# M/V *SELENDANG AYU* RESPONSE: MIXING AND SEDIMENT RELOCATION ON OILED COARSE SEDIMENT BEACHES

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## ABSTRACT

*The grounding of the M/V Selendang Ayu on Unalaska Island in the Aleutian Island chain, Alaska, in December 2004, resulted in a spill of an estimated 339,538 gallons of primarily intermediate fuel oil that affected approximately 300 km of coastline in a remote area. The majority of the oil that stranded was deposited as heavy concentrations on coarse sediment beaches within a few tens of kilometers of the spill site. The shoreline cleanup operation focused on manual methods to minimize sediment removal and waste generation. Mechanical removal, dry mixing, or sediment relocation techniques were approved for eight locations where deeply-penetrated oil could not be effectively or efficiently removed by manual means. On several of the high-energy exposed beaches, the oil had penetrated or been buried to depths greater than 2 m, necessitating the excavation of considerable volumes of sediment to ensure that no untreated oil residues remained. One element of the Unified Command shoreline treatment oversight process required preparation and implementation of a monitoring and sampling plan. The plan included documentation of SCAT observations, surveyed beach profiles, photography, and mussel tissue chemistry. Evaluation of the data collected during the monitoring and sampling program showed that the relocation resulted in little adverse impact. Between 2005 and 2006, SCAT observations and photographs documented steady decreases in shoreline oiling, beach profiles were quickly restored by even modest storm events, and aromatic hydrocarbons in mussel tissues declined significantly. Although in situ treatment does not "clean" beaches, accelerating the weathering of the subsurface oil and decreasing the amount of oil remaining on the beaches ostensibly reduced the residence time of the oil and therefore, also reduced the exposure or risk to coastal birds and animals.*

## INTRODUCTION

In December, 2004, the freighter M/V *Selendang Ayu* lost power in the Bering Sea near Bogoslof Island while in transit on a great circle route from Tacoma, WA, to China. The vessel was carrying a cargo of soybeans and approximately 424,000 gallons of intermediate fuel oil (IFO) and 18,000 gallons of diesel. After grounding on the evening of December 8 several hundred yards offshore of Unalaska Island, along the southern shoreline of Skan Bay, the ship split in two in heavy weather. The volume of oil released from the ship was estimated at 339,538 gallons of IFO, and another 14,680 gallons of diesel.

Surveillance of the oil releases, the assessment of the shorelines in the affected area and the decision process associated with the development of the treatment plan are described elsewhere (Owens *et al.* 2005, 2008). As this is a remote area, safe and feasible cleanup operations were limited and shoreline access was difficult under the best of conditions (Gallagher 2008). The majority of the oil was released within a few days after the grounding during a storm. The largest concentrations of stranded oil were found on exposed coarse sediment (sand, pebble, cobble) beaches, often 3 to 4m above the intertidal zone. On several of these beaches the oil had penetrated, or been buried, well below the surface and had been exposed in the beach face slope by subsequent wave action.

Given the constraints imposed by remote location, exposure, and weather, two remedial techniques identified for potential use during the response were mixing and sediment relocation. Mixing simply exposes subsurface oiled sediments, whereas relocation involves the movement of oiled sediment from higher to lower tidal zones. These are typically referred to as "*in situ*" tactics, as treatment is carried out on an oiled beach and only operational wastes, as opposed to large volumes of oiled sediments, are generated. In both cases the objective is to expose the oil to air, light, tidal washing and wave action; all are important contributors to oil weathering. The underlying concept is that exposure of the oiled sediments in this fashion promotes short-term mobilization of the oil adhering to the beach material, thereby increasing the oiled surface area available for degradation of the oil by physical and biological processes.

Sediment mixing and sediment relocation can be considered together as both involve moving bulk sediments from one part of the beach to another in order to expose oiled material to weathering processes. Mixing and relocation may be accomplished manually for small amounts of oil but typically earth-moving machinery is used for these tasks. Mechanical mixing and relocation minimize manpower efforts and does not involve waste generation: although the common practice is to remove gross surface aggregations of oil or oiled debris in advance. However, they do require access to and the ability to place large pieces of equipment on a given beach. Moreover, they also have the perceived and real downside of not *immediately* removing the oil from the environment. In the case of sediment relocation, oil is reintroduced into the nearshore marine environment when the tide and wave action mobilize oil from the sediments. Although this is an explicit part of the enhanced

weathering process, it can raise concerns from resource managers, fisheries agencies, subsistence users, landowners, and others, because oil that is temporarily on or in the beach is intentionally re-mobilized into the water where it may affect other resources and oil other shorelines. On the other hand, the remobilized oil can be partially contained and collected, and oil in the water column or escaping containment is subjected to much more rapid processes of degradation; and concentrations are reduced through dilution. Mixing and sediment relocation techniques have been used during many spill responses, in the U.S. and elsewhere (Le Floch *et al.* 2002; Lee *et al.* 1997; Levine, 1987; Lunel *et al.* 1996; Owens and Sergy 2003, 2004; Sergy *et al.* 2003). As is always the case for spill remediation, the challenge is to weigh the tradeoffs and select the option with minimal impact and greatest potential for accelerating recovery.

