# EVOS vs. DWH


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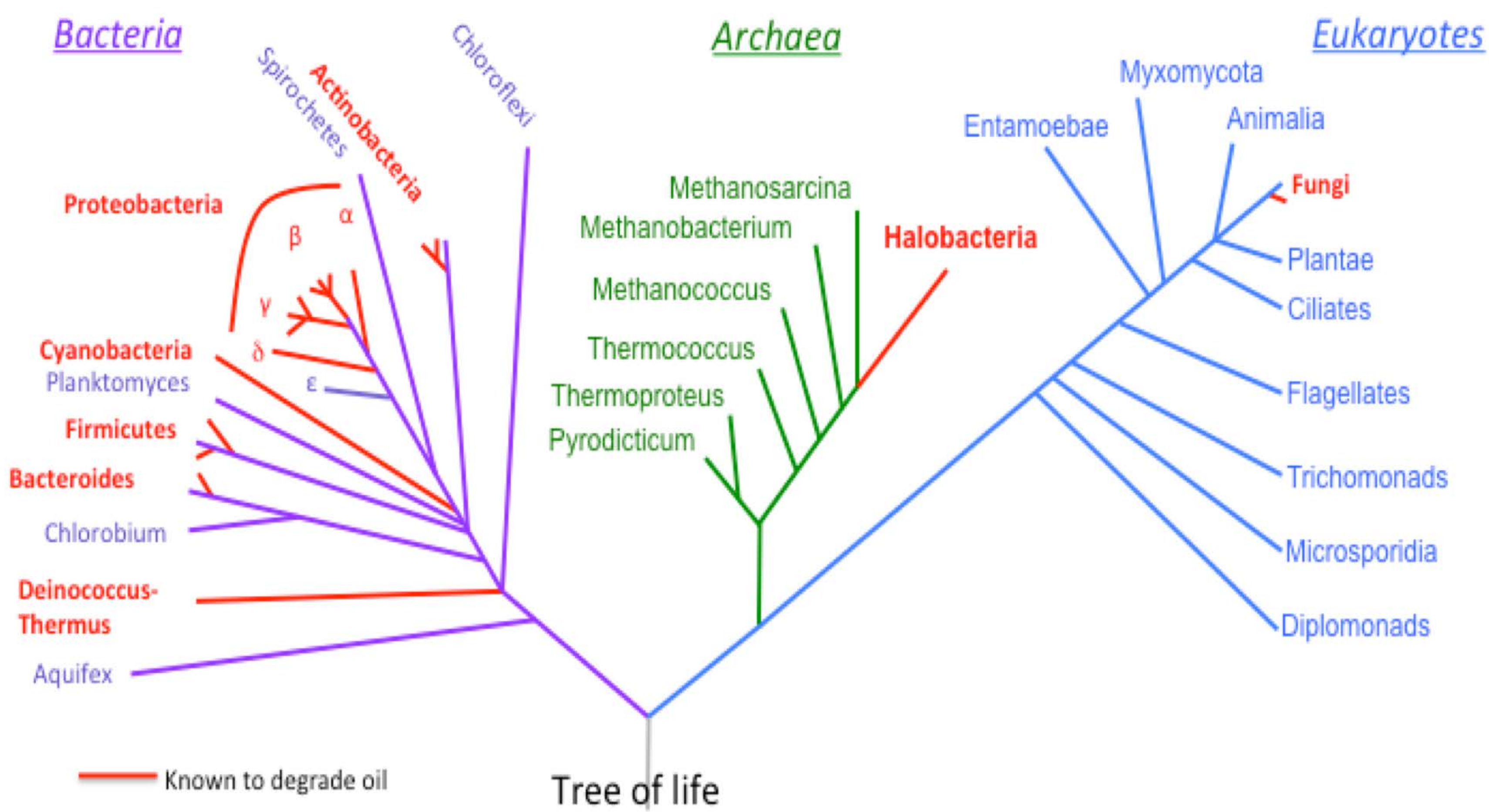
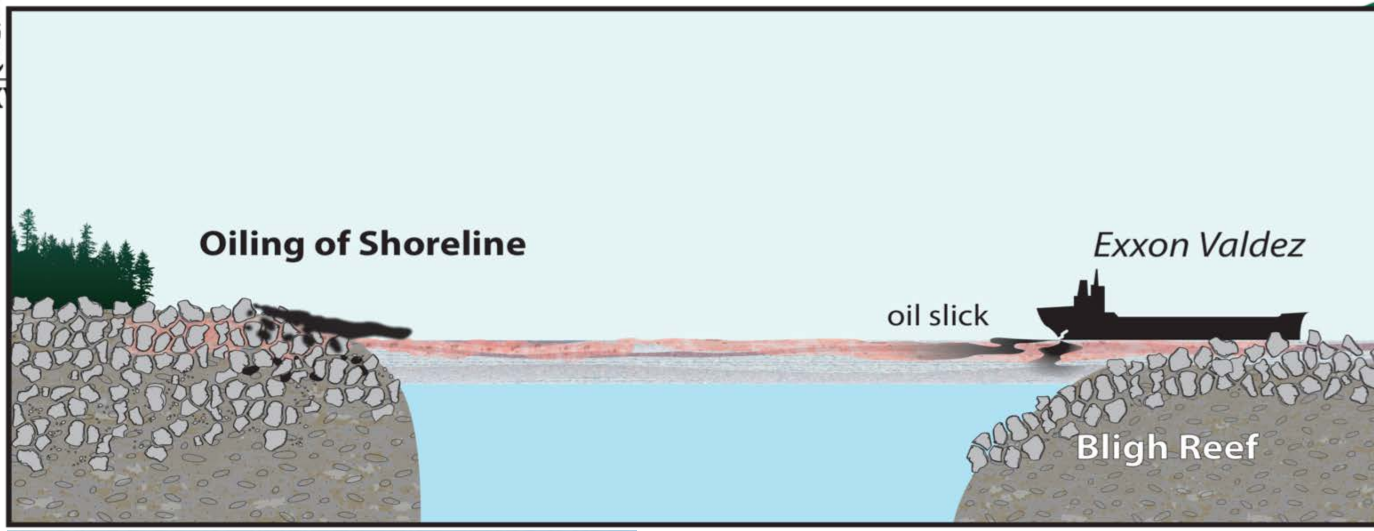
4/19/18

# Images that will be hard forget!

- 11 men, 6,147 birds, 613 sea turtles, 157 marine mammals killed Deepwater Horizon as of 4/17/11 US Fish & Wildlife Collection Report, GoM (4.1 mbbl)
- 2,500 birds killed Cosco Busan, San Francisco (0.0013 mbbl)
- 250,000 birds, 22 orcas, 2800 otters killed Exxon Valdez, Alaska (0.26 mbbl)
- 20,000+ birds, 9,000 tons of shellfish killed Amoco Cadiz, France (1.6 mbbl)
- 10,000+ birds Killed Ixtoc I, GoM (3.3 mbbl)
- 10,000+ birds killed, 800 miles of coast oiled, Gulf War, Kuwait (11 mbbl)

Oil degrading microbial taxa. Oil degrading microbial phyla, highlighted in red, have been identified from all three domains of life. Hazen et al. (2016)



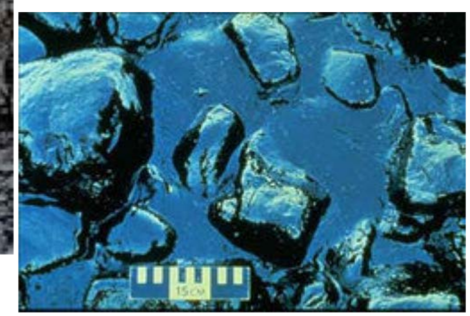



Physical washing of shorelines with high pressure water

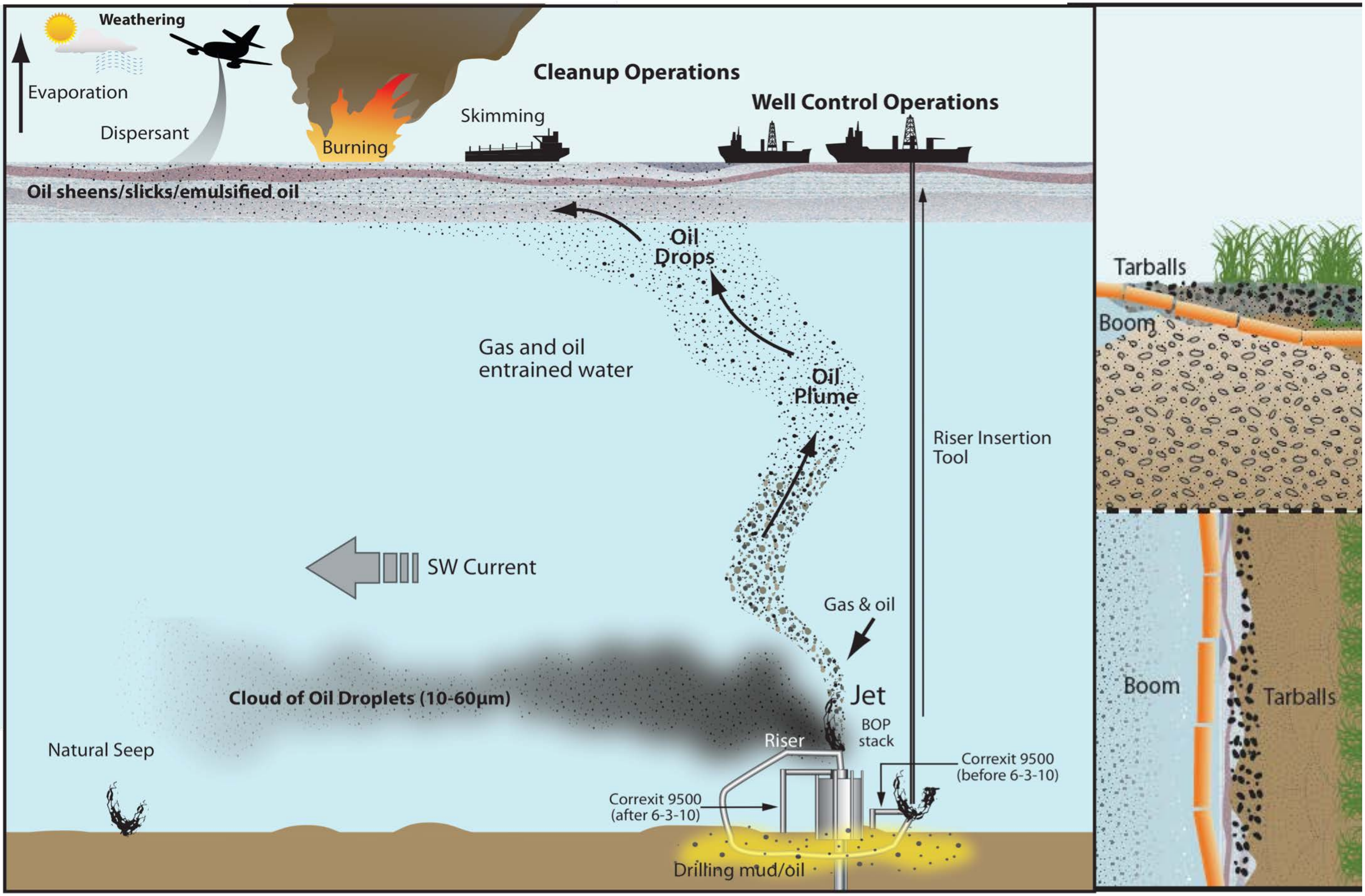
Application of fertilizer for bioremediation

