Fossil Fuels (Part II), The Geology of Oil: Topographic Mapping, Crustal Deformation, Rock Porosity, and Environmental Pollution

SPN LESSON #36

TEACHER INFORMATION

LEARNING OUTCOME: After completing topographic maps, analyzing the geologic history of sections of Earth's crust, and finishing laboratory investigations of the factors controlling porosity, students describe how, why, and where petroleum and natural gas deposits accumulate within Earth's crust. Also, students use emissions-avoidance data supplied by the school's DAS system to evaluate the environmental cost of our dependence on petroleum-derived energy.

LESSON OVERVIEW: Using cross sections of geologic structures associated with oil deposits, students review an interpretation of geologic history and relate it to the formation of oil deposits. They explore and explain factors controlling the porosity and permeability of sediments and sedimentary rocks. Also, they interpret topographic maps and construct topographic profiles.

GRADE-LEVEL APPROPRIATENESS: This Level II or III lesson is intended for use with students in grades 8–12 who are enrolled in Regents Earth Science (Physical Setting).

TEACHING THE LESSON: This is the second of three SPN lessons dealing with the topic of fossil fuels, their formation, and their geology (see also SPN #s 35 and 37). This lesson is divided into four parts. They are fairly self-explanatory but you should review each one to see if your students need further introduction. Part 1 should take three class periods and two nights of homework. You may want to approach cross section A as a class activity using the overhead projector. Part 2 involves at least two days of laboratory work and perhaps one night of homework. Part 3 should require one day and one night to complete. Part 4 is probably best done as a long-term research project with two days set aside for reporting out, or discussing, in class.

ACCEPTABLE RESPONSES FOR DEVELOP YOUR UNDERSTANDING SECTION:

Part 1: Responses to cross sections:

A.
1. Deposition of clay
2. Deposition of sand

B.
1. Deposition of clay
2. Deposition of silt

C.
1. Deposition of clay with sand lenses

3. Deposition of clay
4. Deposition of sand
5. Deposition of clay
6. Deposition of sand
7. Deposition of clay
8. Deposition of sand
9. Deposition of sediments above?
10. Compaction and cementation
11. Folding (gentle)
12. Uplift and erosion
TS: Inland of continental margin
NoT: Upward fold capped w/ shale
SR: Bottom two shale layers

3. Deposition of sand
4. Deposition of clay
5. Accumulation of $CaCO_3$ organic debris
6. Deposition of seds above?
7. Compaction and cementation
8. Faulting
9. Uplift and erosion
TS: Stretching continental interior
NoT: Impervious shale at the fault
SR: Lower-left shale layer

2. Deposition of silt
3. Compaction and cementation
4. Uplift and erosion
TS: Continental Edge
NoT: Overlying Impervious Shale
SR: Shale Layers

D.
1. Accumulation of unknown rocks
2. Intrusion of magma
3. Slow solidification
4. Uplift and extensive erosion
5. Subsidence
6. Deposition of sand
7. Deposition of silt
8. Deposition of clay
9. Deposition of sand with some clay
10. Deposition of clay
11. Compaction and cementation
12. Uplift and erosion?

TS: Older continent section that was formerly collisional plate boundary
NoT: Impervious igneous and shale rocks
SR: Lower beds of shale or unseen shale lower in the section

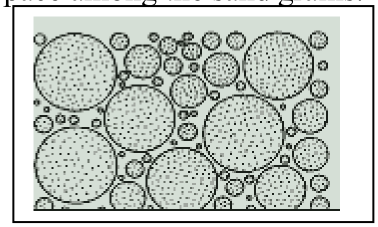
E.
1. Deposition of evaporites
2. Deposition of other sediments below present cross section
3. Deposition of clay
4. Deposition of sand
5. Deposition of silt
6. Deposition of sand
7. Deposition of clay
8. Accumulation of organic $CaCO_3$ debris
9. Density upward flow of salt
10. Uplift and erosion
11. Concurrent compaction and cementation of sediments to sedimentary rock

TS: Sedimentary basin of thick accumulation
NoT: Impervious salt and shale
SR: Lower shale layers

Essay Questions 1 and 2:
1. An increase in the velocity of water current flow brought larger-sized sediments (sand instead of clay) to this area on occasion.
2. The igneous rock was hot when it came into contact with the sedimentary rock: it was an igneous intrusion.

Part 2:
A: Porosity
1. a. Students should see pore space among the sand particles, and perhaps among the coarser silt samples. b. The beaker with sand particles

2. a. The silt particles have filled some of the pore space among the sand grains.
   b. The drawing should resemble this:



3, 4. Responses will vary, depending on several factors including grain shape and grain packing. Responses for the single-sized sediments should be ~10 mL of pore space. The mixed-sized sample should be somewhat less than 10 mL.
5. Responses will vary. However, clay, silt, and sand should approximate 40%, while the mix of silt and sand should be closer to 30%.
6. Students should know that the response should be sand, but experimental results may not verify this. The correct answer may have to be derived during post-lab discussions of the effects of packing and post-depositional mineral and mineral-cement growth.