At a microscopic level, ionic and other physical interactions between hydrocarbons and mineral particulates can enhance and accelerate weathering of spilled oil. This role of oil-mineral aggregate (OMA) formation as part of natural weathering processes has been demonstrated at a number of spill sites under a wide range of environmental and oiling conditions (Bragg and Owens, 1994; Bragg and Yang, 1995; Khelifa *et al.* 2005; Lee *et al.* 1998). The link between mixing and sediment relocation, with OMA formation is well-established, although the majority of studies has involved post-spill sampling and/or laboratory experiments using samples from spill sites or selected oil, water and sediment materials. There have been few opportunities to evaluate the operational effectiveness and effects of mixing and sediment relocation, and on only two occasions have samples or data been collected at the time of sediment relocation or mixing treatment activities (Lee *et al.* 1997; Lunel *et al.* 1996; Sergy *et al.* 2003). In both instances, OMAs were present in the water column adjacent to the beaches that were treated.

During the *Selendang Ayu* spill response, the Unified Command recognized the potential to evaluate performance aspects of these cleanup methods and supported the monitoring of both short-term and longer-term effectiveness and effects. A large body of information was obtained from the treated sites, and this discussion summarizes some of results of those evaluations. We address two primary questions related to the mixing and sediment relocation activities during the *Selendang Ayu* spill response:

- Did dry mixing and sediment relocation methods work as anticipated?
- Do we know enough about *how* mixing and sediment relocation work to predict *when* and *where* it will be effective?

We describe the changes that occurred in the conditions and extent of oiling at selected sites on Unalaska Island over the period of the response. The Unified Command was interested in the effectiveness of oil removal, as well as the temporal "footprint" of the cleanup; i.e., how long would the mark of the cleanup activities remain in the environment? The information collected in 2005 and 2006 permit us to answer, with a few qualifications, the questions we have posed.

## METHODS

Mechanical mixing and/or sediment relocation techniques were approved for eight locations where deeply penetrated oil could not be effectively or efficiently removed manually and manual mixing was approved for one beach that could not be easily and safely accessed with machinery (Table 1). One element of the approval process required preparation and acceptance by the Unified Command of a monitoring and sampling plan. The plan involved documentation of SCAT observations, surveyed beach profiles, photography, and mussel collection for tissue chemistry. Profiles were surveyed along the staked lines before and after treatment on four beaches where sediments were relocated (Table 1). The discussion of the results focuses on one of these segments (SKN-05).

Monitoring tissue concentrations of hydrocarbons in sessile intertidal organisms, such as the common blue mussel, around treatment sites over time was carried out to document the potential consequences of shoreline oiling and the treatment actions, including:

- Risk to wildlife and human consumers of the organisms;
- Short-term "spikes" in environmental concentrations and biological availability attributable to the cleanup action;
- Differences in the rates of hydrocarbon reduction between treated and untreated sites;
- Areal scope of the presumably transient impacts.

Mussels have long been used as "sentinel organisms" to monitor organic compounds from oil and other sources. Mussel samples were collected opportunistically during visits by survey teams in 2005 and 2006. However, mainly due to cost considerations, not all of these were analyzed.

Oil and sediment samples were collected for laboratory analysis of OMA potential. One set was analyzed for oil-particulate interactions (Lee 2005) and the dynamic viscosity of the oil was determined so that this parameter could be compared to previous results (Omotoso *et al.* 2002) correlating physical properties of oil with formation of oil-particulate aggregates.

TABLE 1. DRY MIXING AND SEDIMENT RELOCATION SEGMENTS AND BEACH PROFILES.

| LOCATION | Number of Beach Profiles | Treatment Activities and Beach Profile Survey Dates |
|---|---|---|
| **HMP-12** | 1 | Mechanical mixing and relocation<br>7 February 2005<br>26 May 2005 – pre/post relocation<br>27 May 2005 – post relocation<br>10 July 2005 |
| **MKS-16** | - | Manual dry mixing |
| **MKS-17** | - | Mechanical dry mixing |
| **SKN-05** | 4 | Mechanical mixing and relocation<br>1 July 2005<br>20 July 2005 – post mixing/pre relocation<br>9 August 2005 – post relocation<br>13/16 August 2005<br>27 August 2005<br>14 September 2005<br>24 May 2006 |
| **SKN-06** | - | Mechanical mixing and relocation |
| **SKN-11** | 3 | Mechanical removal and dry mixing<br>7 February 2005 -one profile<br>1 July 2005 – pre relocation<br>7 July 2005 – post relocation: central profile only |
| **SKS-04** | 4 | Mechanical mixing and relocation<br>3 July 2005 – pre relocation<br>27 August 2005 – post relocation |
| **SKS-12** | - | Mechanical dry mixing |

## RESULTS

The value of relocation was initially assessed with a field trial in the heavily oiled segment HMP-12 in Makushin Bay. The highest energy beaches that were treated by mixing and relocation were the Skan Bay SKN-05, SKN-11, and SKS-04 segments. In this discussion we focus on SKN-05, as this has the most complete data base, in terms of beach profiles (surveyed at seven times, Table 1). Furthermore, approximately 1,750 $m^3$ of oiled material was removed from the pocket beach of SKN-11 so that it is not possible to distinguish between the effects of removal and relocation (shoreline assessment diagrams of segment SKN-04 are presented as Figure 8 in Owens *et al.* 2008).