# 29 yrs later Exxon Valdez spill

- 3/24/89 Supertanker spills 11 million gallons of crude into Prince William Sound, 1,300 miles of coastline impacted (largest spill in US history up until that time)
- Cleanup involved: burning, mechanical, and bioremediation
- Litigation is still going after 29 years, cost so far >$7 billion



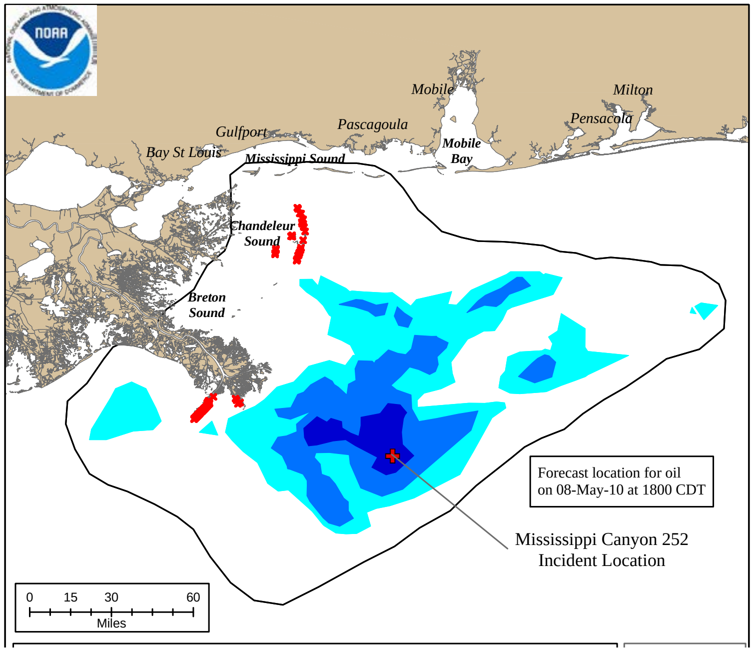
- Congress passed the 1990 Oil Pollution Act
- Fertilized areas were dramatically cleaner the first year
- Long term impact of treatments (fertilizers and bioremediation) will severely impact ecology of sound for many decades



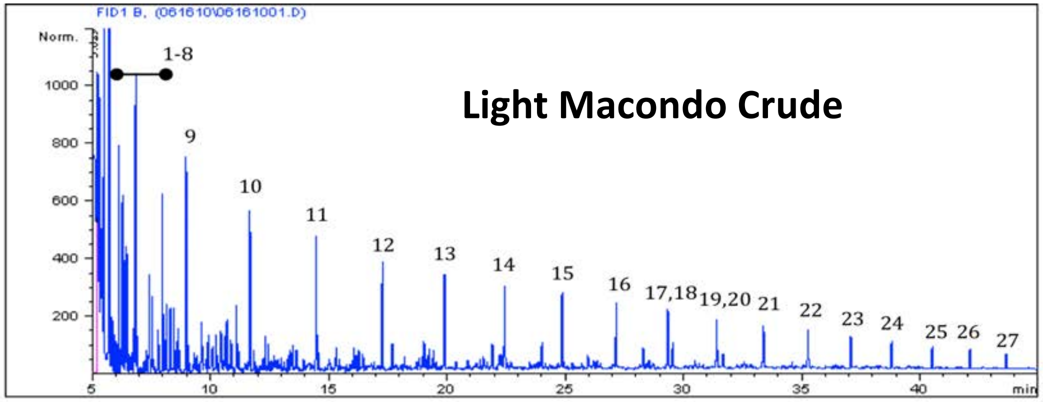
Weathering
Evaporation
Dispersant
Burning
Skimming
Cleanup Operations
Well Control Operations
Oil sheens/slicks/emulsified oil
Oil Drops
Gas and oil entrained water
Oil Plume
Riser Insertion Tool
SW Current
Gas & oil
Jet
Cloud of Oil Droplets (10-60µm)
BOP stack
Riser
Natural Seep
Correxit 9500 (before 6-3-10)
Correxit 9500 (after 6-3-10)
Drilling mud/oil
Tarballs
Boom
Boom
Tarballs

# The Blowout

- On April 20, the *Deepwater Horizon* (*DH*) exploded (rising, rapidly expanding methane)
- The floating rig burned for 2 days killing 11 people and then sank, shearing the 21-inch riser pipe
- There were 3 breaks in the riser pipe
- Originally placed at 5,000 barrels, recent estimates place the oil intrusion to the Gulf of Mexico (GoM) at 60,000 barrels per day, 54.1 million cubic feet of natural gas was flared daily, 4.1 million barrels
- The “spill” surpassed the *Exxon Valdez* spill of 0.26 million barrels in 1989 and the *IXTOC-I* blowout of 3.33 million barrels into the GoM in 1979, *IXTOC-I* was the second largest marine spill in the world.
- Well capped beginning July 12, 2010, no oil input to GoM after July 15, 2010, *Macondo* well declared dead September 19, 2010.

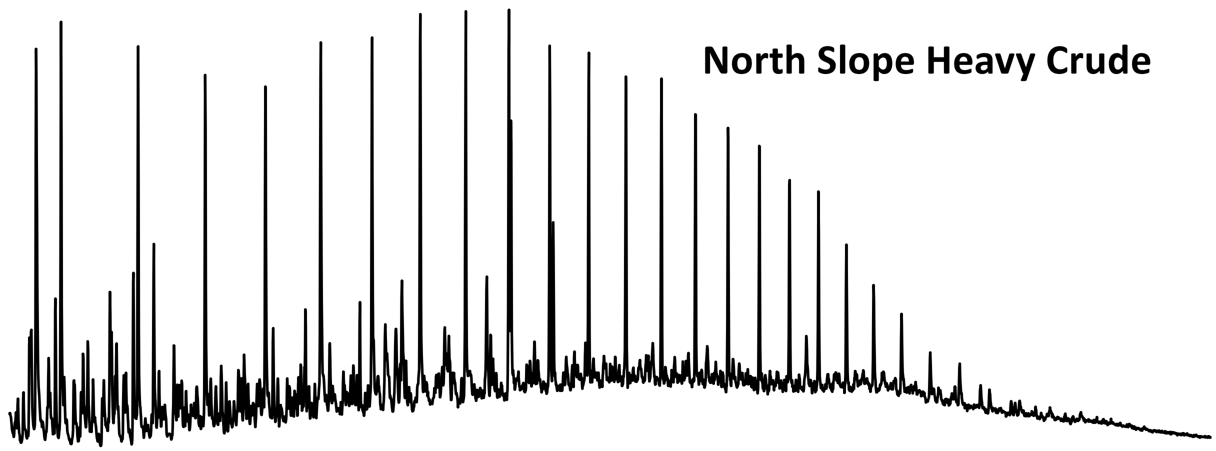


# Hydrocarbon Composition




- **Macondo Oil is light crude**
- **specific gravity of 850 kg/m³ (API gravity 37.2°, *Exxon Valdes* 29°)**
- **typical for the Gulf of Mexico oil reservoirs at 6,000 m**
- **carbon isotope signature is -27.42 ‰ ± 0.10 $\delta^{13}C_{PDB}$**
- **35% evaporates within 2 days in a wind tunnel**
- **45% in 2 weeks**

| Pk# | FID RT (min) | ID |
|---|---|---|
| 1 | 6.3 | heptane |
| 2 | 6.4 | methylcylohexane |
| 3 | 6.5 | ethylcyclopentane |
| 4 | 6.5 | cyclopentane, 1,2,4 trimethyl |
| 5 | 6.7 | cyclopentane, 1,2,3 trimethyl |
| 6 | 6.8 | toluene |
| 7 | 6.9 | 2 methyl heptane |
| 8 | 8.1 | n-octane |
| 9 | 9.0 | n-Nonane |
| 10 | 11.7 | n-Decane |
| 11 | 14.5 | n-Undecane |
| 12 | 17.3 | n-Dodecane |
| 13 | 19.9 | n-Tridecane |
| 14 | 22.5 | n-Tetradecane |
| 15 | 24.9 | Pentadecane |
| 16 | 27.2 | n-hexadecane |
| 17 | 28.6 | n-heptadecane |
| 18 | 29.4 | Pristane |
| 19 | 31.5 | n-octadecane |
| 20 | 31.7 | Phytane |
| 21 | 33.4 | n-Nonadecane |
| 22 | 35.3 | eicosane |
| 23 | 37.1 | Heneicosane |
| 24 | 38.8 | n-Docosane |
| 25 | 40.5 | tricosane |
| 26 | 42.1 | tetracosane |
| 27 | 43.6 | n-Pentacosane |



