Convection Currents
Student Activities

Aims:

- To demonstrate how thermal energy (heat) can generate motion (flow) in a fluid, similar to the convection within the Earth's mantle.
- To show that convection can produce horizontal flow that can cause (or is related to) plate motions.
- To investigate the viscosity of a fluid and illustrate that the Earth's mantle can be thought of as a solid for short duration processes (such as the propagation of seismic waves), and as a very viscous fluid for long duration processes (such as mantle convection and plate tectonic movements).

Materials:

Part A: Thermal Convection Experiments

- 1 Glass square or rectangular Pyrex dish (1.5 or 2 litre)
- 2 Ceramic coffee cups or house bricks or wooden blocks
- 1 methylated spirit burner or 2 small candles
- Vegetable oil (about 800-1,000 mL)
- 10 ml (~ 2 teaspoons) thyme
- Spoon
- Matches
- Ruler
- Stopwatch
- Funnel (to pour oil back into container)
- 3 pieces of thin (about 2mm thick) balsa wood, each 4 x 10 cm

Part B: Viscosity – additional materials

- Honey (about 60 mL)
- Water
- Flat baking tray (biscuit tray)
- Aluminium foil
- Marking pen
- 3 small containers, such as 1/8 cup measuring cups
- Plasticine

Part A – Thermal Convection Experiments

Experiment 1: Observing Convection Currents

1. Mix the vegetable oil and the thyme (spice) in the glass dish.
2. Stir thoroughly to distribute the flakes of thyme.
3. Arrange Pyrex dish and other materials as shown in Figure 1.

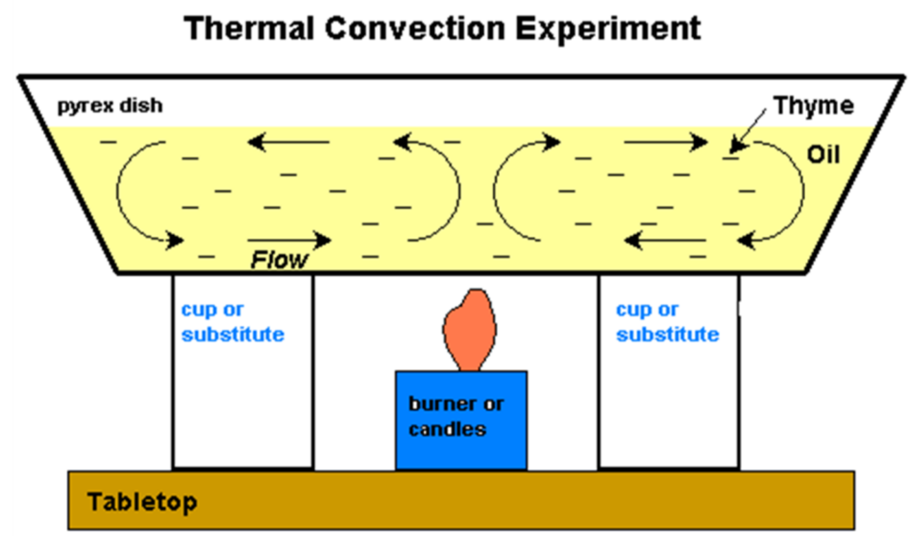

Figure 1: Arrows show expected directions of fluid flow defining convection cells after heating of the fluid.

Note: Because of the viscosity of the oil and the density of the flakes of thyme, the pieces of thyme are approximately neutrally buoyant. If left unstirred for a long period of time, the thyme will not be evenly distributed in the volume of oil – some of the thyme will tend to float and some tend to sink. However, the thyme stays distributed for a sufficient length of time to perform the experiment. If the thyme becomes significantly separated, just stir to mix thoroughly, let the mixture stand without heat until the flakes of thyme are not moving, and begin the experiment again by adding heat.

4. Observe the oil and spice mixture.
   With no heat (energy) being added to the system, these should be little or no movement of the liquid.

