Source Rocks: Generation and Migration of Petroleum

I. Introduction
  a. Majority of global petroleum associated with sedimentary rock environments
    i. Sandstones and carbonate sedimentary rocks = common reservoirs

  b. Limited occurrence of petroleum associated with igneous and metamorphic rock environments
    i. Crystalline reservoirs in contact with sedimentary strata or unconformities
    ii. Examples of mantle-drived hydrocarbons
    iii. Trace Hydrocarbons associated with chondrite meteors

  c. Biogenic models of petroleum generation in sedimentary environments most favored
    i. Majority of fossil organic matter stored in sedimentary rock environment
    ii. Thermal maturation of organic matter + time = process of petroleum generation

    iii. ~10^{20} g of carbon estimated to be stored in Earth's crust ("Sequestered")
      1. ~82% of carbon contained in limestones, dolomites, carbonate rocks
      2. ~18% contained in coal, oil and gas

II. Modern Organic Processes

  a. The Carbon Cycle and Petroleum Generation
    i. Carbon Source: Weathering of crustal rocks; limestones, marble; metamorphism
    ii. CO_2 exchange from oceans-continents to atmosphere
    iii. Photosynthesis – plant basis for food chain
    iv. Animal-plant food associations-life cycle processes
    v. Bacterial decay of plants/animals – recycling of carbon into atmosphere (CO_2, CH_4)
    vi. Sediment Burial and Preservation = carbon storage in lithosphere
      1. Limestone
      2. Fossil fuels (petroleum, coal)
      3. **REQUIREMENT: Preservation** of organic carbon in fossil fuels generally associated with anoxic, bacteria-deficient environments
        a. "Black Stinking Muds"
        b. Rapid Burial in Water Saturated, Sedimentary Basins
        c. <1% of organic carbon stored in sediment record; however occurs over large amounts of geologic time

  b. Chemical Composition of Living Organic Matter
    i. Photosynthesis: algae and plants
      1. Water + Atmospheric CO_2 + Sun Light ==== water and glucose + oxygen

$$6CO_2 + 12H_2O = C_6H_{12}O_6 + 6H_20 + 6O_2$$

      2. Glucose forms basis of more complex organic molecules through food chain
      3. Plants / animals die: converted back to carbon dioxide and water, via bacterial decay

    ii. Organic Composition
      1. Carbohydrates
        a. Sugars + polymers of cellulose, starch, chitin
        b. Energy source for living organisms
        c. General formula: $C_n(H_2O)_n$
        d. Animals and plants

      2. Proteins

a. Animal based primarily
b. CHON- compounds with S and P
c. Comprised of Amino acid compounds

3. Lipids
    a. Animals and plants
    b. Insoluble in water
    c. Fats-oils-waxes
    d. Similar in molecular composition to petroleum; most important oil source
    e. C-H-O molecules
        i. Base molecule C_5H_8

4. Lignin
    a. Found in higher-order plants
    b. Composed of aromatics (carbon ring compounds)

Organic Composition of Living Organisms

Organism	**Wt. % of Major Consitutents**				
	Proteins	**Carbohydrates**	**Lignin**	**Lipids**	
Plants					
Trees	~5%	~55%	~28%	~12%	(averages)
Phytoplankton	23%	66%	0%	11%	
Diatoms	29%	63%	0%	8%	
Animals					
Zooplankton	60%	22%	0%	18%	
Invertebrates	70%	20%	0%	10%	

c. Organic Biomass Production

i. Marine Ecosystems – World Ocean Systems
1. Living Organisms / Organic Carbon Sources
    a. Phytoplankton – basis of food chain
        i. 90% of supply of organic carbon in oceans
        ii. E.g. diatoms, blue-green algae
        iii. Photosynthesis increases oxygen content of water
    b. Zooplankton-bacteria-fish

2. Global Biomass Production
    a. High Productivity Zones
        i. Shallow, well oxygenated, sunlit seas
        ii. Mid-Latitude humid and equatorial latitudes
        iii. Coast Regions Associated with Cold Water Upwelling Currents
            1. E.g. California, Chile, South Africa
    b. Low Productivity Zones
        i. Deep Ocean
        ii. Polar and Arid Tropical Zones