# Comparison of BP and Exxon Spills

- **Exxon Valdez**

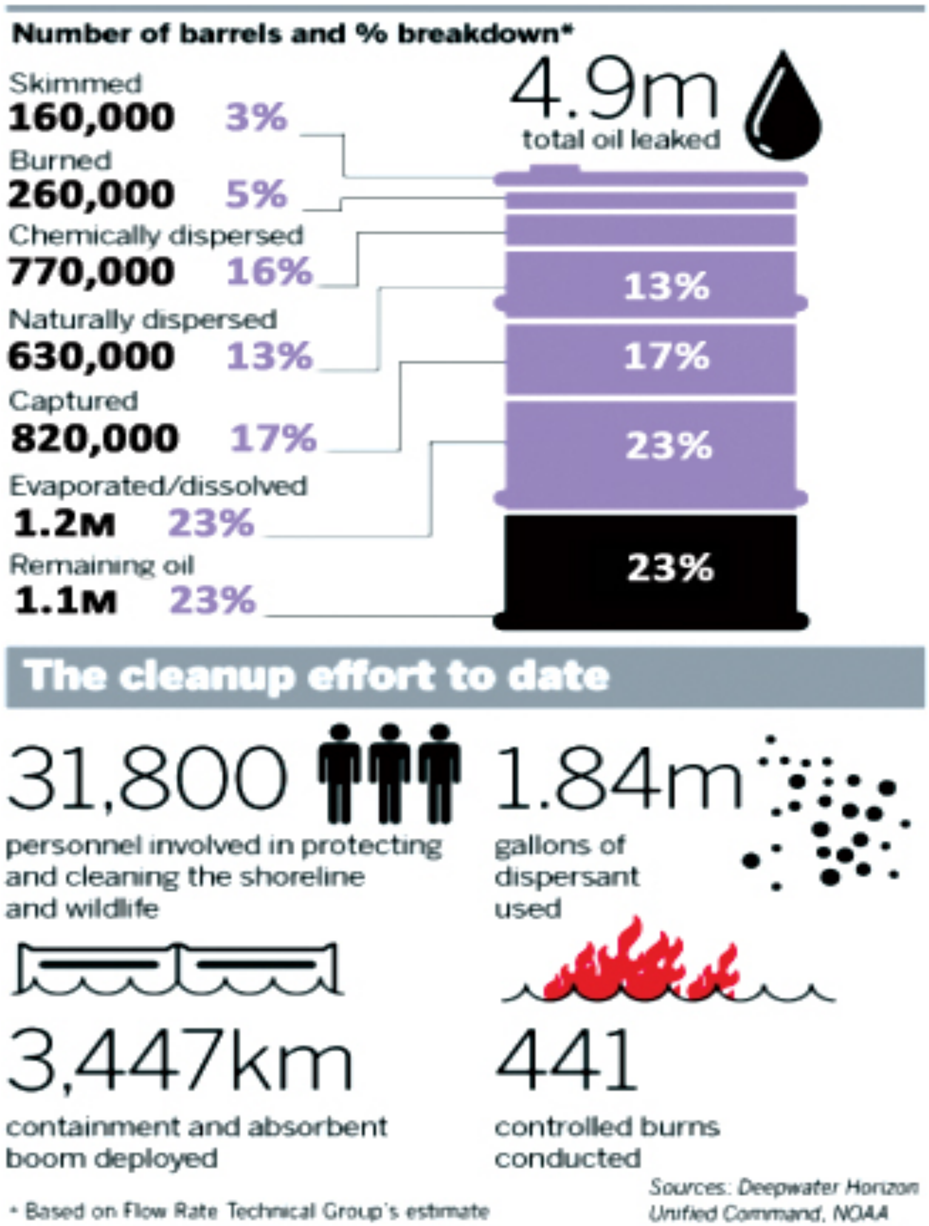
- 11 million gallons (dead oil)
- North Slope Heavy Oil (API 29)
- Discharged as Surface spill
- Impacted cobble/rocky shorelines
- Bioremediation used (Inipol and Costomblen)
- Fate of oil remnants still studied more than 29 years after spill
- Much scientific and operating experience gained is applicable to other spills
- Near shore
- No natural seeps

- **BP Deepwater Horizon**

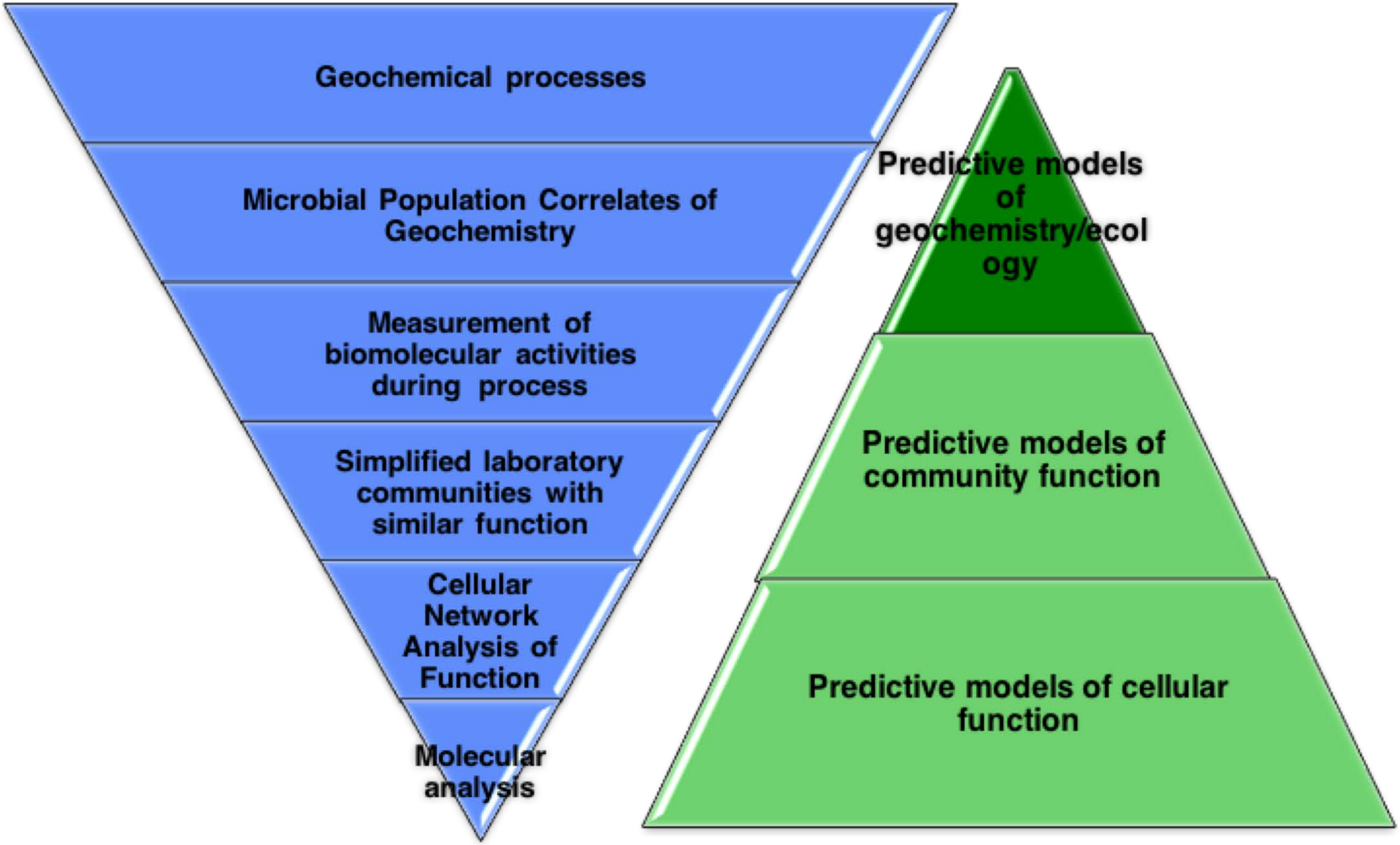
- 4.1 million barrels (approximately 200 million gallons of live oil)
- Light Louisiana Oil (API 35)
- Discharged as Subsurface spill (1500m depth, 200°C, high pressure jetting)
- Formed deep sea cloud of fine droplet/low concentration oil
- Impacted marshes and
- sandy beach shorelines
- Aerial and subsurface dispersants used extensively
- Methane also released
- 50 miles offshore
- Many Oil Seeps

# Where the oil went?

*The Federal Interagency Solutions Group, Oil Budget Calculator Science and Engineering Team (November, 2010)*



# Oil Spill Systems Biology



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# Dominant bacteria at 1099-1219 m, SEM and acridine orange stain inset with distance from wellhead