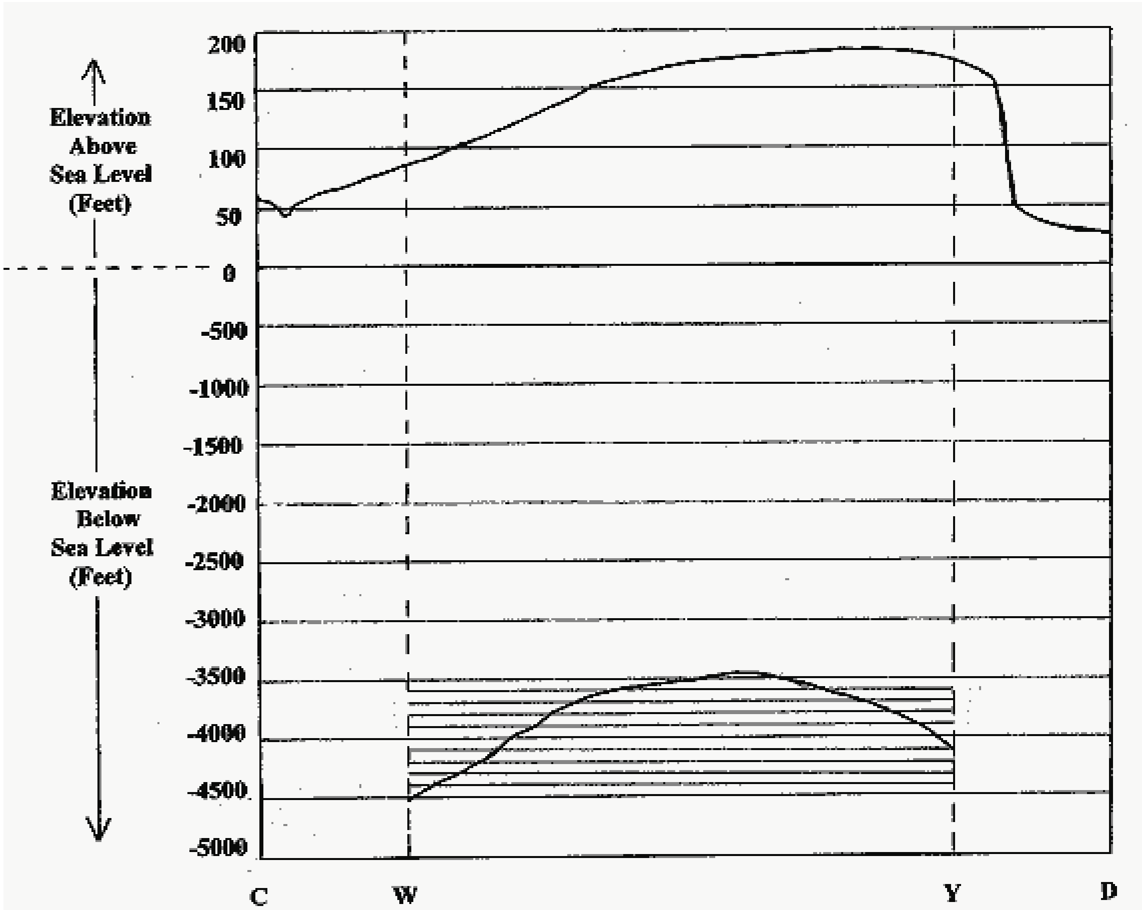
B: Permeability

1. Sand has large pore spaces.
7. a. Times will vary, but the smaller beads should take longer to drain.
   b. Once again rates should vary but the smaller beads should have the slower rate.
8. The larger the pore spaces, the less the friction, the faster the drainage.
9. The sand grains could grow to fill in the pore spaces or the addition of mineral cement could fill the spaces.
10. Shale
11. The clays and micas that become shale are flattened grains that align and overlap during the compression caused by burial. This compression blocks water and oil flow. Also, these grains grow larger as heat and pressure increase.

Part 3: Topographic Maps

1. Upper-left-hand corner has the highest elevations.
2. Southeast (or SSW)
3. The contour lines bend upstream.
4. 100 feet/mile
5. a. No b. 5,280 feet / 175 feet = ~ 30X exaggerated elevation
6. a.—— ..—— ..—— c. Not really, but the rocks could be up-folded

7 a. and 6 b.



7. b. Anticlinal (up) fold c. Sandstone (other rocks also serve as reservoir rocks) d. Shale
8. Responses will vary but many students will probably answer “drill holes.” Some might answer “using seismology.”
9. a. All 12 vibration curves jump up and down at the same time.
   b. The arrival of the second reflection (from the lower limestone bed)

Part 4: The Environmental Costs of Oil Use

Results of this research will vary greatly according to the dedication and abilities of the students. Teachers may wish to assign some of the task to each group so that students are not overwhelmed by the enormity of the project.

ADDITIONAL SUPPORT FOR TEACHERS

SOURCE FOR THIS ACTIVITY: This is not an adapted lesson.

BACKGROUND INFORMATION: Factors controlling porosity and permeability of sediments and rocks are complex, extending well beyond the scope of normal high school Earth Science classrooms. However, they certainly can be simplified with a degree of accuracy for these students. The compression of shales to drive out the accumulated organic materials that were becoming oil and gas can be likened to squeezing a wet sponge as the clay minerals align themselves perpendicularly to the direction of pressure from above. Also, clays, over time and with increased temperatures, become converted to higher percentages of illite crystals. These crystals develop and grow in this same plain, creating a typically impermeable seal that blocks the movement of fluids. As the clay turns to shale, this seal is generally maintained unless fracturing of the rock becomes too severe.

Sands as well as clays are subjected to compaction but have a high variability in overall porosity. The larger particles provide larger pore spaces. Large pore spaces are especially important because they maintain the permeability of sands, thereby allowing the migration of fluids that escape from nearby clays. Permeability is directly proportional to the diameter of pore spaces. Both porosity and permeability of sand are greatly altered by the addition of mineral cements as the sand turns to rock. The continued permeability of sandstone depends in part on the fracturing of brittle sandstones, and this fracturing creates cracks within the rock.