**Segment HMP-12**

A 100-m section of this beach in Humpback Bay was selected in May 2005 as a test site for relocation. The pebble-cobble sediments contained a >1-m thick layer of subsurface oil that was exposed in the beach face above the intertidal zone and filled all of the spaces between the sediments (Figure 1: 26 May). The oiled sediments from the supratidal area were spread over the middle and upper intertidal zone by a front-end loader working within an area of sorbent ("snare") booms during a low-tide period.

The visual observations during this trial were that the layer of black oil in the pebbles and cobbles present prior to treatment was altered to a more acceptable stain with an incorporated layer of fines (sands) (Figure 1: 27 May). The profiles show that the depth of removal in the upper beach was on the order of one meter (Figure 2).

FIGURE 1. HMP-12: (LEFT) LAYER OF SUBSURFACE OIL EXPOSED IN THE BEACH FACE 2M ABOVE THE MEAN HIGH TIDE LEVEL ON THE TEST BEACH (26 MAY 2005): (RIGHT) RELOCATED OILED PEBBLES AND COBBLES IN THE MIDDLE INTERTIDAL ZONE 27 MAY. LARGE SQUARES IN SCALE = 5 CM).

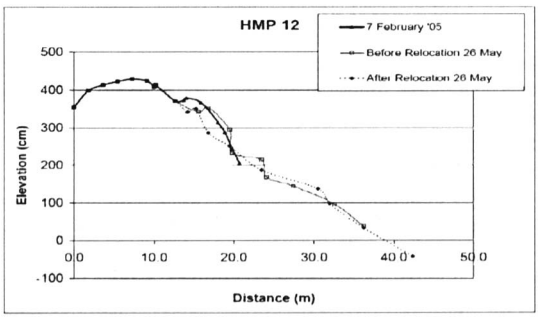



FIGURE 2. PRE- AND POST-RELOCATION BEACH PROFILES ON HMP-12 TEST BEACH (THE HIGH TIDE LEVEL IS AT APPROXIMATELY 200 CM).

Following completion of the test the remainder of the oiled sediments in the segment, a beach length of approximately 500m, were mixed and/or relocated in July 2005.

**Segment SKN-05**

The scale of the operation on SKN-05 was considerably greater than on the HMP-12 test beach. At this site, the operator was instructed to excavate all of the subsurface oiled sediments. While the work was in progress, it became apparent that some oil was as much as 2m below the beach surface (Figure 3: Profile #2, 13 August). The excavated oiled sediments were initially piled adjacent to the excavated area until clean sediments were reached (Figure 4: 13 July) and then the piles leveled (Figure 4: 14 July). Based on the comparison of beach profiles surveyed on 1 July, prior to mixing, and on 20 July, after the mixing, the treatment did little to alter the beach morphology.

On July 18, a recommendation was made to move the mixed oiled sediments to the intertidal zone to expose them to wave action. The relocation created a wide (20m) and deep (2m) trough above the normal intertidal zone and the sediments were deposited as a ridge, at or above the mean high tide level (Figure 3: both profiles of 13 August: and Figure 5: 20 August). The volume relocated, based on the 20 July and 13 August profile data, was on the order of 100 to 190m$^3$ per meter length of beach. A storm passed through the area on 22-23 August and resulted in large-scale redistribution of the relocated sediments from the intertidal zone back to the supratidal area (Figures 3 and 5: 27 August). The volumes removed from the intertidal zone at elevations less then 300cm on the profiles was on the order of 90 to 135 m per meter length of beach. This redistribution restored the beach profiles to a form very similar to that surveyed prior to the tilling and relocation activities.

On 27 August, a Unified Command inspection team documented the oiling conditions on the beach profile lines and reported a marked change with "occasional coated pebbles and cobbles and residual stained gravel throughout the beach…Coats and pooled oil…along the upper gravel storm scarp". One 4m by 15m section of pooled oil was observed mixed with seaweed and other debris in the supratidal zone. A SCAT survey on 15 September 2005 documented that oiled sediments were present as a 30% distribution in a 15m wide band along an approximately 200m section. As a result, the segment did not meet endpoint criteria. With the operational season coming to a close, no further treatment was recommended for 2005.

SKN-05 was surveyed as part of the 2006 spring SCAT program on 17 May (Figure 6), and the team found scattered (<1% distribution: less than one per square meter) tar patties that were mixed in with the recent tidal wrack line. In order to be certain that no subsurface oil remained, this beach was again mixed by an excavator in early June, and the inspection sign-off team on 11 June found no remaining oil.