3. Controlling Factors of Biomass Production

a. Sunlight – generally < 100 m in ocean = photic zone
b. Nutrient Supply – nitrates and phosphates important for plants
    i. Currents
    ii. River influx
c. Turbidity: low turbidity = favorable
d. Salinity = high salinity unfavorable
e. Water Temperature: species dependent; 5-20 ^{o}C optimal

ii. Non-marine Continental Ecosystems
    1. Living Organisms / Organic Carbon Sources
        a. Land plants, fresh water algae
    2. High Productivity Zones
        a. Tropical Regions; abundant water
        b. Swamps, deltas
    3. Low Productivity Zones
        a. Polar regions

NOTE: Organic Biomass Production does not lead to petroleum generation; it's the combination of Production and Preservation in the Environment!

III. Preservation of Organic Matter and Prediction of Source Rocks
  a. Controlling Factors
    i. Anoxia – low oxygen depositional environments critical for organic carbon preservation
        1. Bacterial decay consumes oxygen over time
        2. Restricted water circulation limits oxygen supply
        3. "Stagnant" water conditions optimal

    ii. Bacterial Decay
        1. Preservation favored by anerobic bacteria
        2. Aerobic bacteria will destroy organic matter, recycle back to CO_2

    iii. Scavenging Fauna
        1. Benthic Worms, burrowing organisms consume organics as part of feeding cycle
        2. Bioturbation – will make you go blind, and consume your organic carbon
        3. Anoxic environments favorable to preservation

    iv. Sedimentation Rate and grain size
        1. Rapid settling rates, deposition and burial dilutes organic mass
        2. Fine sediment particles disseminated in clays = highest organic mass ratio
        3. Clay/mud = low permeability and oxygen content; restricted fluid flow; preserves organics
        4. "Black Stinking Muds"

    v. Depositional Setting
        1. Anaerobic depositional conditions, moderate burial
        2. Thermal Stratification of Water – limited circulation to promote oxygen-deficient environments
        3. Isolated seaways and basins, with limited water flux; high organic production
            a. Marginal Marine Basins
            b. Lakes
            c. Deltas
        4. Sedimentary Facies Models – important predictor of source-rock and reservoir rock predictions

IV. Petroleum Generation – metamorphism of preserved organic matter over time; a function of geologic time and temperature

a. Steps of Petroleum Development
    i. Step 1: Preservation of organic matter in sediment record
    ii. Step 2: Development of Kerogen – disseminated insoluble organic matter in sediments
    iii. Step 3: Conversion of Kerogen to petroleum compounds (crude oil and gas)

b. Kerogen Types
    i. Type I – algal kerogen
    ii. Type II – zooplankton and phytoplankton
    iii. Type III – humic kerogen; woody plant materials

c. **TIME-TEMPERATURE Thermal Maturation Process** – Oil and Gas Generation with Burial, increasing geothermal temperatures; 40 to 150 ^{o}C over time = the sweet spot for petroleum generation

    i. Stage 1: Diagenesis (“Immature Stage”)
        1. Shallow subsurface, recent sediments
        2. 0-70 ^{o}C; shallow lithostatic pressures; burial depth increasing
        3. Microbial degradation; Hydrogen/Carbon ratio decreases with time
            a. Early phase biogenic gas production

    ii. Stage 2: Catagenesis (“Mature Stage”)
        1. Kerogen transformation; oil transformation; mixed gas production
        2. Increased temperature and pressure 50- 200 ^{o}C;
            a. 100 – 150 ^{o}C early phase oil generation with mixed wet gas
                i. 60 – 120 ^{o}C = oil generation
                ii. 120 – 150 ^{o}C = gas generation (wet gas)
            b. >150 ^{o}C later phase gas generation (dry gas)
        3. Bacterial action diminished; Hydrogen/Carbon ratio decreases with time
        4. Thermogenic Gas production

    iii. Stage 3: Metagenesis
        1. High temperatures and pressures; upper limits of dry gas production
        2. >200 ^{o}C; depth of burial, temp. and pressures increase
        3. At ultimate end, metamorphism occurs, hydrogen depleted, and graphite forms

d. Measurement of Source Rocks and Thermal Maturity

    i. Drilling / sampling from well logs

    ii. Chemical Analysis
        1. Rock Pyrolysis – flame ionization, measure of total organic carbon
        2. Gas Chromatography – organic molecule identification
        3. Visual Kerogen Identification (under microscope)