REFERENCES FOR BACKGROUND INFORMATION
Bateman: *The Formation of Mineral Deposits*, Wiley, 1966.
Blatt, Berry, and Brande: *Principles of Stratigraphic Analysis*, Blackwell, 1991.
Ehlers and Blatt: *Petrology*, Freeman, 1982.
Pettijohn, Potter, and Siever: *Sand and Sandstone*, Springer-Verlag, 1972.
Strahler: *The Earth Sciences*, Harper and Row, 1971.

Produced by the Research Foundation of the State University of New York with funding from the New York State Energy Research and Development Authority (NYSERDA)
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(STUDENT HANDOUT SECTION FOLLOWS)

Name ___________________________________

Date ____________________________________

Fossil Fuels (Part II), The Geology of Oil: Topographic Mapping, Crustal Deformation, Rock Porosity, and Environmental Pollution

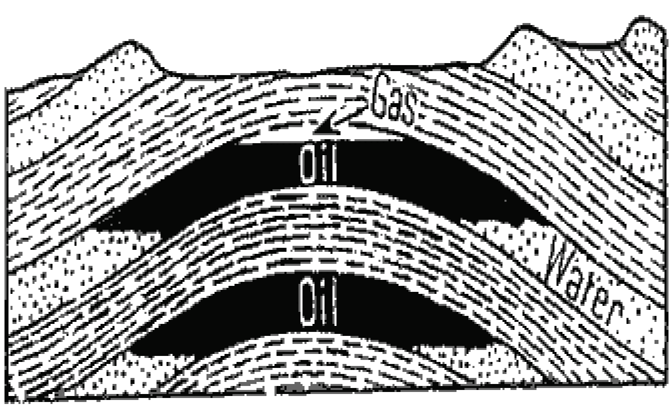
SPN LESSON #36

Part 1: Where Is Oil Found?

As we learned in SPN #35, oil is formed gradually from the accumulated organic materials found in buried sediment deposits. These deposits—usually silts and clays—have been subjected to of the heating and pressure associated with burial under additional sediments, and perhaps, including prolonged mild metamorphism. These pressures squeeze a mix of seawater and oil out of these source beds into surrounding, more porous sediments, usually sands. From these sediments, the seawater and oil rise upward until they are blocked by impervious barriers. Here the oil, water, and natural gas form a pool. The challenge for oil geologists is to locate these oil pools, known as oil traps.

The diagrams below show cross sections of some of the more common types of oil traps. Use the symbols for rock types in your Earth Science Reference Tables to help you interpret the geologic history of each of these cross sections. Fill in the numbered list to indicate the order of the geologic events (uplift and erosion, deposition of silt, folding, compaction and cementation of sediments to rock, faulting, etc.) that occurred in each area. Then complete the box below each diagram: The tectonic setting is where in Earth's crust the type of structure shown in the cross section is most probably found.

Oil Trap Type A:



Tectonic Setting: ______________________

Nature of Trap: ________________________

Lightly Color Most Likely Source Rock of Oil

Geologic History Events:

1______________________

2______________________

3______________________

4______________________

5______________________

6______________________

7______________________

8______________________

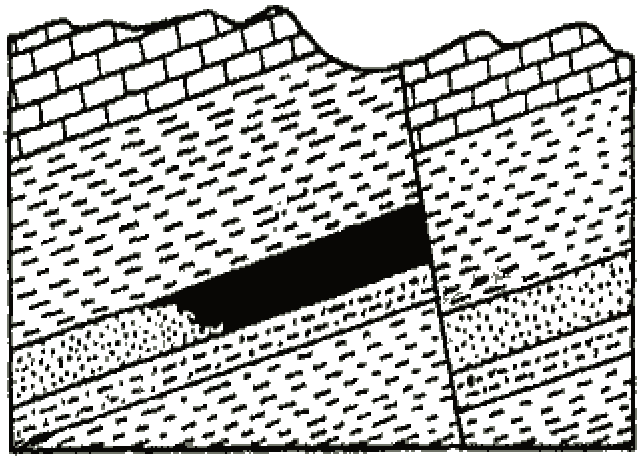
9______________________

10_____________________

11_____________________

12_____________________

Oil Trap Type B:



Tectonic Setting: ___________________________

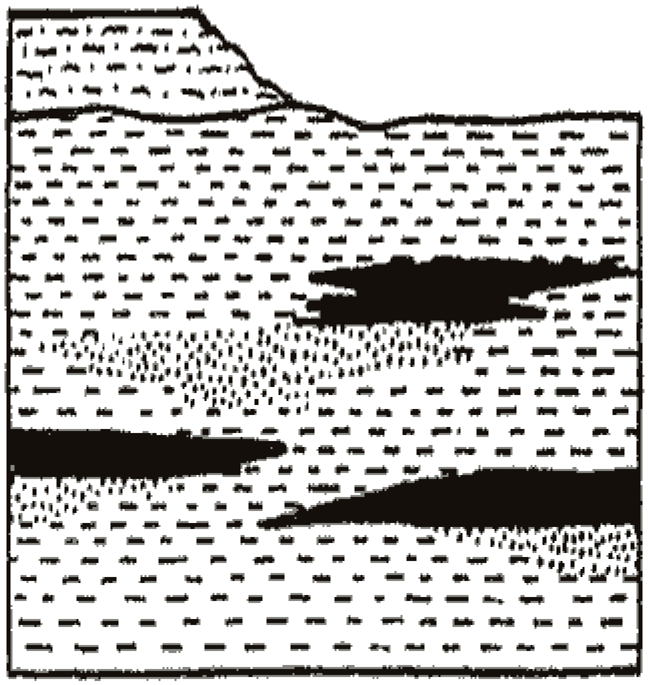
Nature of Trap: ____________________________

Lightly Color Most Likely Source Rock of Oil

Geologic History Events:

1. ___________________________
2. ___________________________
3. ___________________________
4. ___________________________
5. ___________________________
6. ___________________________
7. ___________________________
8. ___________________________
9. ___________________________

Oil Trap Type C:



Geologic History Events:

1. ______________________

2. ______________________

3. ______________________

4. ______________________

Tectonic Setting: ______________________

Nature of Trap: ______________________

Lightly Color Most Likely Source Rock

1. During the deposition of the original sediments that formed these rocks, what might have happened that would account for the pockets of sandstone now present within a thick layer of shale?