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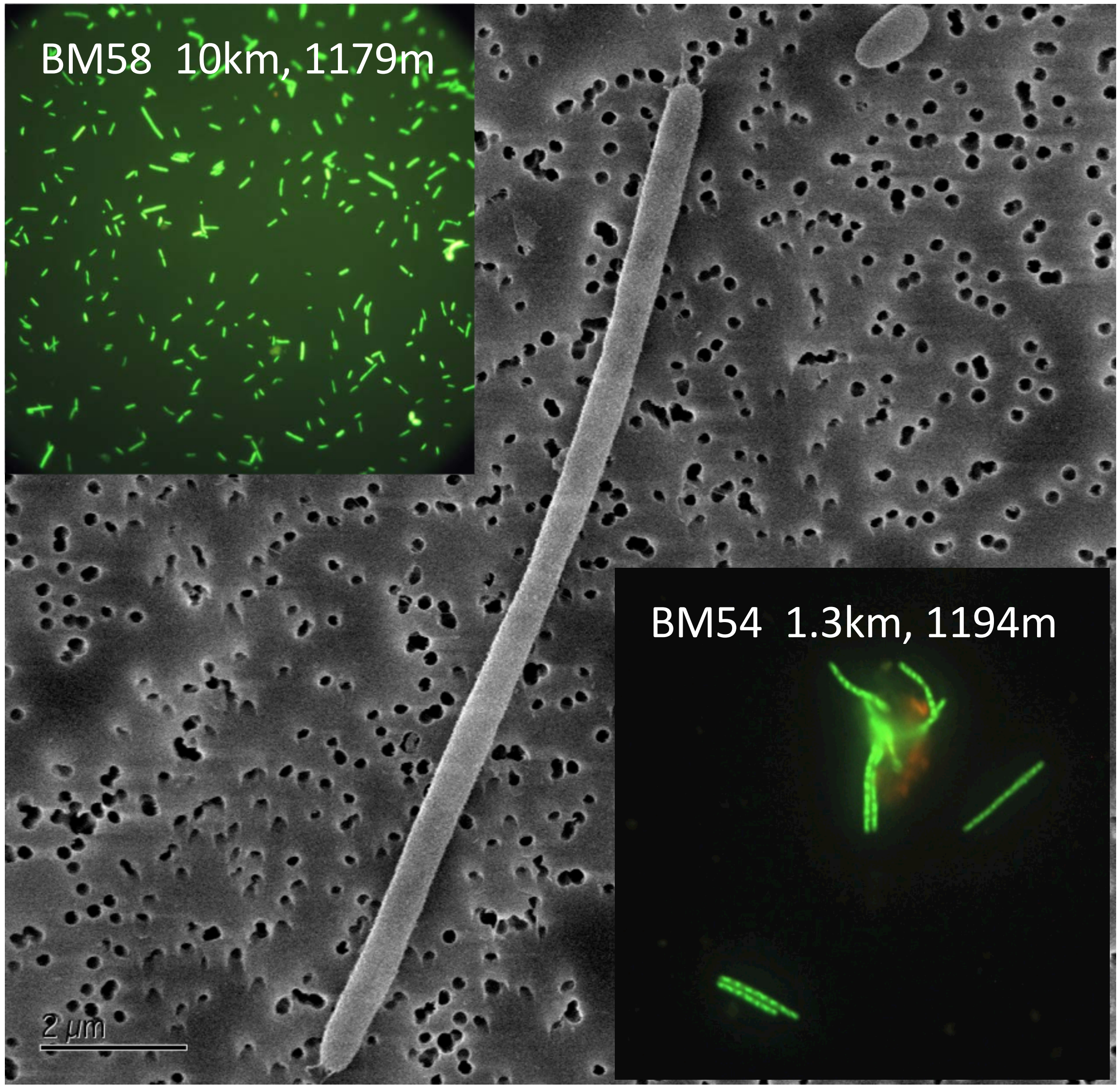
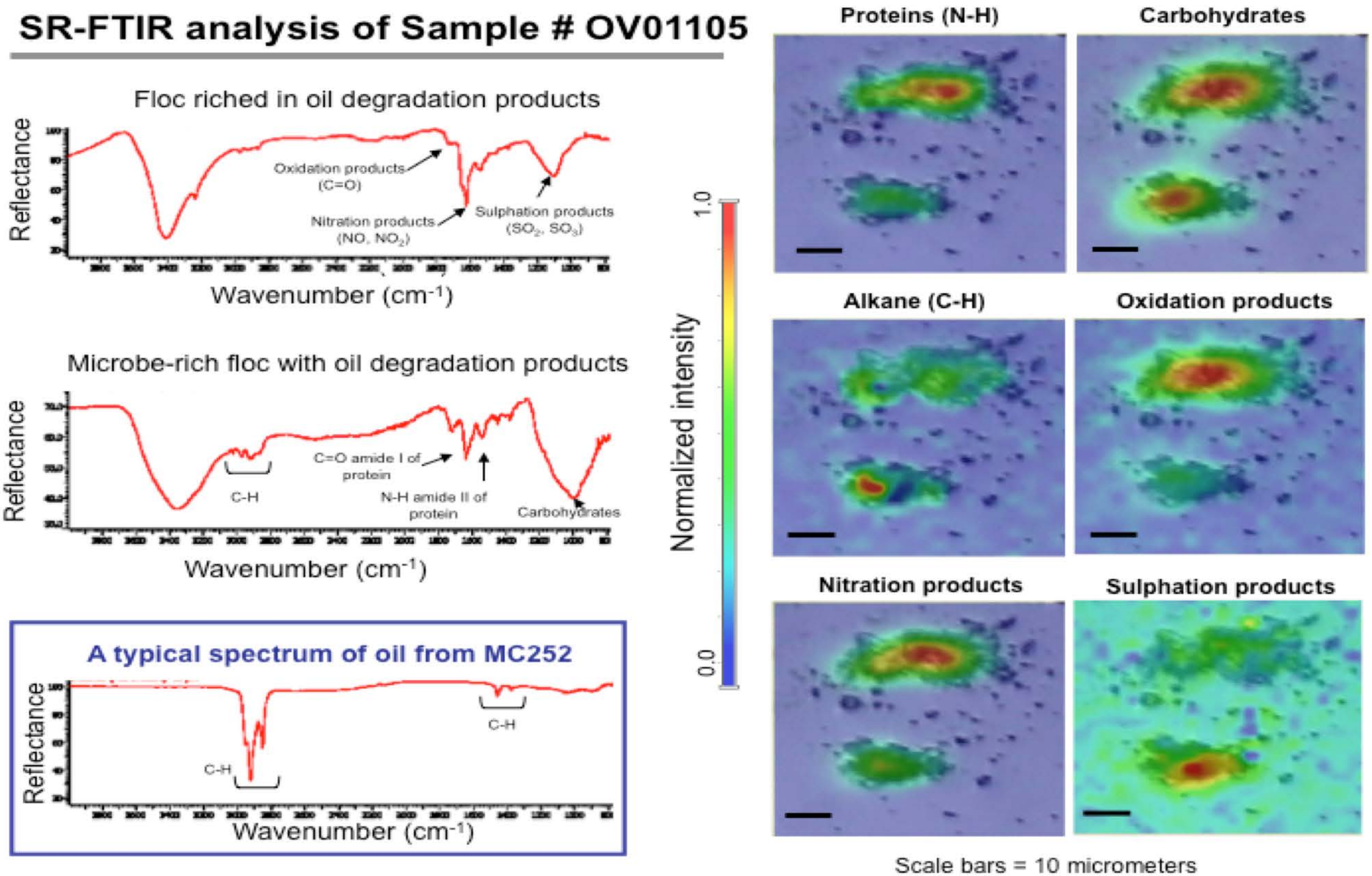
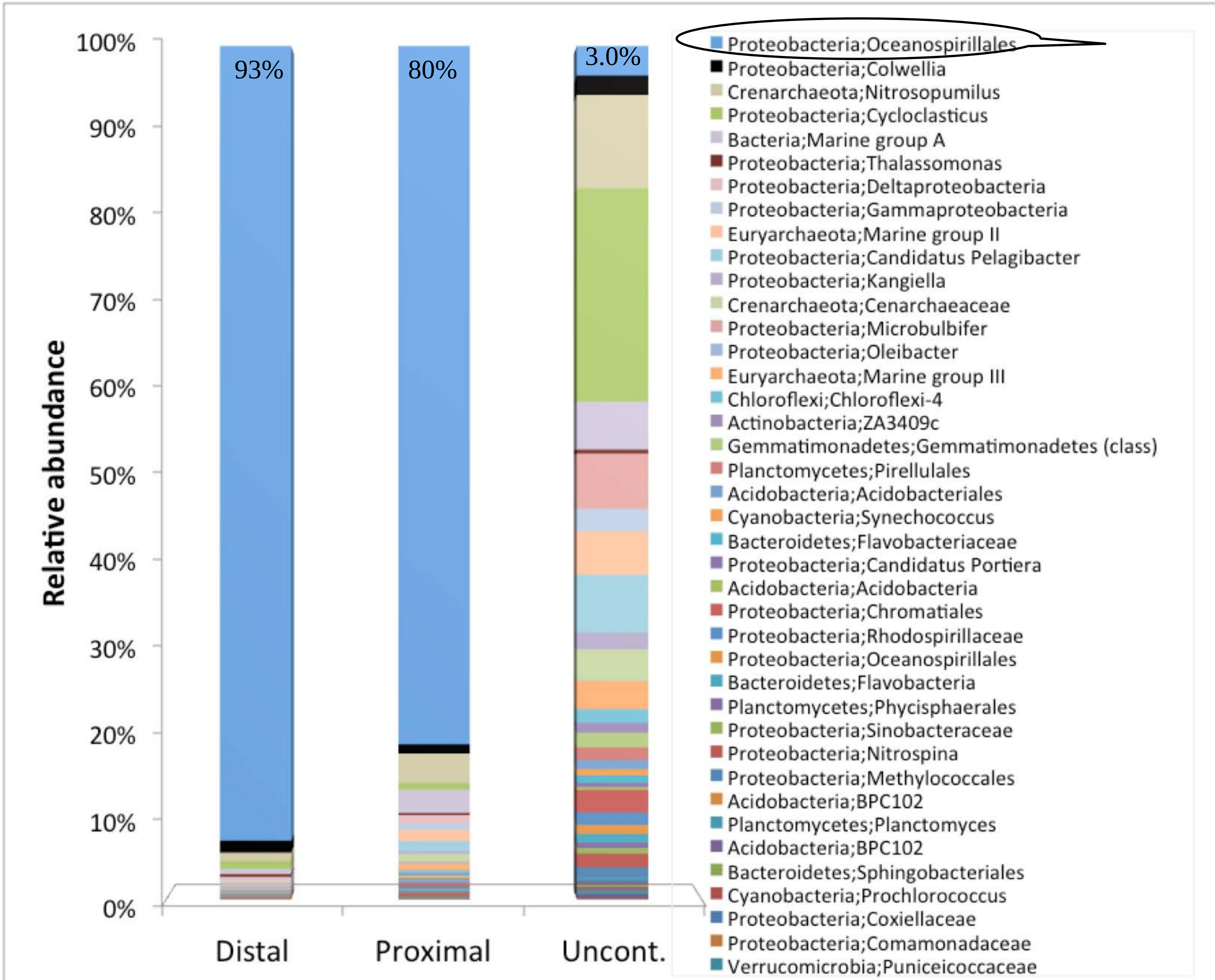
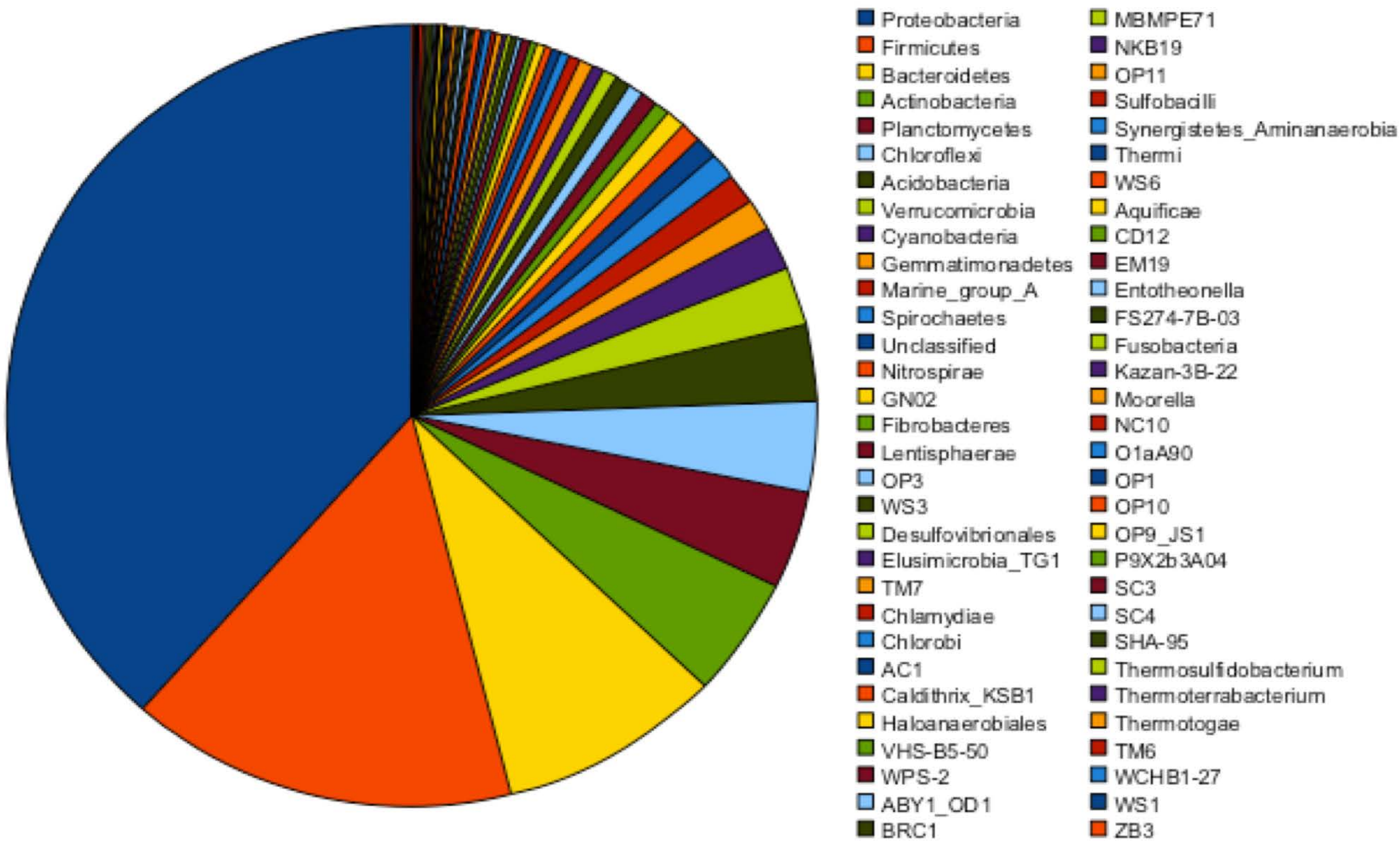