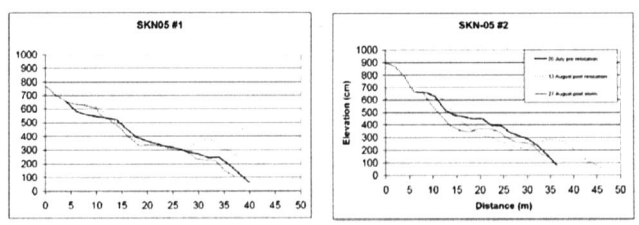



FIGURE 3. SKN-05 BEACH PROFILES SURVEYED BEFORE RELOCATION (20 JULY 2005), AFTER RELOCATION (13 AUGUST), AND AFTER THE STORM OF 22-23 AUGUST (27 AUGUST).

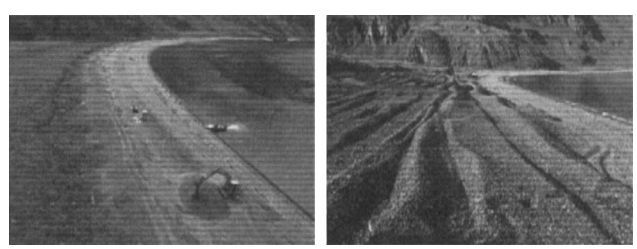


FIGURE 4. AERIAL AND GROUND VIEW OF SKN-05 DURING TREATMENT (LEFT: 13 JULY 2005 AND RIGHT: 14 JULY 2005). THE EXCAVATOR IS WORKING ABOVE THE INTERTIDAL ZONE.

FIGURE 5. GROUND VIEWS POST RELOCATION (LEFT: 20 AUGUST 2005), AND FOLLOWING THE STORM OF 23-24 AUGUST (RIGHT: 27AUGUST 2005). IN THE LATTER PHOTOGRAPH, THE PERSON (CENTER LEFT) IS STANDING AT THE LAST HIGH TIDE LEVEL AND THE STORM SWASH LINE (CENTER RIGHT) IS CLEARLY VISIBLE.

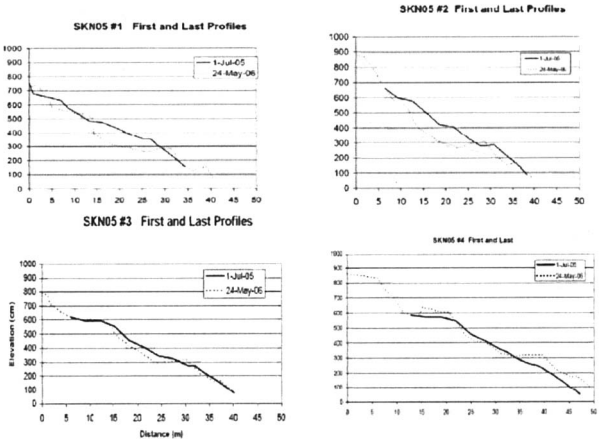



FIGURE 6. SKN-05: 1 JULY 2005 PRETREATMENT AND 24 MAY 2006 BEACH PROFILES (MEAN HIGH TIDE LEVEL IS APPROXIMATELY THE 300 CM ELEVATION).

## MUSSEL CHEMISTRY

In the *Selendang Ayu* spill, mussels were abundant throughout the affected area, particularly along rocky shorelines. As many of the beaches considered for sediment relocation included or were bordered by rocky substrate where mussels could be found, the field team collected samples for archiving and potential analysis. Samples that were analyzed had been collected on two occasions (25/28 April 2005 and 24 May 2006) from segments SKN-11 and SKS-04.

The mussel tissue chemistry results for both sites are consistent and indicate that the oil from the *Selendang Ayu* was biologically available to the mussels at heavily impacted beaches in 2005. Mussel chemistry results collected elsewhere on Unalaska Island during the response showed that background levels of polynuclear aromatic hydrocarbons (PAHs) were very low. For example, a tissue sample from segment KMK-26, collected in May of 2006, contained at total quantifiable PAH level (summed across 61 analytes) of 14 µg/kg (parts per billion, ppb). At SKN-11 in April, 2005, in contrast, the summed concentration in mussels was 8700 ppb at the north end of the beach and 7800 ppb at the south end. Although these values are high in comparison to the background concentration measured at KMK-26, another point of reference is the highest mussel tissue concentration measured by NOAA in 1990 during the *Exxon Valdez* monitoring program. Using a smaller list of target analytes than was the case for *Selendang Ayu*, a mussel tissue concentration ten times as high as the SKN-11 results, an order of magnitude or 80,000 ppb, was found at Smith Island in Prince William Sound over a year after the spill occurred.

By May 2006, measurable concentrations of PAHs remained in mussels bordering SKN-11. However, summed concentration levels had declined sharply over the intervening year, to 610 and 470 ppb at the north and south margins of the beach, respectively. This represented an order-of-magnitude decline from 2005. A similar pattern of relative decline between 2005 and 2006 was reflected in the mussel tissue from SKS-04. However, the absolute levels of summed PAHs at this site were much lower than those observed at SKN-11. In April 2005, total PAHs in mussels at the northeast end of the beach were measured at 1000 and 1700 ppb in two samples collected a few days apart. At the southwest end, the tissue level was 640 ppb. One mussel tissue result is available for the north end of the site in May 2006, and the measured level was 160 ppb.