        4. Vitrinite Reflectance / optical properties common in coal evaluation
            a. Vitrinite – immature organic matter, derived from lignin and cellulose in plant material
            b. Vitrinite Reflectance – predictor of petroleum potential in source rock, a measure of thermal maturation
                i. Calibrated to reflectance of crude oil; Ro index = 1.0 (fully mature hydrocarbarbon)

1. Ro >0.8 thermally mature organic matter, in oil and gas present
2. Ro < 0.55 thermally immature organic matter
3. Ro 0.55-0.8, organics in petroleum/gas producing range

5. Clay mineral diagenesis
   a. Degree of clay mineral alteration of source rocks; temperature dependent

V. Petroleum Migration and Expulsion from Source Rock
   a. Petroleum Generation Model
      i. Petroleum products derived from thermal maturation of organic material to kerogen in source rocks
         1. General Pattern: organic rich sources rocks in clays, muds and shales
      ii. Petroleum migrates to porous and permeable reservoir rocks; via expulsion pathways from source rocks
         1. General Pattern: reservoir rocks comprised of sands, sandstones and porous limestones/dolomites
      iii. Oil, gas, formation water buoyantly structured according to density in traps; implies that the fluids have migrated to the reservoir location under the influence of gravity
         1. Water-oil-gas in ascending order of buoyancy

MORAL OF STORY: hydrocarbons migrate into reservoir rocks in the subsurface environment, at some time after burial and generation. Optimal sequencing of burial, generation, migration and entrapment over time is necessary for economic accumulations of hydrocarbons.

   b. Migration Processes
      i. Primary Migration
         1. Migration of hydrocarbons from source rock (organic-rich clay or shale) into permeable reservoir rock (sands, sandstones, limestones/dolomites)

         2. **"MIGRATION PARADOX"** – source rocks involve thermally heated, organic, impermeable clays, muds/shales undergoing compaction over time… how do the fluids migrate out of the source rocks in such low permeability conditions at the maturation stage?

            a. Possible mechanism: over-pressure source rocks with micro-fracturing bursts and episodic release of fluids from source rocks

      ii. Secondary Migration
         1. Movement of oil and gas in reservoir rocks – buoyancy/gravity driven by density contrasts

      iii. Controlling Factors
         1. Timing of generation and migration
         2. Physical parameters of source bed (temperature, pressure, permeability, porosity)
         3. Chemical composition of source bed (organics and mineralogy)
         4. Timing of kerogen transformation to oil and gas
         5. Mixture of migrating fluids: combinations of water, oil, gas
         6. State of fluids: liquid, gas, dissolved gases

      iv. Migration Models – exact process unknown, difficult to observe in real time
         1. Expulsion of Hydrocarbons as water-soluble "Proto-petroleum"
            a. Hydrocarbon ingredients migrate with expelled formation water as soluble ketones, organic acids and esters

2. Expulsion of Hydrocarbons in Aqueous Solution
    a. Hot Oil Theory – oil solubility increasing in formation water at higher temperatures above 150 C. Petroleum transported with formation waters during source rock compaction.
3. Expulsion of Oil in Gaseous Solution
    a. Gas content (natural gas, carbon dioxide) decrease viscosity of oil during expulsion process out of low-permeability source rocks
4. Primary Migration of Free Oil
    a. Immiscible free oil migration as droplets with formation water during compaction
    b. High-pressure micro-fracturing of source rock at time of expulsion
5. Adsorption of Hydrocarbons in Source Rocks (“Oil Shale”; “Gas Shale”)
    a. In-situ hydrocarbons in source rocks
    b. Requires enhanced recovery techniques