5. Light the burner (or candles) and let the liquid heat up for a couple of minutes.

6. As the oil heats and begins to flow, observe the pattern of fluid flow (circulation) by noting the location of individual flakes of thyme over time.
   The flakes of thyme will flow with the liquid, showing the direction and velocity of any fluid flow.

Be sure to view the model several times during the experiment, both from above the dish and from the side of the dish.

Questions:

1. Draw a labelled sketch of the circulation that *you observe* within the Pyrex dish

2. Is the pattern approximately symmetrical on the two sides of the heated area?

3. Where do you observe upward flow?

4. Where do you see downward flow?

5. Where do you observe horizontal flow?

Explanation:

- The flow defines a convection cell (actually two cells) in which upward flow above the flame (caused by heating of the fluid which causes expansion and a reduction in density) causes horizontal flow near the surface of the liquid.
- Cooling of the liquid near the ends of the container increases the density of the liquid and produces sinking and a return horizontal flow toward the center of the container, thus completing a "cycle" of fluid flow in the convection cell.
- The heat added to the bottom of the container is carried to the surface and distributed primarily by movement of the heated liquid (convection current) rather than by conduction.
- This type of energy movement is called **thermal convection** because added heat causes the fluid flow (circulation by convection) by lowering the density of the liquid.
- The difference in temperature between the near surface region of the oil measured above the heat source and near the ends of the Pyrex dish (far from the heat) will be about 2-3°C and can be observed using a sensitive thermometer.

Important point: It is not necessary to heat the oil for a long time, or to a high temperature, to cause convection. The convection will begin shortly after the heat is applied to the bottom of the Pyrex dish. The heating time will be somewhat longer using the candles.

Experiment 2: Measuring the horizontal velocity of the convective flow near the surface of the liquid

1. Place a ruler on the top of the container (oriented along the long direction of the Pyrex dish).
2. By looking down on the convecting fluid and observing an individual flake of thyme, measure the distance that one flake moves in a period of time such as 10 or 20 seconds. (One can also perform this measurement by viewing from the side of the dish.)
3. Divide the distance (in cm) by the time (in s) to determine the velocity in cm/s (usually slower than about 1 cm/s).
4. Measure the velocity and direction of movement at several locations for the near-surface flow of the liquid.

Questions:

1. Are all of the measurements approximately the same?

2. Where are the velocities the largest?

3. Where are the velocities the smallest?

4. What could explain these variations in velocity?

5. Are the directions of flow "away from" the heated central area of the container?

6. What effects or characteristics of the model might cause variability in the velocities?

Experiment 3: Plate Motion

1. Place the thin pieces of balsa wood on the surface of the liquid as shown in Figure 2.

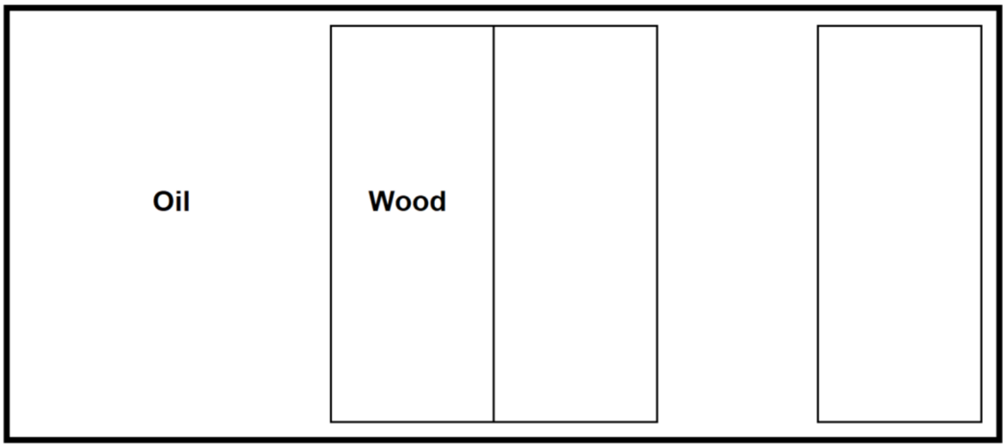

Figure 2: Pyrex dish viewed from above

2. Observe the motion of the pieces of wood (representing the relatively rigid parts of plates, such as in most continental regions) over time.
You should see plate separation or divergence (analogous to continental rifting and subsequent sea floor spreading of the oceanic lithosphere along mid-ocean ridges) at the center of the container where significant upward fluid flow is caused by the heating.