The data show that:

- the oil on both of these exposed cobble-boulder beaches was biologically available and accumulated prior to shoreline cleanup; and concentrations appeared to be higher at SKN-11 than at SKS-04, and
- an order-of-magnitude, or tenfold, decline occurred between the spring of 2005 and spring of 2006; absolute concentrations remained higher at SKN-11 than at SKS-04.

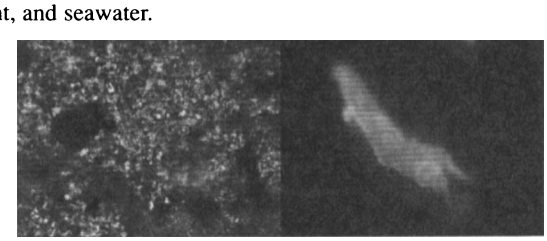
As encouraging as these declines in tissue PAH levels were, they cannot be directly attributed to the cleanup activities that took place in 2005.

## OMA LABORATORY STUDIES

Lee (2005) studied the formation of aggregates to evaluate the inherent capacity and potential for oil-mineral interactions with the spilled oil and local sediments and seawater. Previous research (Stoffyn-Egli and Lee 2002) had defined three structural categories of oil-mineral aggregates (OMA): droplet, solid, and flake. Droplet OMA appear as dispersed oil spheres with mineral particles attached to their surface only. In contrast to droplet OMA, solid OMA are non-spherical in shape and are mineral particles covered by oil. Flake OMA appear as membrane-like structures, with dendritic or feather-like microstructure. Flake OMA have been observed only in the laboratory.

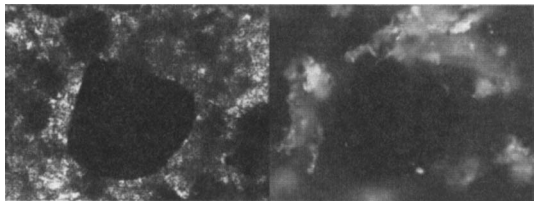
Two OMA experiments were performed with the *Selendang Ayu* materials. The first investigated whether OMAs formed under basic conditions of clean sediment, oil, and seawater mixed together and agitated by hand for 10 minutes. Under these circumstances, no significant formation of OMA occurred. The viscosity of the oil (described as having the consistency of tar) was not conducive to mixing and dispersion into the water, and the product tended to adhere to the side of the laboratory containers.

In the second experiment, the energy of the system, i.e., the degree and duration of agitation, was increased. Observations with a UV fluorescence microscope were made at 18, 114, and 164 hours. At 18 hrs, a few flake OMA and no droplet OMA were observed. At 114 and 164 hours, flake and solid OMA were abundant and droplet OMA remained absent. Figures 7 and 8 illustrate some of these results from these experiments with *Selendang Ayu* oil, sediment, and seawater.



(a) (b)

FIGURE 7. (a) UNALASKA MINERAL PARTICLES AS SEEN IN TRANSMITTED LIGHT, 16X OBJECTIVE; (b) FLAKE OMA, 16X OBJECTIVE. PHOTOMICROGRAPHS BY K. LEE, FISHERIES AND OCEANS CANADA.



(a) (b)

FIGURE 8. (A) A LARGE MINERAL GRAIN AS SEEN IN TRANSMITTED LIGHT, 16X OBJECTIVE; (B) OMA SURROUNDING LARGE MINERAL GRAIN AS SEEN IN UV EPI-FLUORESCENCE, 16X OBJECTIVE. PHOTOMICROGRAPHS BY K. LEE, FISHERIES AND OCEANS CANADA.

These results with materials from the *Selendang Ayu* are consistent with the previous discussion of results from Omotoso *et al.* (2002): on the basis of viscosity measurements alone, the *Selendang Ayu* oil would not be expected to readily form OMA.

Previous laboratory studies have shown that the inherent capacity to form OMA depends at least in part on the dispersability of the oil, and higher viscosity products (such as the *Selendang Ayu* oil) do not easily disperse. However, Lee showed that increasing the energy of the system apparently overcame that inherently low OMA formation potential and he documented the formation of abundant OMA complexes under more vigorous mixing conditions. Extrapolation from these results would suggest that *Selendang Ayu* oil-mineral interactions (OMA) would not be expected under low energy conditions, but with increased agitation (as would be expected on exposed beaches and/or under winter storm conditions), there could be a ready formation of the flake and solid OMA types.

The viscosity of an archived sample of *Selendang Ayu* fuel oil was measured as Omotoso *et al.* (2002) identified oil viscosity and mineral type as key parameters in oil-mineral interactions. Low viscosity oils tended to bind more readily with mineral particulates than higher viscosity products. Omotoso *et al.* tested six oil products with their respective viscosities to which we have added the *Selendang Ayu* fuel oil data (Table 2).

In the investigation by Omotoso et al., oils with viscosities equal to or greater than the Alaskan North Slope Crude grouped similarly low with respect to potential for flocculant formation. Omotoso *et al.* defined an index they called the flocculation index (FI, which = floc-volume increase) to portray this tendency. Values for the index range from 0 to 1, with 0 reflecting no oil-mineral interaction at all. The Alaska North Slope, IFO 180, and Bunker C oils all yielded FI values between 0.1 and 0.2 and were classified as "low."