# Floc SR-FTIR spectral analysis



# Microbial community composition (Pyrotag)*(Mason et al. 2012)*

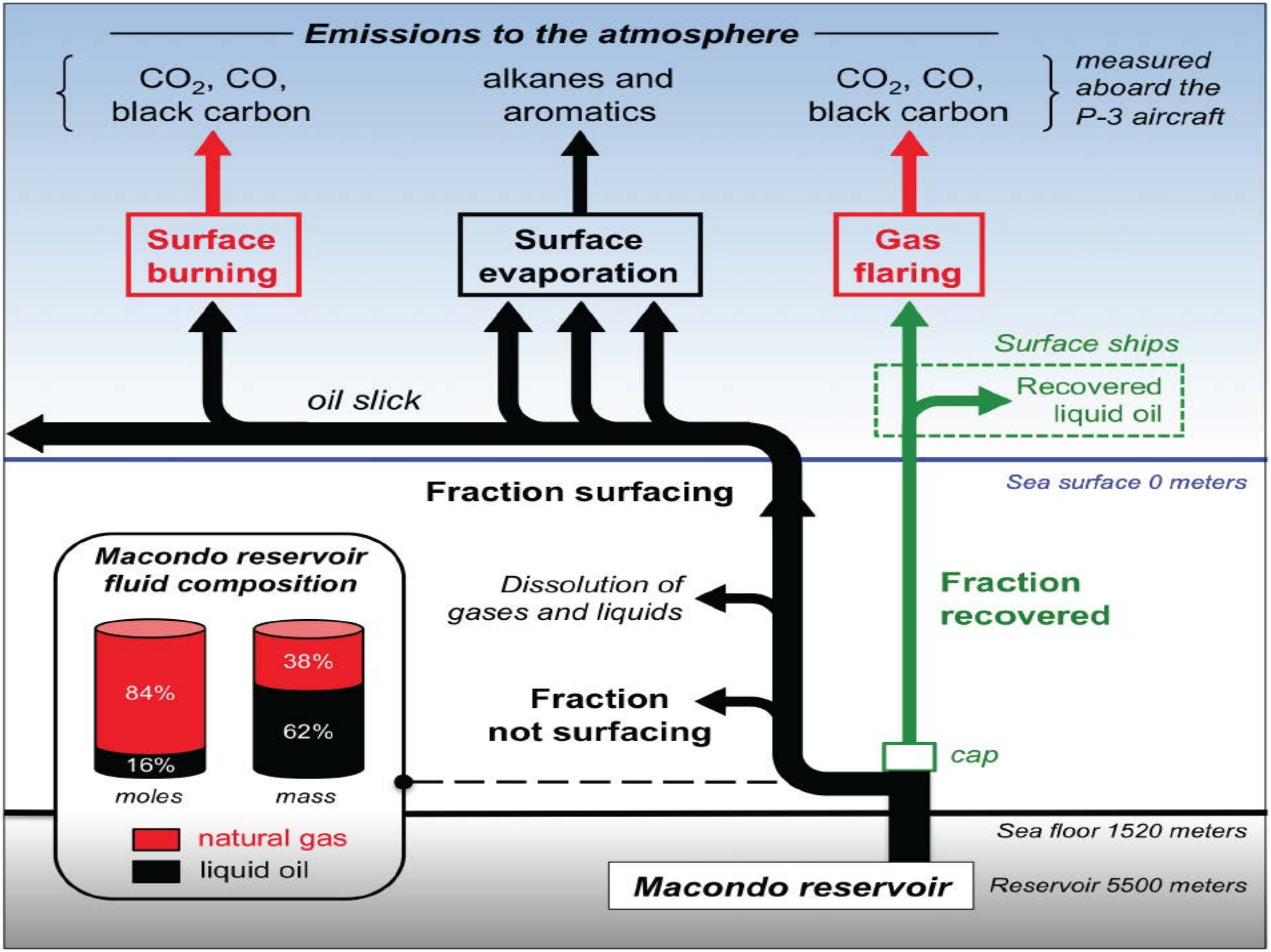





Deep water microbial communities during Deepwater Horizon oil spill (951 subfamilies were detected in 62 bacterial phyla. Only 16 subfamilies in γ-proteobacteria significantly enriched in plume). Hazen et al. (2010).

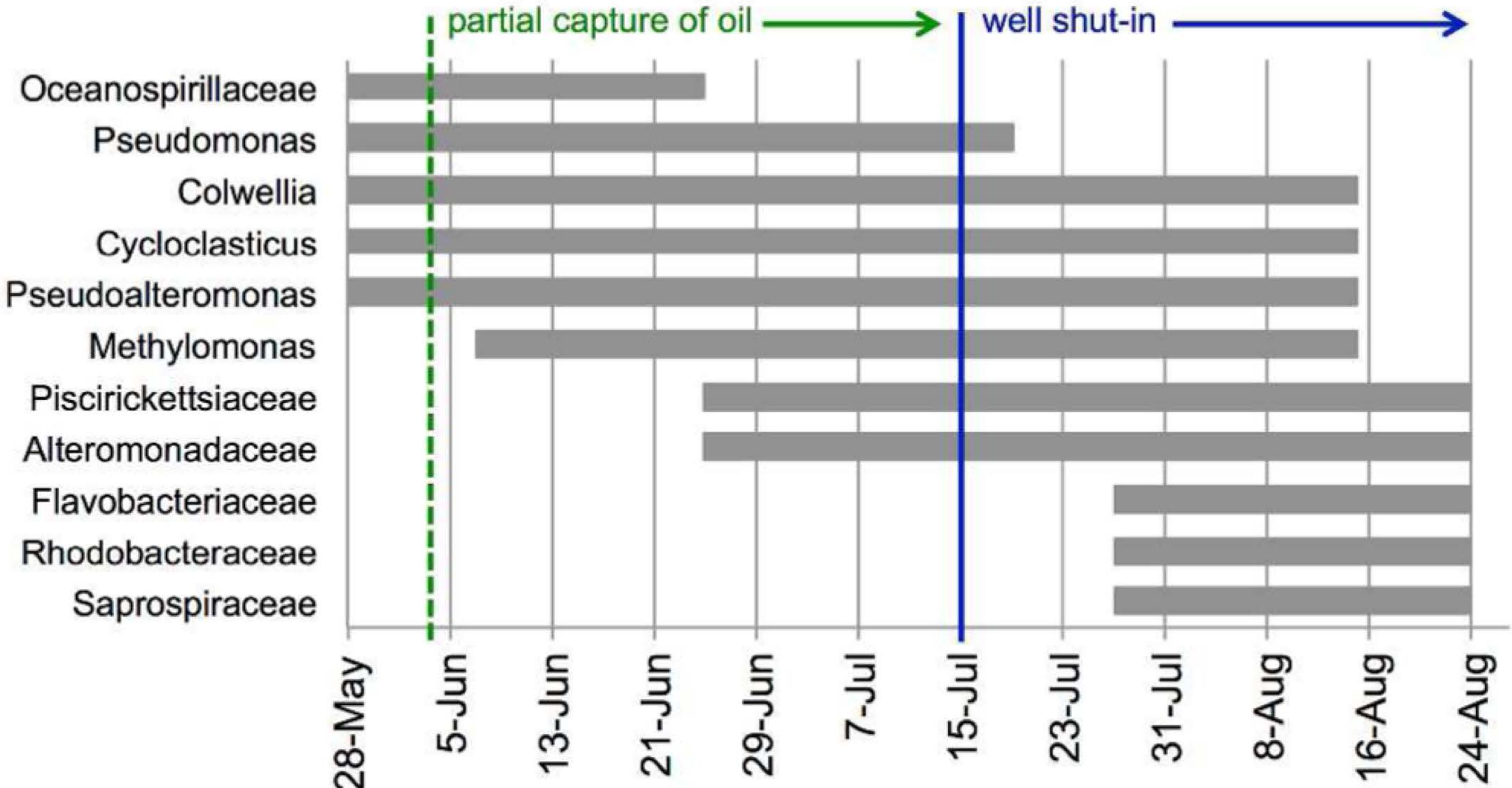
# Half-life Comparisons

| Crude Type | Source | Concen. | Disp. | Matrix | Cels | Half-Life (d) | Temp | Method | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Light Crude | MC252 | 1-19ppm | C9500 | 1100m | $<10^5$ | 1.2-6.1 | 4-5°C | 2 in situ disappearance | Hazen et al, 2010 |
| Light Crude | MC252 | 100ppm | C9500 | 1100m | $10^5$-$10^6$ | 2.2, 3.5 | 4-5°C | 1 microcosm, 1 enriched | Hazen et al, 2010 |
| Heavy Crude | Prudhoe Bay | 60ppm | C9500 | Sea media | | 4.6 alkanes | 5°C | enriched consortia | Venosa & Holder, 2007 |
| Heavy Crude | Prudhoe Bay | 60ppm | | Sea media | | 9.9 alkanes | 5°C | enriched consortia | Venosa & Holder, 2007 |
| Light Crudes | Forties, WSB | 4.6-66ppm | C9527 | Marine | $10^3$-$10^5$ | 1.5-1.7 PAH | -1.8-5.5°C | PAH loss, Mesocosms | Siron et al, 1995 |
| Light Crudes | Forties, WSB | 4.6-66ppm | C9527 | Marine | $10^3$-$10^5$ | 2.4-7.5 DMPA | -1.8-5.5°C | Naph. Loss, Mesocosms | Siron et al, 1995 |
| diesel oil | Shengli oilfield | .2/100ml | G-ming | seawater | $10^5$ | 1.6 | 10°C | loss of TPH | Xia et al, 2009 |
| | | | | | | | | | |
| Light Crude | Lousisana | 35ml (in core) | | LA marsh sediment | | 11.9-69 | 22°C | core disappearance | Enoc, 2002 |