3. Because of surface tension, the two pieces of wood at the center of the loaf dish may tend to "stick together". In this case, use a pencil or other tool to slightly separate the wood. Once the surface tension is reduced, the plates will move with the underlying fluid flow.

4. With time, two of the plates should collide corresponding to the continental collision.

5. Measure the velocity of one of the pieces of wood using a ruler as in Experiment 2.

Question:

How does this velocity compare to the fluid flow velocities that were obtained previously?

Explanation:

Convection in the Earth:

- Thermal convection is inferred to exist on a large scale in at least two regions in the Earth.
- The liquid outer core and the upper mantle behave as a solid for seismic wave propagation and as a very viscous fluid for long duration geologic processes, including convection.
- The heat that causes convection within the Earth comes from two sources – original heat from accretion and heat released during radioactive decay of unstable isotopes.
- Although the Earth is about 4.5 billion years old, some heat remains from the accretionary processes of its formation. This is because fragments of Earth materials were heated to very high temperatures by impact during formation of the planet and Earth materials have relatively low thermal conductivity, so that significant heat has been retained from the early stages of Earth history.
- A larger source of heat, however, is the natural, spontaneous, radioactive decay of unstable isotopes of elements that are distributed throughout the Earth, particularly in the crust and mantle.
- These radioactive elements include uranium, thorium and rubidium.
- These sources of heat cause the Earth's temperature to increase with depth to a temperature of about 5,000°C in the inner core.
- The Earth's outer core is inferred to be mostly liquid iron.
- Convective flow within the outer core not only brings heat to the core-mantle boundary, where some of it is transferred into the mantle, but also causes the Earth's magnetic field by motions of the electrically conductive inner core material.
- Temperatures are hot enough in the upper mantle ≥ 1,200°C to cause thermal convection of the highly viscous upper mantle rocks, although the flow velocity is apparently very low - on the order of cm/yr.
- Our current understanding of mantle convection is that currents happen throughout the entire mantle (Figures 3 and 4).