TABLE 2. PETROLEUM PRODUCTS EVALUATED FOR MINERAL INTERACTION POTENTIAL BY OMOTOSO ET AL. (2002); *SELENDANG AYU* FUEL OIL VISCOSITY INCLUDED FOR REFERENCE.

| Oil type | Viscosity (cP), 20° C |
|---|---|
| Standard blend | 7 |
| Federated crude | 440 |
| IFO 30 fuel | 2460 |
| Alaska North Slope crude | 5940 |
| *Selendang Ayu* fuel | 6100 |
| IFO 180 fuel | 33,500 |
| Bunker C fuel | 252,000 |

Therefore, on the basis of viscosity alone, the flocculation index expected for *Selendang Ayu* fuel oil would be similar to that for Alaska North Slope, or "low," and we would not expect this oil to exhibit a strong tendency to interact with fine particulates.

Recent research by Environment Canada (Khelifa and Brown, in progress) conducted for the Coastal Response Research Center at the University of New Hampshire supports the notion that under nominal mixing conditions, *Selendang Ayu* oil and Unalaska Island sediment would not tend to aggregate.

Khelifa and Brown investigated whether the effectiveness of chemical dispersants was enhanced or inhibited by OMA. Specifically, since chemical dispersants reduce the size of oil droplets in the water column and alter their surface chemical properties, high concentrations of aggregates might affect dispersant performance. As the researchers noted: suspended particulate material is denser than most crude oils, and it is possible that chemically-dispersed oil droplets in the water column would aggregate and settle to the seafloor. The study utilized sediments collected around the coast of the U.S., including a sample collected from a site impacted by the *Selendang Ayu* spill.

The fine-grained beach sediments found on many of the impacted shorelines of Unalaska Island near the *Selendang Ayu* wreck site are mostly volcanic in origin and thus substantially differ from the sediments collected at the other U.S. locations (Delaware Bay, Cook Inlet, Mississippi River delta, Columbia River estuary). The Unalaska sediment contained no sediment fines less than 5 μm in diameter. It also contained a very small concentration of organic matter (0.6 percent by weight). Because of the large grain size and high density (2.96 g/mL), the sediment remained on the bottom of the reaction chambers and did not react with suspended oil droplets in tests with three crude oils. As a result, most of the oil adhered to the glass reaction chambers. This was a very different result than was encountered with the sediments from the other U.S. locations.

The caveat in taking these laboratory results and extrapolating to field conditions is that Bragg and Yang (1996) demonstrated that OMA readily formed in Prince William Sound from weathered Alaskan North Slope crude. Other studies have shown that OMA can form with Bunker C, albeit with a need for elevated energy levels, much as described above by Lee for the *Selendang Ayu* fuel oil. Prince William Sound and the Makushin Bay-Skan Bay environments are similar in terms of the ready availability of fines, in both cases from glacier-fed streams. Given the similar viscosities of Alaskan North Slope crude and the *Selendang Ayu* fuel oil, the argument could be made that in the presence of vigorous storm-induced wave energy, OMA formation could be expected on the shorelines oiled from the *Selendang Ayu*.

## DO WE KNOW ENOUGH ABOUT *HOW* SEDIMENT RELOCATION WORKS TO PREDICT *WHEN/WHERE* IT WILL WORK?

If we were to consider only the results of laboratory experiments incorporating oil and/or sediment from the *Selendang Ayu* spill, it seems reasonable to predict a low probability of success for methods relying on oil-sediment interactions. On the one hand, we have indications that the oil and sediment types encountered during the *Selendang Ayu* are not good candidates for oil-mineral interactions. On the other hand, it appears that sediment relocation methods worked, and shoreline oiling was substantially reduced when oiled beach material was reworked by surf action. Can these apparent incongruities be reconciled?

The second experiment of Lee, when the mixing energy of his experimental systems was increased, may offer a clue: by substantially increasing the vigor and the length of time of the mixing, Lee was able to readily create oil-mineral aggregates. In the spill-affected areas of Unalaska Island, winter storm energy would

seem to be the obvious natural source of extremely vigorous mixing of oiled beach sediments and nearshore water.

## THE ROLE OF STORM EVENTS

Why was there little apparent "natural" cleanup between the time the ship grounded and spilled its oil, and the spring of 2005 when the cleanup began in earnest? An analysis of winter storm data offers a possible answer.

The storm that accompanied the original grounding of the *Selendang Ayu* in December, 2004, determined which beaches were impacted and the elevation at which oil was stranded. The highest observed oil on a beach was 4m above the normal high tide level on Skan Bay segment SKN-11. Equally significant was the fact that during the remainder of the winter storm season of 2004-2005, the magnitude of this original storm event was not exceeded; there were no other storms of equivalent size or intensity for the remainder of the winter. This is important, because storms of equal or greater intensity would have mobilized/removed considerable amounts of oil from the shorelines. Wave-driven nearshore turbulence reworks sediment, abrades oiled sediments and helps to expose pockets of oil that might otherwise remain sheltered from both natural weathering processes and human cleanup activities. Once oil is exposed, storm-driven waves break aggregations into smaller pieces, facilitating initial breakdown, redistribution, and decrease in relative concentrations followed by microbial weathering of those particles in the water column. The effects of winter storms on shoreline oiling conditions were well-documented during the *Exxon Valdez* cleanup, with shoreline surveys in the autumn (when cleanup operations were suspended for the season) providing the basis for showing the consistent decrease in oiling by the following spring when operations re-commenced.