____

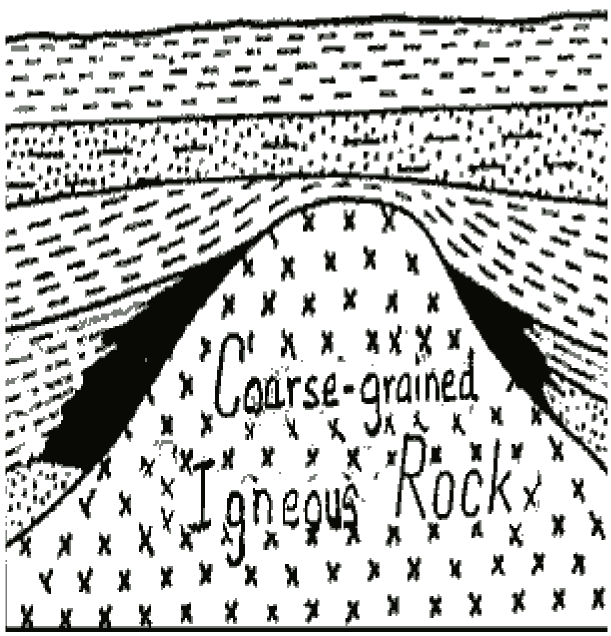
____

Oil Trap Type D:

Notice that there is no indication of contact metamorphism between the igneous rock *x* and the overlying sedimentary rocks; that fact should reveal to you the relative age of the igneous rock compared to the age of the other rocks.

2. What would the presence of contact metamorphism in the edge of the sedimentary rocks touching igneous rock *x* indicate?

____



Tectonic Setting: ________________________

Nature of Trap: __________________________

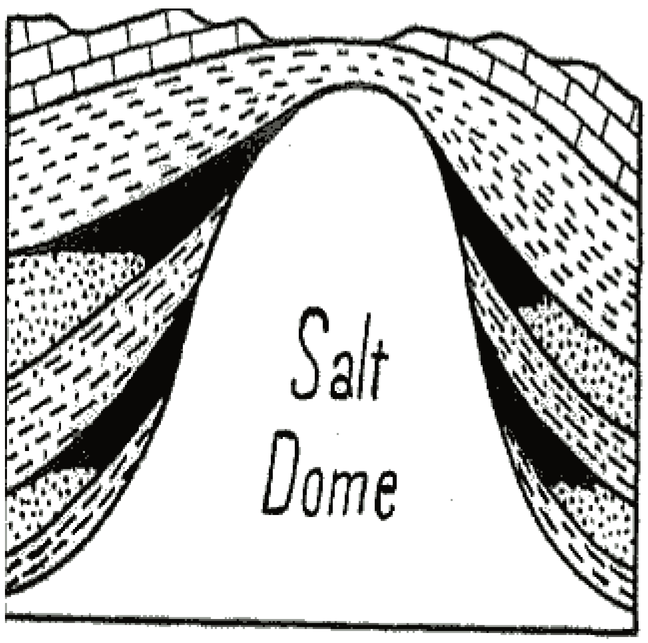
Lightly Color Most Likely Source Rock

Geologic History Events:

1. ________________________
2. ________________________
3. ________________________
4. ________________________
5. ________________________
6. ________________________
7. ________________________
8. ________________________
9. ________________________
10. ________________________
11. ________________________
12. ________________________

Oil Trap Type E:

This may seem to most of us a strange geologic feature, but salt domes are very important oil traps along the Gulf coast in the southern United States. These actively rising concentrations of salt are much less dense than surrounding sediments and rocks. Much like oil and water, the salt tends to rise toward the land surface as the surrounding materials settle downward. The rising dome tilts adjacent rock layers, providing slanting channels of oil.



Tectonic Setting: ___________________________

Nature of Trap: ____________________________

Lightly Color Most Likely Source Rock

Geologic History Events:

1. ___________________________
2. ___________________________
3. ___________________________
4. ___________________________
5. ___________________________
6. ___________________________
7. ___________________________
8. ___________________________
9. ___________________________
10. __________________________
11. __________________________

Part 2: Porosity and Permeability Laboratory Activity

A: Porosity

Why is sandstone typically the reservoir rock in which oil is found, and why does shale so often block the upward movement of oil? To answer these questions, first determine the porosity and permeability of the sediments of which these sedimentary rocks are made. Next, explore how lithification (the process of turning to stone) changes the characteristics of these sediments.

Materials (per student group):

100 mL graduated cylinder
10 mL graduated cylinder
100 mL beakers (4)
Different-sized sediment samples: clay, silt, sand
Hand lens
Stirring rod

Procedure:

1. Using the 100 mL graduated cylinder, measure 50 milliliters of each of the three sediments. Place each sample in a separate 100 mL beaker. Gently tap the beakers to settle and level the sediments. Look at the particles in each of the beakers from the side through the hand lens.
   a. Can you see pore space between the particles in the beakers? _______

   b. In which beaker are the pore spaces the largest? ______________________

2. In a fourth beaker, place 25 mL each of sand and silt, blend them together with the stirring rod, and then tap the beaker to settle and level the sediments. Look at the particles in this beaker with the hand lens.
   a. How have the pore spaces among the sand grains changed from those seen in the beaker filled with sand alone?