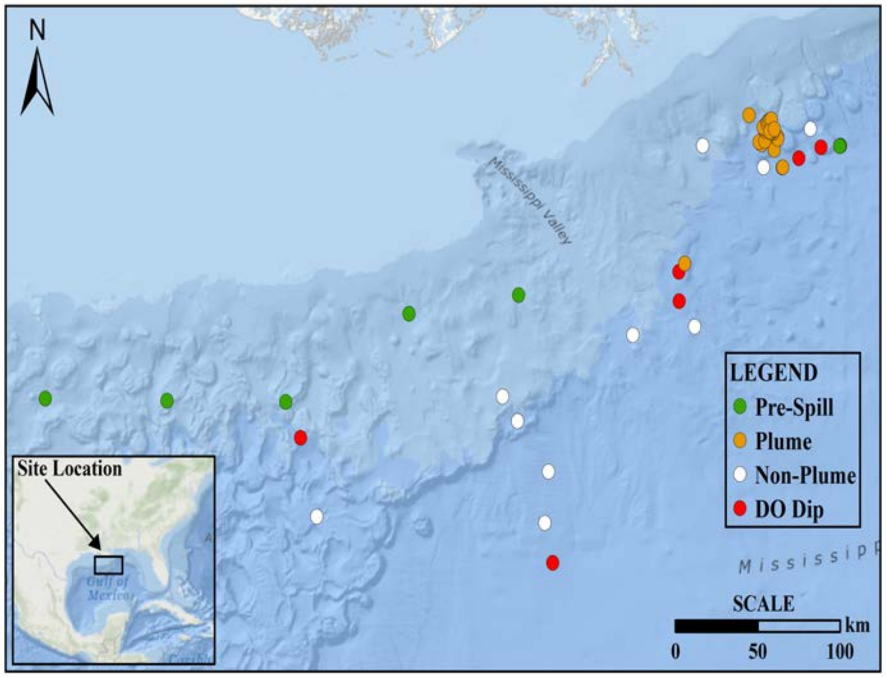


Emissions to the atmosphere
CO2, CO, black carbon
alkanes and aromatics
CO2, CO, black carbon
measured aboard the P-3 aircraft
Surface burning
Surface evaporation
Gas flaring
Surface ships
Recovered liquid oil
oil slick
Sea surface 0 meters
Fraction surfacing
Macondo reservoir fluid composition
84%
16%
38%
62%
moles
mass
natural gas
liquid oil
Dissolution of gases and liquids
Fraction not surfacing
Fraction recovered
cap
Sea floor 1520 meters
Macondo reservoir
Reservoir 5500 meters

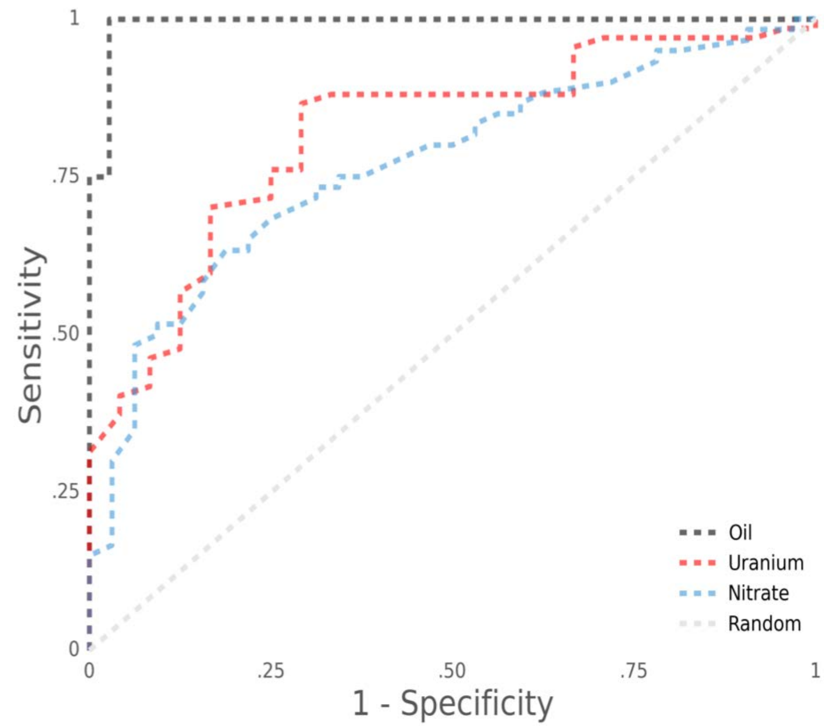
Succession of the microbial community in the deep water of the Gulf of Mexico during the various phases of the response to the *Deepwater Horizon* oil spill. For each bar relative abundance was enriched over background in any sample (>2-fold mean nonplume intensity). Dubinsky et al. (2013).



# SLiME identified biological features associated with the presence of oil




Sampling locations in Gulf of Mexico




Quality of classifiers
(oil in black; groundwater chemistry in red, blue)

*(Smith Rocha et al, 2015)*

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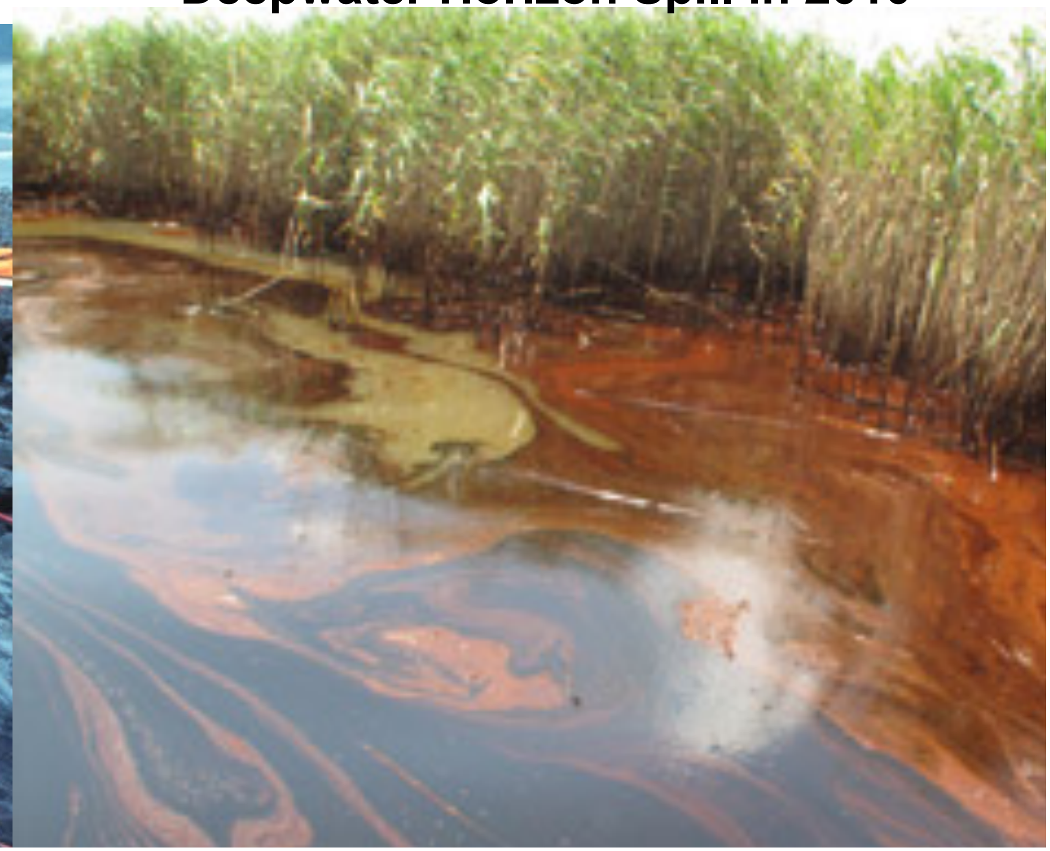
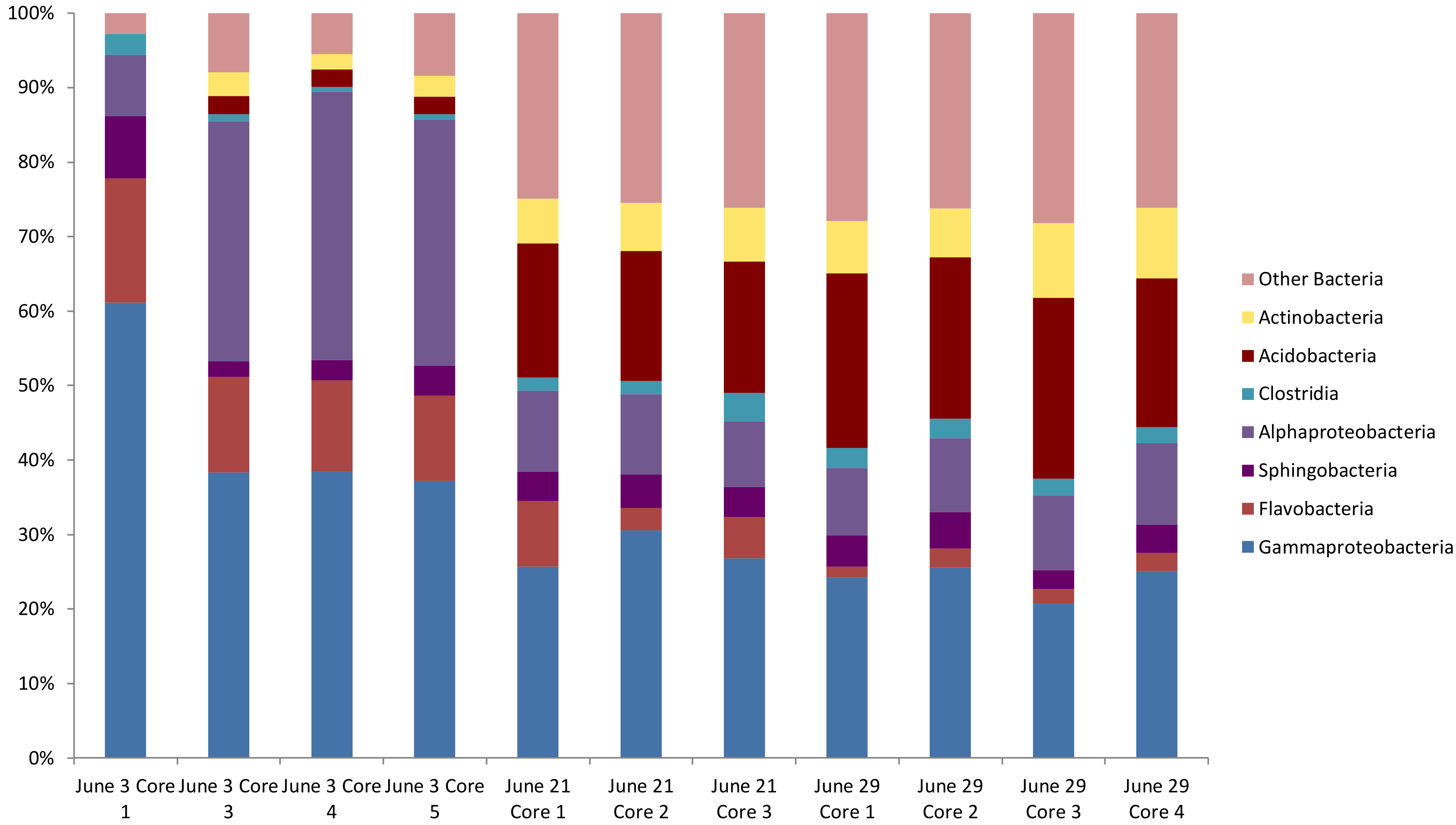
**Rocky Shorelines Heavily Oiled by Exxon Valdez Oil Spill in 1989**