The response team fully expected that there would be a degree of natural cleaning of oiled shorelines during the months that followed the spill, considering that the spill occurred in mid-winter in an extremely harsh marine environment. Unfortunately, there were very few storms in the affected area that winter and none that even closely matched the severity of that which had led to the grounding and breakup of the vessel. In contrast, the winter of 2005-2006 was more active and several storms were recorded by NOAA weather buoys near the Aleutian Islands to have been at least as intense or of a greater intensity than the storm that occurred during the original grounding period. Figure 9 shows wave heights during the 2005-2006 winter storm season, with a reference line for the 8 December, 2004, storm. Figure 10 shows wind speed in similar fashion. These graphics show that large storms exceeding the conditions of the original grounding and oiling incident occurred on several occasions in the winter of 2005-2006. Unfortunately, direct comparisons with 2004-2005 data are not possible as that set is discontinuous.

Figures 9 and 10 document that the winter storm season of 2005-2006 was more vigorous than that of 2004-2005. Not only could this have supplied enough energy to drive the formation of oil-sediment aggregates even with the less-than-optimal oil and sediment characteristics that typified this spill, but also the storm conditions exceeding those of the original storm would have resulted in natural reworking of the originally oiled beaches and probable exposure of much of the subsurface oil.

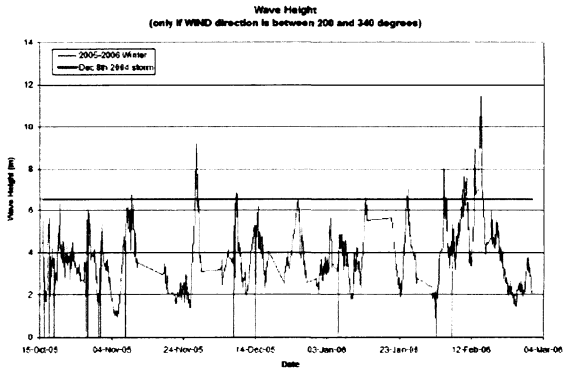



FIGURE 9. WAVE HEIGHTS DURING THE 2005-2006 WINTER STORM SEASON, AS REPORTED BY NOAA WEATHER BUOY IN THE BERING SEA.

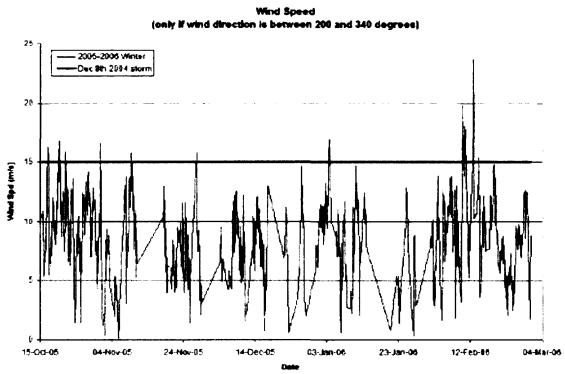



FIGURE 10. WIND SPEEDS DURING THE 2005-2006 WINTER STORM SEASON, AS REPORTED BY NOAA WEATHER BUOY IN THE BERING SEA.

## SUMMARY AND CONCLUSIONS

The tactics of dry mixing and sediment relocation are, in most respects, the same actions. The intent is to accelerate the weathering and microbial breakdown of stranded oil where the oiled sediments either were buried or had penetrated into the subsurface (dry mixing) or were deposited above the normal limit of wave action (sediment relocation). The only real difference between the two tactics during this response was the decision to relocate heavily oiled surface and subsurface sediments from the supratidal zone, in some cases several meters above the normal high water mark. In all other applications the focus was to expose oiled subsurface intertidal sediments.

Typically, the focus of a spill response is on operational issues and it is very difficult to obtain definitive answers to technical questions during an incident. The decision process and approval to apply dry mixing and sediment relocation in this response required a basic monitoring and documentation program. The results documented a net reduction in oiling, the return of beach profiles, and decline in biological availability of hydrocarbons over the course of the response and cleanup activities, and showed no unanticipated adverse impacts despite the large scale of sediment movement on several of the beaches. However, the lack of detailed data leaves the unanswered question whether or not shoreline treatment itself generated a positive environmental benefit. That is, we do not know whether or not subsequent winter storms alone would have yielded the same result. Intuitively, accelerating the weathering of the subsurface oil reduces the residence time of

the oil and, therefore, also reduces the exposure or risk to coastal birds and animals. Empirically, we were not able to prove this. The storm events between 2005 and 2006 resulted in extensive sediment redistribution on the exposed beaches where oil was found more than 2m below the surface. Whether or not this sediment reworking would have removed the subsurface oil is another open question; to answer it would have required a much more extensive and narrowly-targeted monitoring effort. Nevertheless, the positive lesson learned from the *Selendang Ayu* experience is that the treatment actions ensured that the subsurface residual oil was weathered more rapidly than if the oil had been left to attenuate naturally.