      ____

   b. Make a drawing showing the arrangement of particles in the fourth (mixed) beaker in the box provided to the right. (x30)

3. Fill the 10 mL graduated cylinder to the 10 mL mark so that the meniscus sags to the 10 mL line. Carefully and slowly, one drop at a time, add water to the beaker containing sand. Continue to add water until the water level becomes just visible at the surface of the sand. Record the amount of water you have added by reading the water level remaining in the graduated cylinder.

   Sand:_____________mL

4. Repeat this procedure with each of the sediment containers and record the amount of water in the spaces provided below.

Silt:______________mL

Clay:______________mL

Mixture of sand and silt:______________mL

5. Construct a bar graph of the % Porosity of each of these materials on the form below.

Clay
Silt
Sand
Mix

0 10 20 30 40 50 60 70 80 90 100
% Porosity

[Note: To calculate % Porosity, follow these instructions. Divide the amount of water you added to each beaker of sediment by the total volume of sediment in each beaker (50 mL), and then multiply by 100.]

6. Which type of sediment has the most room to store liquids such as water and oil?

____

B: Permeability

Yet, porosity is only part of the oil story. As you know, the oil gets squeezed out of the muds (clays and silts) where it has formed from the organic material present. The oil then migrates through other sediments and rocks, especially sand and sandstone, and it concentrates in the open pore space. The ability of the oil to move through the rock material depends on the presence of interconnected pore spaces and cracks within rock material. **Permeability** is the measure of the rate of fluid movement through passageways.

1. What information from your study of porosity might explain why sand typically has high permeability?

____

Now, collect some data regarding permeability rates and particle size and see if your response is correct. Although this laboratory work represents a fairly uncommon situation in the real world of sediment sorting, you will be able to demonstrate the effect of one of the more important variables controlling the rate of fluid movement through sediments.

d. What is probably the impermeable cap rock that traps the oil?

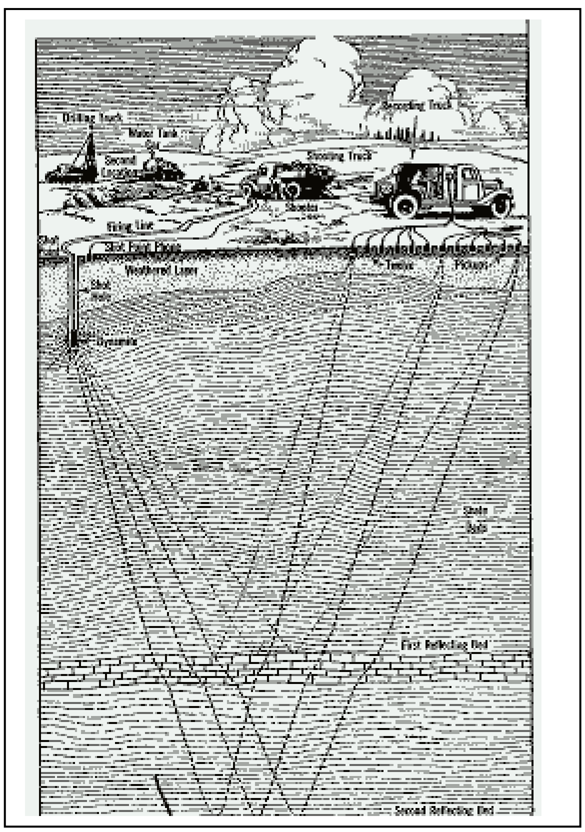
____

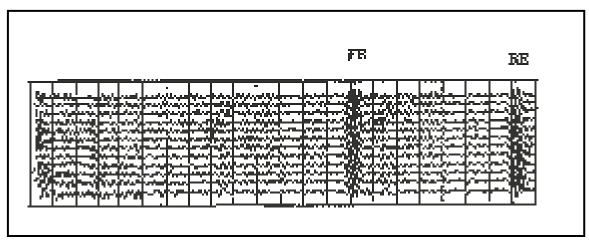
8. How do oil geologists find subsurface structures such as this? What's your inference?

____

If you said, "by drilling several holes in the ground," you might be right—but realize that drilling through rock down to these depths becomes very expensive, and until oil is found there is no return on the investment. A more likely method is the tool geologists have used to interpret much of the basic structure of Earth's interior: seismology. Figure 4 below shows one of the seismology methods used extensively by oil geologists. Only a shallow hole is drilled so that a dynamite charge can be inserted and exploded (diagram left), sending out vibrating waves comparable to earthquake waves. Geologists have found that changes in the characteristics of rocks underground act as reflective surfaces for these waves, bouncing them back to the surface where sensors (pickups in the diagram) receive them. A record of their arrival is made. The seismogram recording shown to the right in figure 4 shows the vibrations picked up by each of the 12 receivers.

Figure 4: Seismic Reflection Method (showing resulting seismogram at right)





[modified from Bateman: *The Formation of Mineral Deposits*, Wiley, 1966, p. 292]

9. Why might sandstone have neither a high porosity nor a high permeability?

____

As important as oil migration is in forming oil deposits under natural conditions, the blocking of the oil movement by *impermeable* rock is also an important part of the process. This blocking allows the oil to accumulate in the underground traps as previously described.