**Coastal Marshes of the Gulf Coast Threatened by Oil from the Deepwater Horizon Spill in 2010**

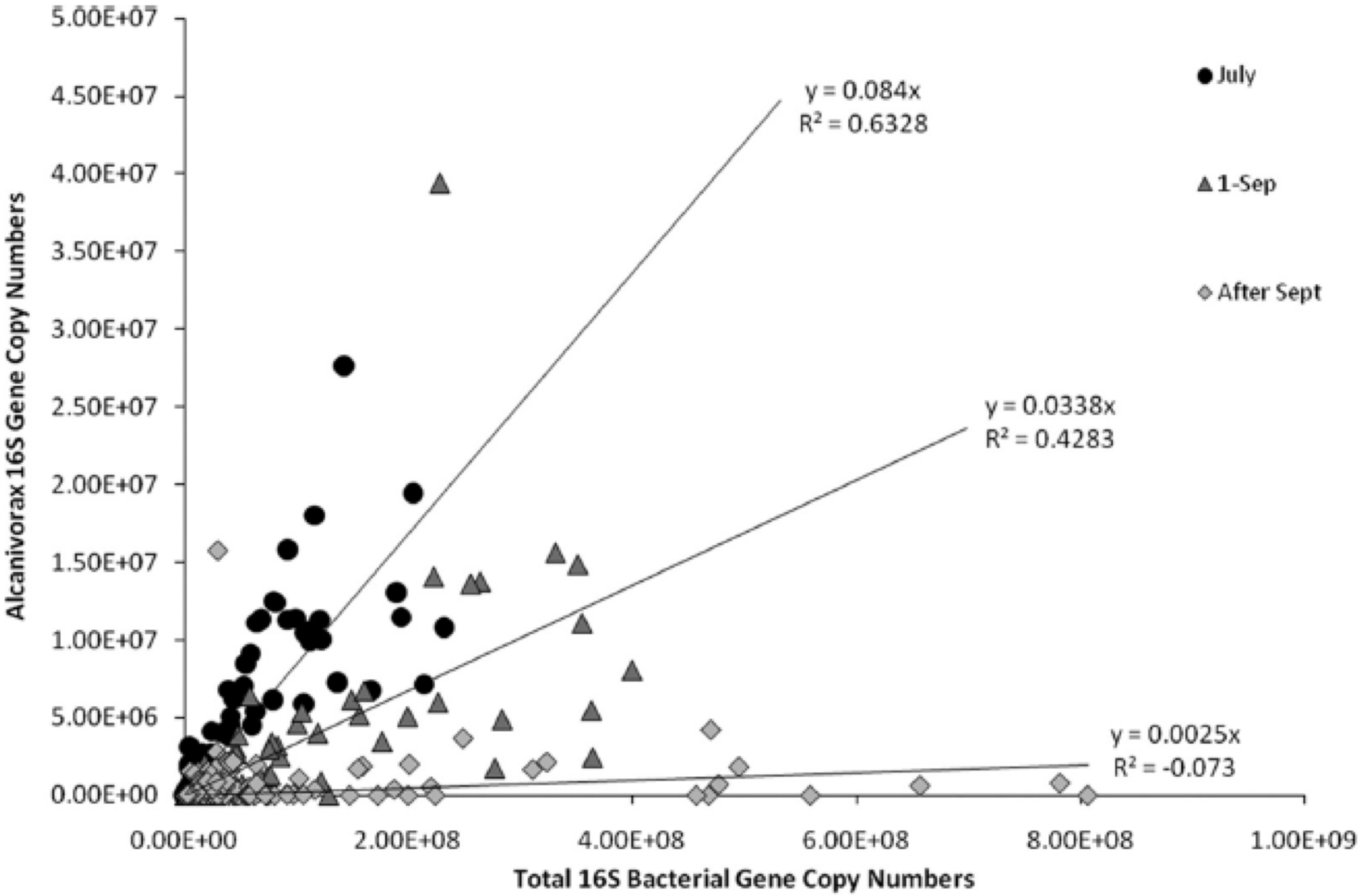


# Beach Experiments

# Microbial communities – Elmer's Beach



# Kostka et al., 2011, AEM. Alcanivorax succession over time



## Because of its success in 1989-1991, bioremediation has been proposed for treating remaining subsurface oil (SSO) residues 29 years after the spill

### Applying fertilizer in 1989-1991

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# Input of Oil in North America. NAS (2003)

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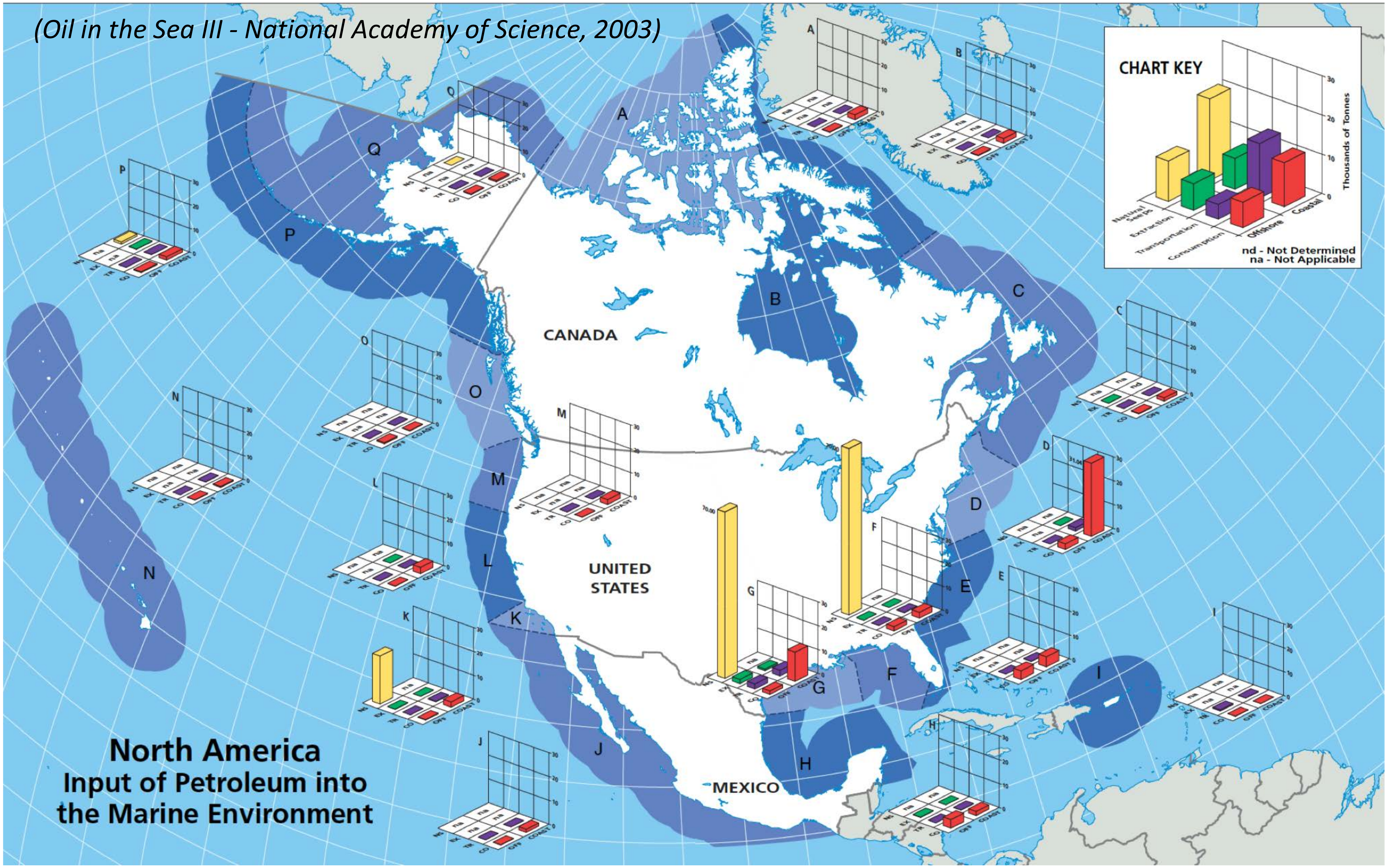


**Synergistic effects that impact biodegradation of oil. Hazen et al. (2016).**

| Factor working synergistically | Impact on biodegradation |
|---|---|
| **Chemical dispersants + mineral fines.** | Individually each will promote dispersion of the oil. Combined, the formation and transfer of oil from the surface into the water column is enhanced. |
| **Autoinoculation + 'memory response" of hydrocarbon degraders.** | Introduction of hydrocarbons to previously exposed water parcels leads to an increase in microbial abundance and accelerated hydrocarbon biodegradation. |
| **Oil droplet size + dispersion + biodegradation rates + dissolution.** | Enhances biodegradation, dissolution and dispersion rates of oil hydrocarbons. |
| **Cometabolic biodegradation + dispersion + secondary electron donors.** | Enhances biodegradation, dissolution and dispersion rates of oil hydrocarbons even when the oil itself cannot be a suitable electron donor. |
| **Biosurfactants from multiple microorganisms.** | Enhances bioavailability of poorly soluble compounds. |

# Lessons Learned from Exxon Valdez Oil Spill

- **Biodegradation and other natural weathering processes will remove most of contaminating hydrocarbons but it may take months-years-decades**
- **Bioremediation is an effective means for speeding up the rate of oil biodegradation**
- **Oil that is sequestered from water contact will persist longer and will not respond to bioremediation unless sequestration is physically removed**
- **Establishing limiting factors is critical for determining appropriate treatment**
- **Applicability of bioremediation depends upon environment, oil composition, and whether natural nutrients will be limiting**
- **One should not expect 100% removal of oil by bioremediation—patches of highly weathered oil likely will remain in some environments but will be at low risk.**