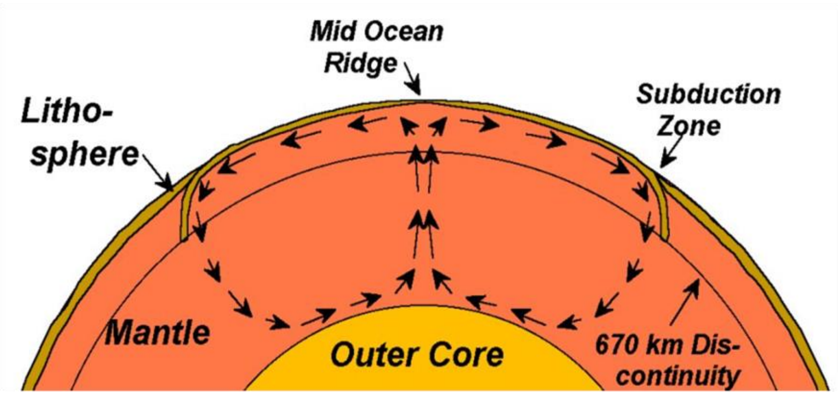

Figure 3: A simple model of convection in the mantle

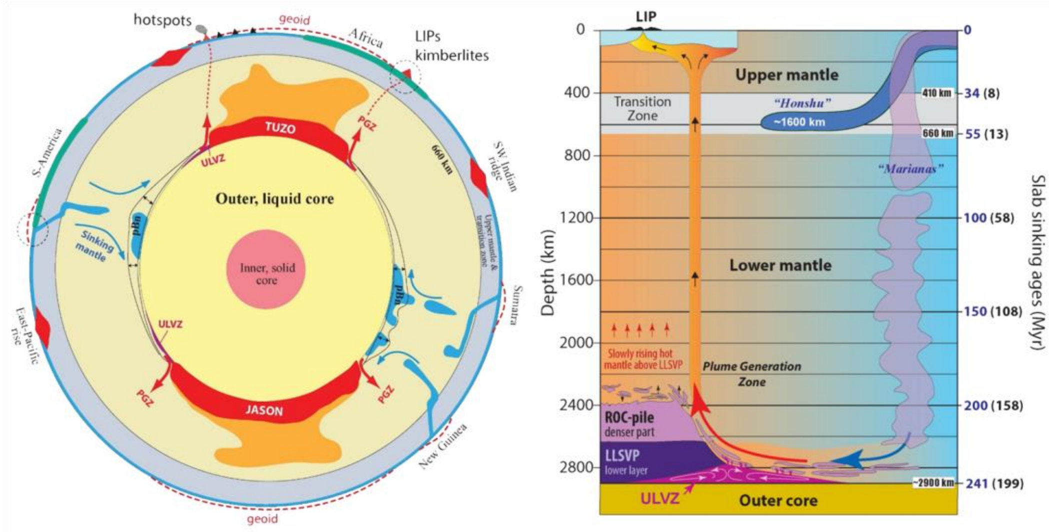

Figure 4: Burke's model of mantle dynamics and thermal plumes

- The mantle flow is one cause of plate tectonic motions. However, it is no longer considered the main driver. Those plates with large subducting slabs move more rapidly indicating that gravity-driven slab pull is possibly more important to plate motion.

Part B: Viscosity Experiments

What is viscosity?

- Newtonian viscosity is a law of friction for fluids.
- Viscosity is defined as the shearing stress divided by the rate of shear for the fluids.
- Shearing stress is the force per unit area (at a point) directed parallel to the direction of shear or flow.
- Viscosity can be thought of as resistance of a fluid to flow. For example, if a fluid (such as water) flows easily, it has low viscosity; if it does not flow easily (such as molasses, honey, or heavy oil), it has higher viscosity.
- Viscosity is measured in units of Pascal-seconds (Pa-s) which are equivalent to Newton-seconds/m^2.

Experiment 1: Shearing stress and low-viscosity fluids

1. Place a piece of the balsa wood on the surface of the oil in the loaf dish.
2. Press down very lightly on the wood with your finger (to create friction between your finger and the wood) and then push horizontally (parallel to the surface of the fluid) on the wood.

Questions:

1. Is it easy to move the wood on oil or does it require some force?

____

2. Does movement of the wood along the surface affect the rest of the fluid? (Watch the thyme.)

____

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Explanation:

- The oil, and the thyme in the oil, do not flow (except for the oil immediately below the wood or adjacent to the sides of the wood which is affected by surface tension of the oil).
- In addition to illustrating the low viscosity of this fluid, this experiment demonstrates that fluids are not capable of sustaining or propagating shear stresses (the movement of the wood and associated movement of the fluid adjacent to the wood do not cause flow in the remaining volume of the oil), and thus do not propagate seismic shear waves, which, in solids, involve shearing motion and shear stresses.

Experiment 2: Shearing stress and elastic solid/high viscosity liquid

1. Make a cube of plasticine.
2. Place the cube on a table and a piece of balsa wood on top of the cube.
3. Using the same procedure as in the previous experiment, push down lightly on the wood (just above the plasticine cube) and push horizontally.
4. Continue to apply a force in the horizontal direction.
5. After some time (many seconds), the flow in the plasticine will be visible and the cube will be distorted by shearing.