10. What type of rock is typically the impermeable barrier?

____

11. Why is this rock typically impermeable?

____

Part 3: Topographic Maps

The job of the oil exploration geologist is to find these various oil-bearing rock layers and the structural oil traps that confine them. Topographic features and the maps that represent them are the usual starting point for this exploration. The ability to read these maps is an essential skill for these scientists.

Figure 1 below shows how topographic maps represent the shape of the land's surface through the use of lines of equal elevation called contour lines. The top section of the map shows a topographic map of a region of Earth's surface. The curving lines on the map are contour lines that have been labeled to show elevation above sea level in feet. Every point on a particular contour line has the same elevation. Points in between these lines have elevations with values between those of the lines above and below.

1. Where are the highest elevations on this map?

   ____

2. In which direction does the creek (stream) flow?

   ____

3. In addition to the changes in elevation along the creek, notice the shape of the contour lines in the vicinity of the creek. In which direction do the lines bend as they cross the creek?

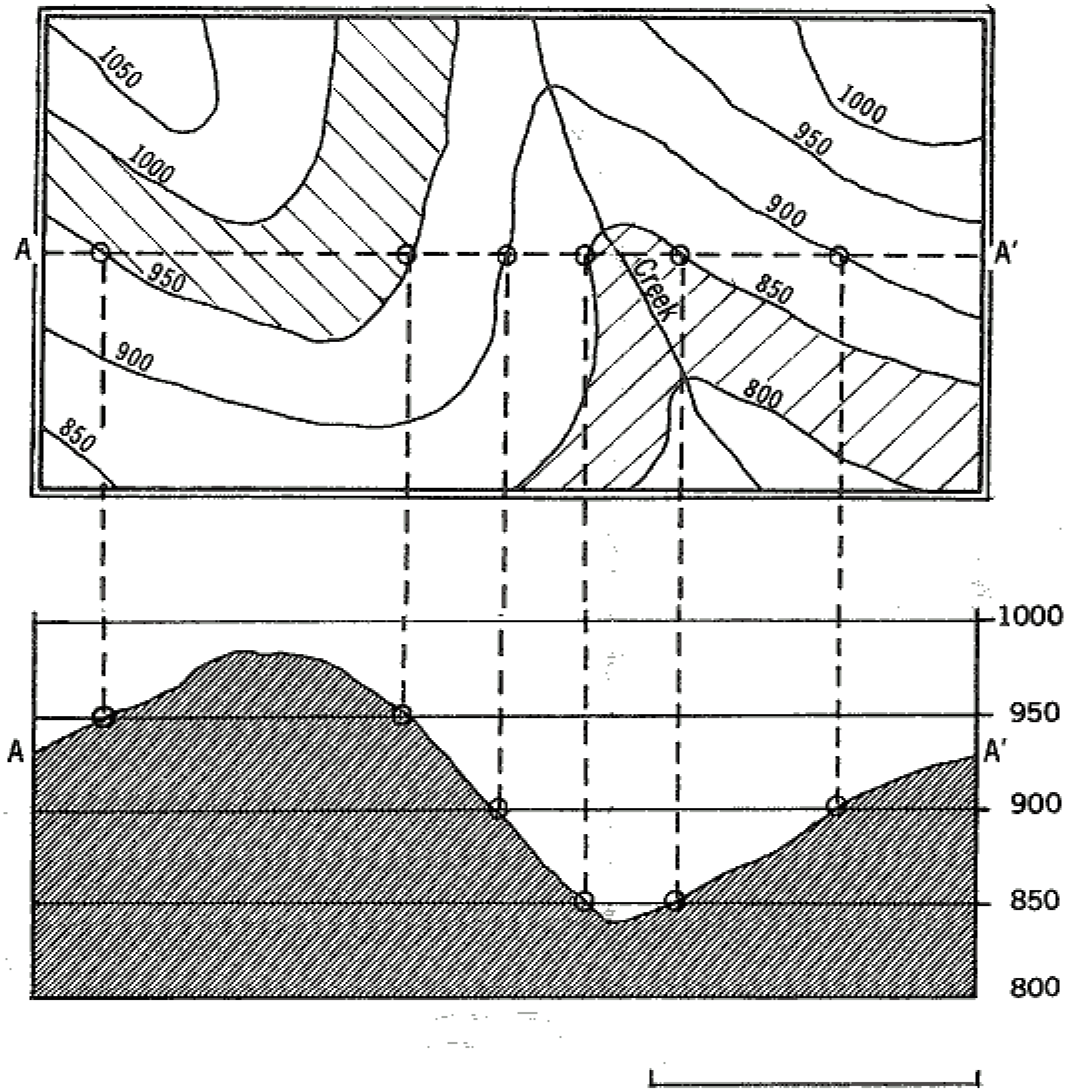
   ____

4. What is the gradient of the creek from the 900-foot contour line to the 800-foot contour line? (Use the formula for average gradient on the front page of your Earth Science Reference Tables.)

Show your work:

The average gradient is________________________feet/mile

Figure 1: Topographic Map and Topographic Profile



1 Scale Mile

[modified from *AGI Geology and Earth Sciences Sourcebook*, Holt Rinehart Winston, 1970, p. 402]

The lower portion of figure 1 shows a topographic profile, which represents the changes in elevation along line *A – A'* across the map. A profile can be constructed by placing the edge of a piece of paper along line *A– A'* on the map, marking the points where the contour lines intersect the edge of the paper (the small circles), and then transferring those elevations to an elevation grid as shown by the dashed lines. Be sure to mark the endpoints *A* and *A'* so you can correctly mark the distances of the elevation points. Also, notice the diagonally marked portions of the map and see how the profile line is drawn in these regions. Both of these areas are between points of the *same* elevation on the profile but lie between points of *different* elevation on the map. Notice that the profile of the hill rises above 950 feet and that the valley falls below 850 feet in these two instances.

