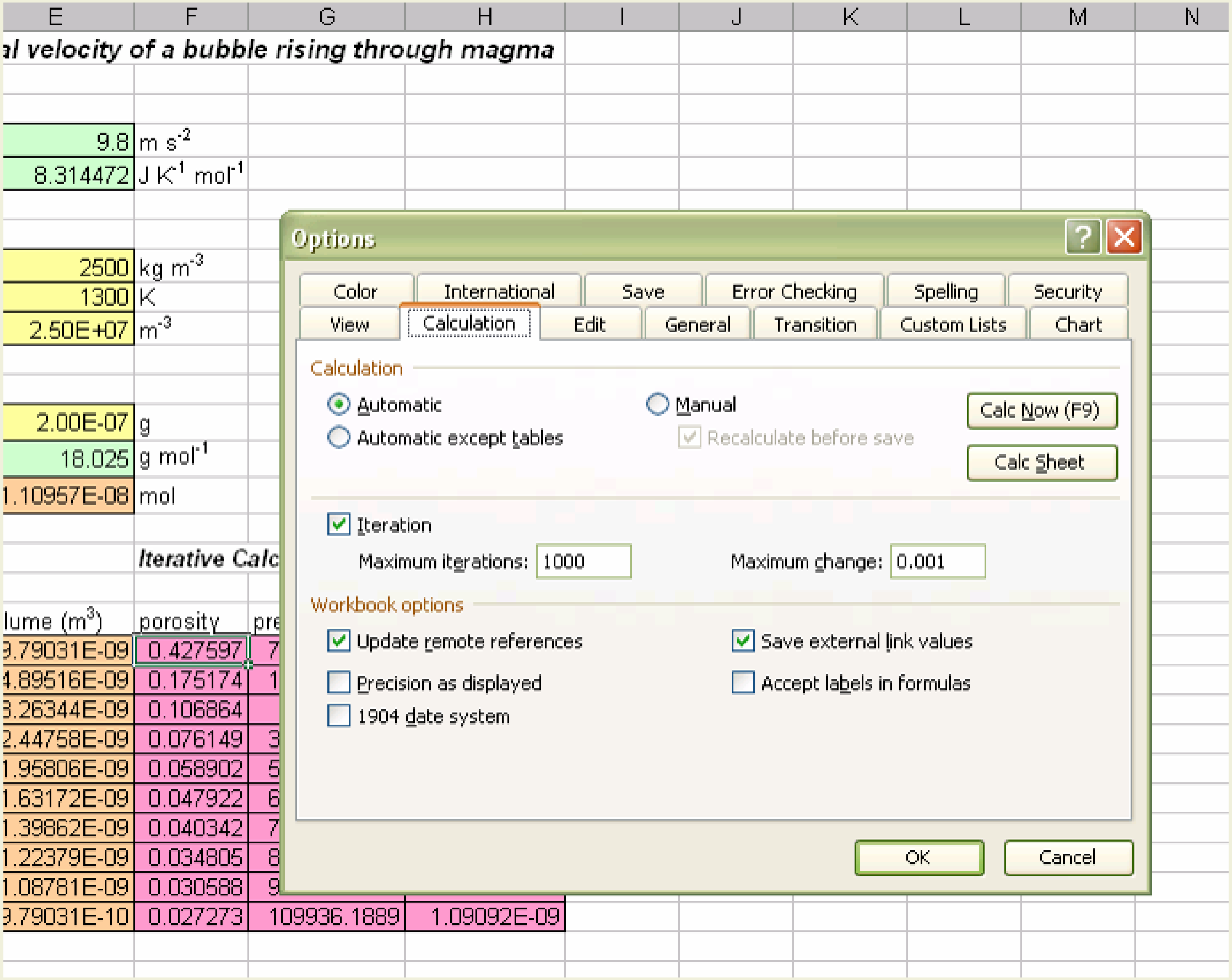
A screen-shot from excel showing the "iteration set-up"



Arrive at Options by using the Tools menu.

Note that the F9 key on your computer runs the iterative calculation.

Sometimes it helps to click on an empty cell on the spreadsheet, then press the F9 key, even if "automatic" calculations are selected.

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