Questions:

1. Is it easy to move the wood on the plasticine or does it require some force?

____

2. Does movement of the wood along the surface affect the rest of the plasticine? (Watch the block shape.)

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Explanation:

- The plasticine can be thought of as an elastic solid for short-duration stresses (if you roll it into a ball, it will bounce off the floor, similar to a rubber ball, if dropped), and a viscous fluid for longer time processes.
- After some time (many seconds), the flow in the plasticine will be visible and the cube will be distorted by shearing.
- In this experiment, the shearing stress is larger (you have to push harder on the plasticine in a horizontal direction to get the plasticine to flow) and the rate of shear is much slower. Therefore, the viscosity of the plasticine is much higher than the oil.

Experiment 3: Viscosity and temperature

1. Line a flat baking tray with aluminium foil.
2. Make an inclined plane by placing one side of the tray on the cups or bricks, raising that side by approximately 10 cm.
3. Use the marking pen and ruler to draw a horizontal line on the foil at the top and a second line 10 cm ‘downslope’ from the first line.
4. In sequence, pour the following fluids (about 20 mL each) onto the foil just above the first line:
    - honey heated to 40°C,
    - water, vegetable and honey at room temperature (~ 20°C),
    - Refrigerated honey (~5°C).

    (*Use the 3 measuring cups for the honey; heat the honey in one container; refrigerate the honey in one container; and use the third container for the room temperature water, vegetable oil and honey.)*
5. Using the stopwatch, time how long it takes for the liquid to flow the 10 cm from the upper line to the lower line.
6. Record your results sin the following table.

Results:

Title of table:____

Fluid	Temperature (°C)	Flow time (sec)
Honey	40	
Honey	20	
Refrigerated honey	5	
Water	20	
Vegetable oil	20	

Questions:

Assume that the viscosity of the fluids is roughly proportional to the flow time:

1. Which fluid has the highest viscosity? ______________________________

2. Which fluid has the lowest viscosity? ______________________________

3. Explain the effect of temperature upon viscosity.

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____

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4. What other factors may influence the viscosity of a fluid?

____

____

Explanation:

Examples of viscosities for some common fluids and some Earth materials are shown in Table 1. Note that there is a very large range of viscosities.

Table 1: Viscosity of Selected Fluids and Materials

Fluid/Material	Temperature (°C)	Viscosity (Pa-s) (Pascal-seconds = Newton-seconds/m^2)
Air	20	1.8×10^{-5}
Water	20	1.0×10^{-3}
Honey	20	1.6
Flowing hot lava (Hawaiian volcano)	~ 1150	~ 80
Glass	~ 20	~ 10^{12}
Ice	0	~ 10^{12}
Rock Salt	20	~ 10^{14}
Shallow mantle	~ 1000	~ 10^{23}-10^{24}
Asthenosphere	~ 1300	~ 10^{19}-10^{20}
Deep mantle	> 1500	~ 10^{21}-10^{22}

- *Note that the viscosity of the Earth's mantle is very large.*
- *Mantle rocks, even at high pressure and temperature, behave approximately as solids except over long time periods or when the rock is molten, such as in magma chambers.*
- *Magma chambers have been identified in the hot mantle beneath mid-ocean ridges and in the crust beneath volcanoes.*
- *Mantle flow (thermal convection of the mantle) occurs with very low rates (velocity of flow of a few cm/year).*

Summative questions:

1. Which substance in this series of experiments is most like Earth's mantle? Justify your choice.

2. Why is it useful to perform a series of experiments rather than just one simulation when trying to understand convection in Earth's mantle?

3. *Challenge question:* How much faster is the flow velocity of the vegetable oil in the thermal convection model experiment as compared to mantle flow velocities? Show your calculations.

References:

Braile L (2000). Explorations in Earth Science. Permission granted for reproduction for non-commercial uses. https://web.ics.purdue.edu/~braile/edumod/convect/convect.htm

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