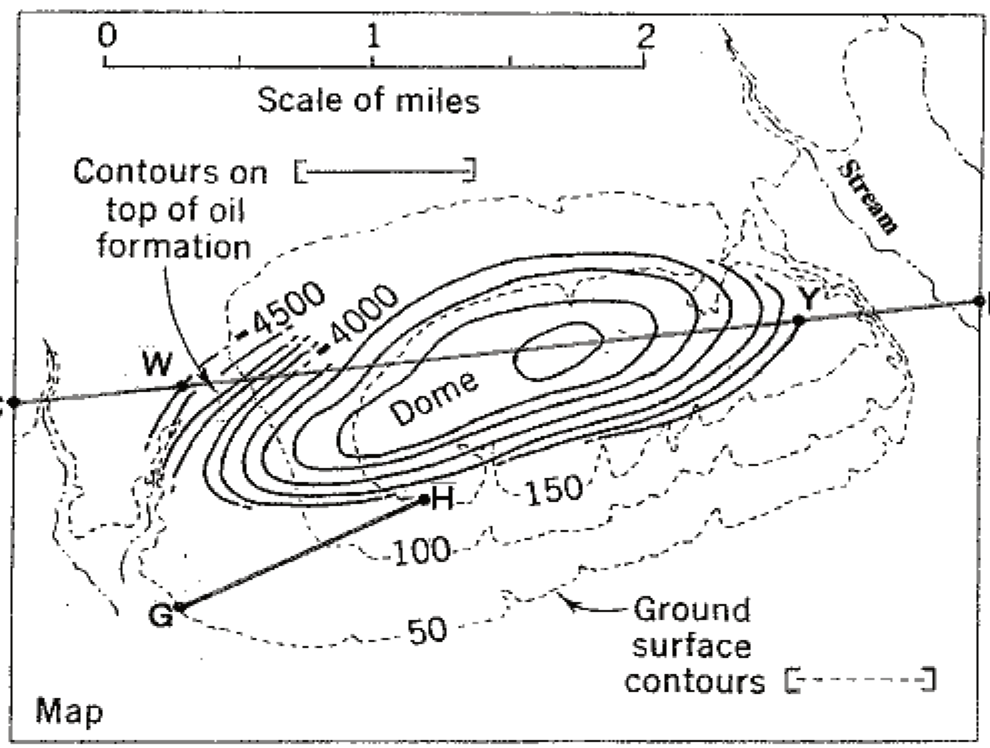
5. Take a piece of paper and see if you can construct the same profile shown in figure 1, using the method described above.
   a. Is the vertical scale of the profile the same as the horizontal distance scale of the map and the profile? ________
   b. How much vertical exaggeration is there in the profile? (To obtain this value, divide 5,280 feet [the mile shown on the horizontal scale at the bottom of figure 1] by the number of feet in elevation that the length of the mile line represents on the vertical scale.)

Show your work:

The vertical scale is exaggerated approximately________times.

6. Figure 2 below shows a topographic map from an oil trap in California. Notice that there are *two* sets of contour lines on this map. This may seem confusing at first but the oil geologist's task is to find oil underground. If you concentrate on one set of lines at a time, the map will become easier to understand.