# Lessons Learned from Deepwater Horizon

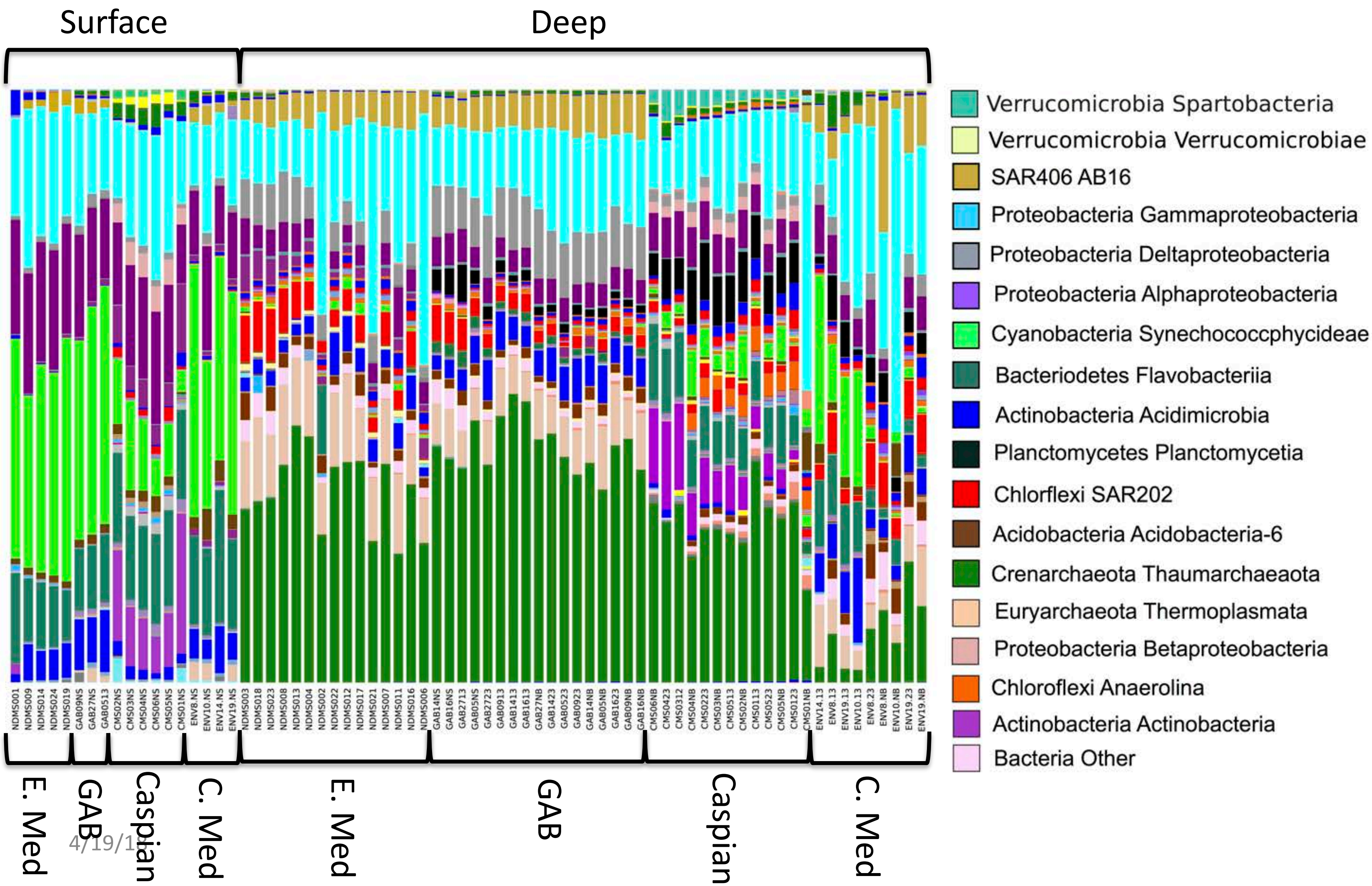
- Marine Oil Biodegradation like all Politics is Local and DWH had many unique aspects. Many factors worked synergistically to impact oil biodegradation and dispersion.
- Oil in the water column and in coastal sediments biodegraded faster than expected. Millions of years of natural oil seep adaption.
- Establishing limiting factors is critical for determining appropriate treatment. Natural attenuation was a dominant process in the water column.
- Jetting and Dispersants at the well head increased Oil Biodegradation.
- Comparisons of DWH with Exxon Valdez Oil Spill for Oil Biodegradation were not appropriate.
- Models for DWH were inappropriate at first.
- Cometabolic Oil Biodegradation may be Important in Deep Marine Basins.
- Blooms of Oil Degraders in the Deep led to a Temporal Succession of other Bacterial Communities, unknown effects on Trophic Levels.
- Molecular techniques led to a more thorough and faster understanding of DWH Oil Biodegradation.
- Research Needs: Simulations, Mesocosms, Microcosms, Lab and field sampling all need better SOPs.


Nine important hydrocarbon (oil) basins where off-shore petroleum leases have been licensed. (1. Eastern Mediterranean's Nile Deep Sea Fan, 2. Central Mediterranean and the Sirte Basin, 3. North Sea, 4. Caspian Sea, 5. Trinidad and Tobago, 6. Angola, 7. Great Australian Bight, 8. Brazil's Amazonian Deep-Sea Basin, 9. Gulf of Mexico)

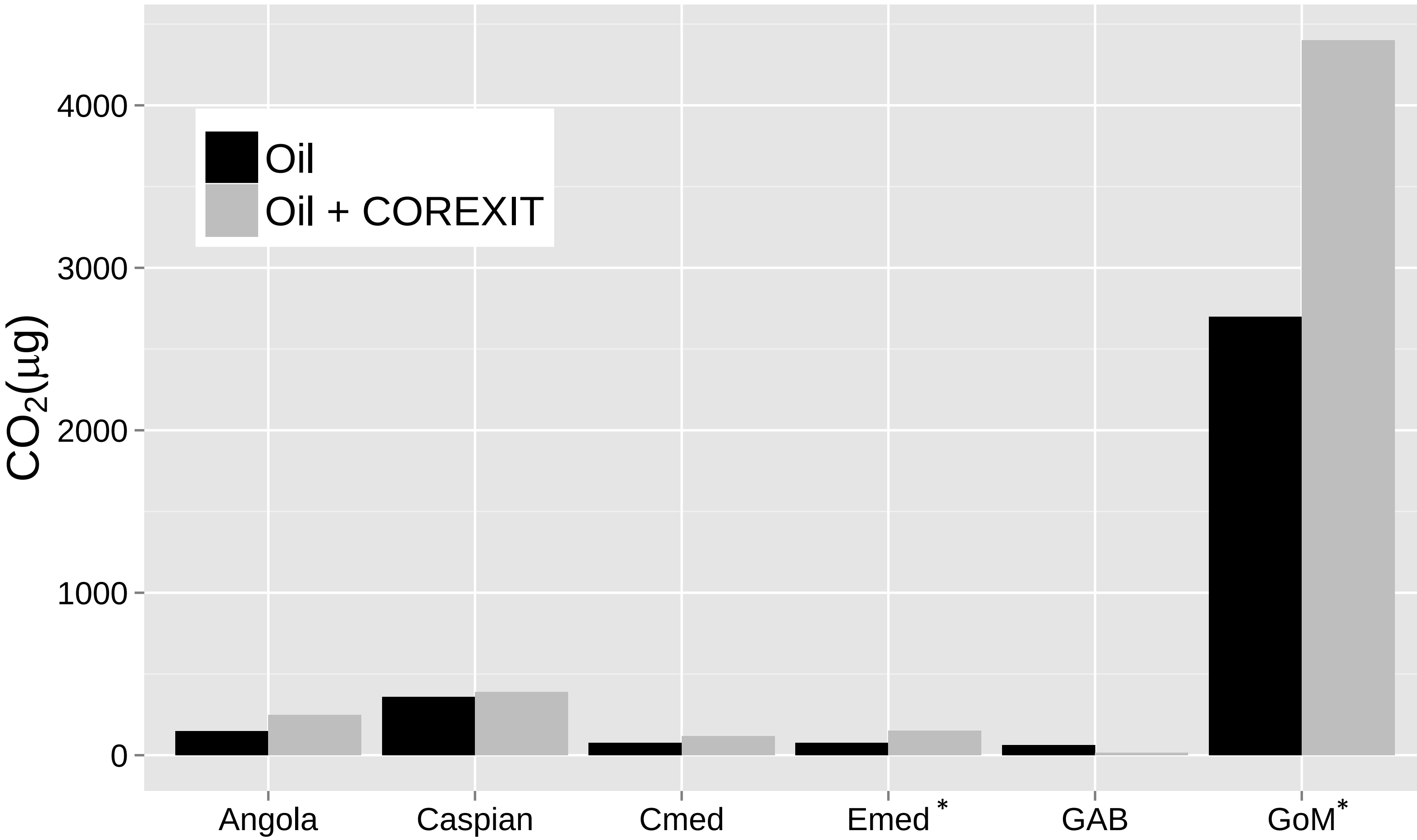
# Physical/Chemical comparison of deep basin with oil biodegradation. (ND = No Data)

| Nutrient | Eastern Med | Central Med | Great Australian Bight | Caspian | North Sea | Angola Basin | Brazil Basin | Gulf of Mexico |
|---|---|---|---|---|---|---|---|---|
| Nitrate (µg/kg) | 178.4 | 160.0 | 144.7 | 127.8 | 569.6 | 20 | 25 | 208 |
| Phosphate (µg/kg) | 39.7 | 29.3 | 153.5 | 56.9 | 33.5 | 1.6 | 1.1 | 205 |
| Ammonia (µg/kg) | 28.0 | 30.0 | 125 | 739.6 | 12.5 | 10.2 | ND | 78 |
| Iron (µg/kg) | 6.5 | ND | 5.8 | 4.7 | ND | ND | ND | 56 |
| Sulfate (µg/kg) | 4.7 | ND | 1.6 | 1.9 | ND | ND | ND | ND |
| Salinity (psu) | 38.9 | 38.6 | 34.8 | 11.3 | 33.7 | 36 | 37 | 35 |
| Temp (°C) | 13.8 | 13.7 | 2.5 | 6.8 | 3 | 4 | 5 | 4.8 |
| Dissolved oxygen (mg/L) | 6.4 | 5.5 | 5.0 | 0.5 | ND | 3.4 | ND | 4.9 |

# Comparison of Microbial Communities Across Basins



# Oil Mineralization




* 60 ppm COREXIT 9500

# Oil (TPH) Half-life in Days

| | |
|---|---|
| 1.2-6.1 | Gulf of Mexico |
| 12 | Eastern Mediterrenean |
| 19-21 | Great Australian Bight |
| 16 | Central Mediterrenean |
| 16 | Angolan Coast |
| 11 | Caspian (anaerobic) |
| 15 | Caspian (aerobic) |

# *Environmental Systems Biology*



***1. Hypothesis to be tested***

**2. Boundaries of Environment System**

**3. Measurements to be made**

**4. Sampling (Protocols, holding times, storage, etc.)**

**5. Resources needed (costs, equipment, people, time, etc.)**

6. Field Test Plan (including permits, HaSP, protocols, responsibilities, budgets, priorities, database, science of opportunity

7. Mobilization

Feedback

8. Implementation

Feedback

9. Demobilization

10. Reports and publications

***(Hazen & Sayler, 2016)***

## A Systems Biology approach may be one of the only ways that we that we can enable sustainable environmental remediation applications.