## DISCLAIMER

The views expressed in this manuscript do not necessarily represent those of the U.S. Government or the National Oceanic and Atmospheric Administration. Mention of trade names or commercial products does not constitute endorsement or recommendation for their use.

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## REFERENCES

Bragg, J.R., and Owens, E.H, 1994. Clay-oil flocculation as a natural cleansing process following oil spills: Part 1- Studies of shoreline sediments and residues from past spills. *Proceedings 17th Arctic and Marine Oilspill Programme (AMOP) Technical Seminar,* Environment Canada, Ottawa ON, 1-23.

Bragg, J.R. and Yang, S.H., 1995. Clay-oil flocculation and its effects on the rate of natural cleansing in Prince William Sound following the *Exxon Valdez* oil spill. In, "*Exxon Valdez Oil Spill - Fate and Effects in Alaskan Waters*" (eds. P.G. Wells, J.N. Butler, and J.S. Hughes), ASTM STP 1219, American Society for Testing and Materials, Philadelphia, PA., 178-214.

Gallagher, J., 2008. *Proceedings International Oil Spill Conference*, American Petroleum Institute, Washington, D.C.

Khelifa, A., Ajijolaiya, L.O., Macpherson, P., Lee., K, Hill, P.S., Gharbi, S., and Bloiun, M., 2005. Validation of OMA formation in cold brackish and sea waters. *Proceedings 28th Arctic and Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa ON, 527-538.

Le Floch, S., Guyomarch, F.-X. Merlin, P. Stoffyn-Egli, J. Dixon and K. Lee, 2002. The Influence of Salinity on Oil-mineral Aggregate Formation. *Spill Science and Technology Bulletin*, Vol. 8, No. 1, 65-71.

Lee, K,. 2005. Determination of Oil-Mineral Aggregates from the *Selendang Ayu* Oil Spill. Fisheries and Oceans Canada, Dartmouth, NS, Unpub report, 4pp.

Lee, K., T. Lunel, P. Wood, R. Swannell and P. Stoffyn-Egli, 1997. Shoreline Cleanup by Acceleration of Clay-oil Flocculation Processes. *Proceedings International Oil Spill Conference*, American Petroleum Institute, Washington, DC, Publication No. 4651, 235240.

Lee, K., Stoffyn-Egli, P, Wood, P.A. and Lunel, T., 1998. Formation and structure of oil-mineral fines aggregates in coastal environments. *Proceedings 21st Arctic and Marine Oil spill Programme (AMOP) Technical Seminar*, Environment Canada, Ottawa ON, 911922.

Levine, R.A., 1987. Operational Aspects of the Response to the *Arco Anchorage* Oil Spill, Port Angeles, Washington. *Proceedings International Oil Spill Conference*, American Petroleum Institute, Washington, DC, Publication No. 4452, 3-7.

Lunel, T., K. Lee, R. Swannell, P. Wood, J. Rusin, N. Bailey, C. Halliwell, L. Davies, M. Sommerville, A. Dobie, D. Mitchell and M. McDonagh, 1996. Shoreline Clean Up during the *Sea Empress* incident: The Role of the Surf Washing (Clay-Oil Flocculation), Dispersants, and Bioremediation, *Proceedings 19th Arctic and Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa ON, 1521-1540.

Omotoso, O.E., Munoz, V. and Mikula, R.J., 2002. Mechanisms of Crude Oil-Mineral Interactions. Spill Science & Technology Bulletin, 8, 45-54.

Owens, E.H. and Sergy, G.A., 2003. Accelerating the Natural Removal of Oil on Beaches: Part 1 - Sediment Relocation. *Proceedings 26th Arctic Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa ON, 661-677.

Owens, E.H. and Sergy, G.A., 2004. Accelerating the Natural Removal of Oil on Shorelines: Part 2 – Tilling or Mixing Techniques. *Proceedings 27th Arctic Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa ON, 685702.

Owens, E.H., Parker-Hall, H.A., Mauseth, G.S., Graham, A., Allard, T., Reimer, P.D., Engles, J.W., Lehmann, S., Whitney, J., Penland, S., Williams, C. and Wooley C., 2005. Shoreline and Surveillance Surveys on the M/V *Selendang Ayu* Spill Response, Unalaska Island, Alaska. *Proceedings 28th Arctic Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa ON, 509-525.

Owens, E.H., Engles, J.W., Lehmann, S., Parker-Hall, H.A., Reimer, P.D., and Whitney, J., 2008. M/V *Selendang Ayu* Response: Shoreline Surveys and Data Management; Treatment Recommendations; and the Completion Inspection Process. *Proceedings International Oil Spill Conference*, American Petroleum Institute, Washington, D.C.

Sergy, G.A., Guénette, C.C., Owens E.H., Prince, R.C., and Lee, K., 2003. *In-Situ* Treatment of Oiled Sediment Shorelines. *Spill Science and Technology Bulletin*, 8(3), 237-244.