Figure 2: Topographic Map of Surface Features and of Subsurface Oil Deposit

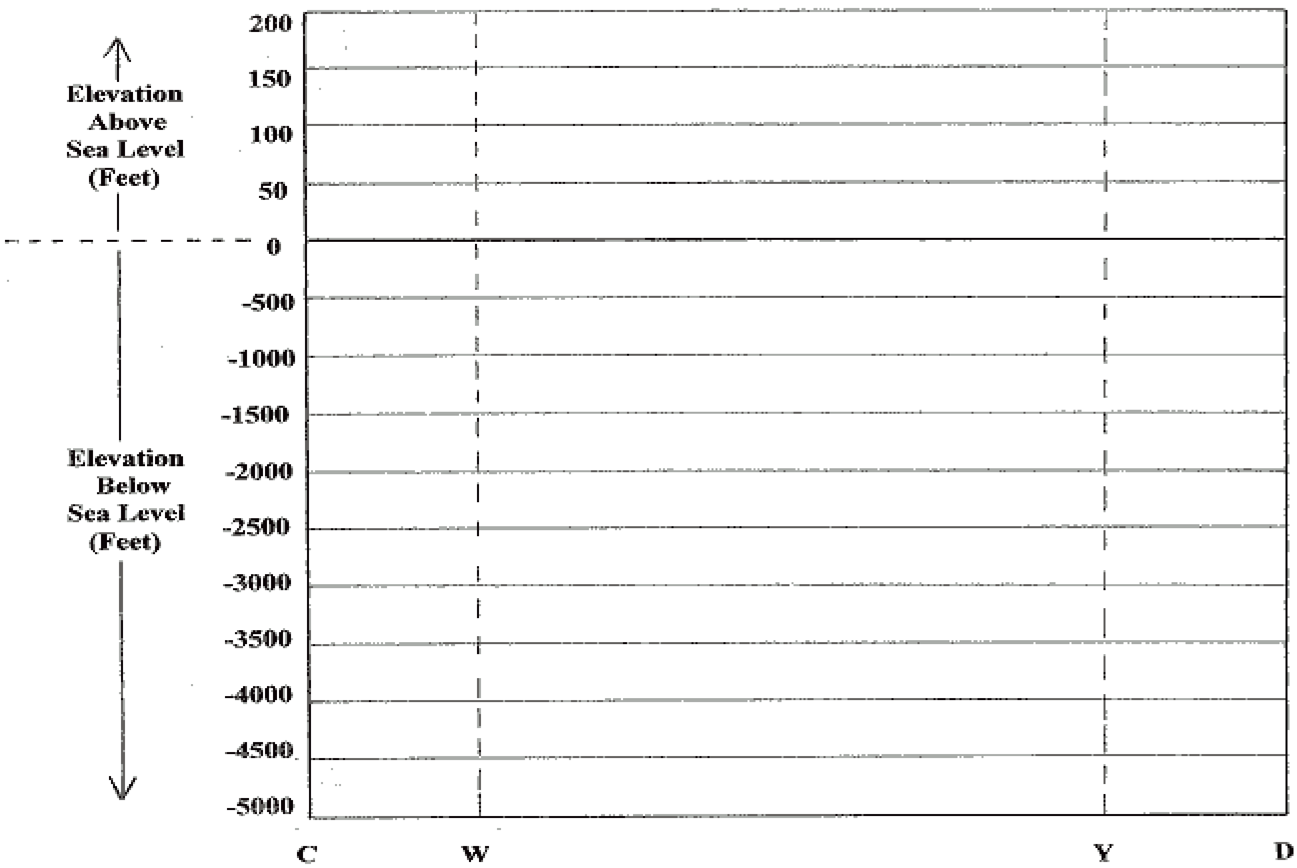


[modified from Strahler: *The Earth Sciences*, Harper Row, 1971, p. 383]

a. The dashed set of contour lines is used to show the elevation of the land surface in feet above sea level. Draw the symbol used to show the streams on this map. ______________________________
b. On the top section of figure 3 below, construct a topographic profile of the land surface from point *C* to point *D* using the method shown in figure 1.
c. Is there any indication in the surface topography that an oil trap exists in the rock below?

____

Figure 3: Form for the Construction of Topographic Profiles



7. The dark, solid lines show the *depth below sea level* of the top of the oil-bearing layer of rock discovered by the oil geologists.
   a. Reading only these solid lines, construct a profile of the shape of this oil-bearing layer in the bottom section of figure 3 above. [Note that the vertical scales of these two profiles are different.]
   b. What kind of oil trap structure is this?

   ____

   c. What kind of porous rock is holding the oil?

   ____

d. What is probably the impermeable cap rock that traps the oil?

____

8. How do oil geologists find subsurface structures such as this? What's your inference?

____

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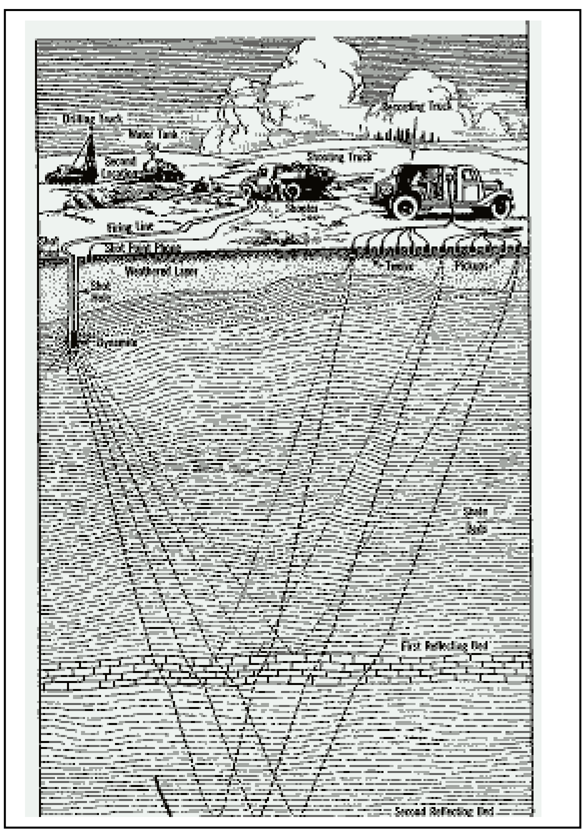
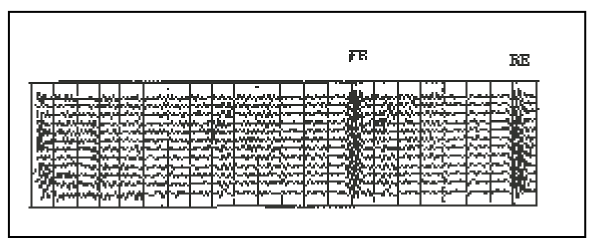
Figure 4: Seismic Reflection Method (showing resulting seismogram at right)





[modified from Bateman: *The Formation of Mineral Deposits*, Wiley, 1966, p. 292]

9. a. How does the seismogram show the arrival of the reflection from the first reflecting limestone bed?

____

b. What does *RE* represent on the seismogram?

____

Part 4: The Environmental Costs of Oil Use

Working in teams and using your school's DAS system, determine the amount of air pollution that results from burning 100 gallons of oil to produce electricity. Investigate further in your library and on the Internet to complete each of the following tasks.

1. Determine the products produced by oil combustion.
2. Describe how each of these materials affects the environment.
3. Determine the natural processes that help remove some of these materials from the environment.
4. Evaluate the long-term environmental costs of continued oil combustion.
5. Determine the additional costs of oil production and use.
6. Compare oil usage costs to those of using solar energy: try to evaluate in dollars the dollar cost of each / kilowatt-hour using each energy source.
7. Be prepared to take part in a classroom discussion of each of these points.