Chapter 2

Distribution of surface and subsurface oil on shoreline habitats four years after the *Selendang Ayu* oil spill

J. Michel and Z. Nixon

Introduction

In this chapter, we determine the presence, distribution, and relative amount of *Selendang Ayu* oil remaining on beach segments of greatest concern (Objective 1). To accomplish this, each segment was investigated in July-August 2008 using standard methods to describe remaining surface and subsurface oil, similar to those used during the response and cleanup activities in 2005 and 2006. The locations of pits for description of subsurface oil were randomized to allow estimation of the percent remaining oil within the original boundary of each zone. Sediment samples representative of the different oiling descriptors and from each segment were collected for characterization of oil weathering. See Chapter 1 for greater design and sampling detail and Chapter 3 for discussion of the sediment analysis methods and all of the chemical results.

Methods

Presence and distribution of surface oil along the entire length of each segment were evaluated by visual survey using the methods described in the NOAA Shoreline Assessment Manual[1]. Each segment was described, sketched, and photographed. The intent was to replicate the nature and coverage of the SCAT surveys carried out after the spill and during the 2005 and 2006 cleanup activities, to allow temporal comparisons.

Presence and distribution of subsurface oil were evaluated within each identified oiled zone by locating and excavating pits using methods modified from studies conducted in Prince William Sound of the lingering oil from the *Exxon Valdez* oil spill[2]. The emphasis of the subsurface oil investigation was on the oiled zones identified during previous SCAT surveys. It was assumed that the boundaries delineated by previous SCAT surveys represented the area of greatest potential for remaining oil.

Pits were allocated to oiled zones proportionally to the zone surface area as follows:

Buffered Oiled Zone Area (m^2)	Zone Count	Pits
0-<100	1	5
100-<500	11	10
500-<1,000	2	20
1,000-<2,000	10	40
≥2,000	3	80

The area of each zone was calculated as the reported alongshore length times the reported cross-shore width (from the most recent SCAT data) plus a buffer of 2 meters (m) each on the seaward and landward sides. The buffer allowed for minor inaccuracies in the zone dimensions and reoccupation process, as well as potential mobilization of oiled sediments landward or seaward of the oiled zones defined by the SCAT surveys. Pits were located within each zone using a Generalized Random-Tesselation Stratification (GRTS) that has statistical properties similar to random sampling, but balances the samples across geographic space to the extent possible. The new pit data provided the basis for estimating the percent remaining oil within the original boundary of each zone. Pit locations within each oiled zone were generated as random pairs of x and y coordinates based upon a coordinate system derived from the most recently documented dimensions of the oiled zone (based on review of the 2005 and 2006 SCAT surveys, sketches, GPS data, and photographs). Additional pits (in addition to the pits inside the oiled zone generated by GRTS) were located seaward of the oiled zone boundaries within each sampled segment on an as-needed basis to confirm assumptions about the intertidal elevations of the majority of oiling.

Pits were excavated to a minimum depth of 0.5 m, or the maximum depth possible before encountering bedrock or immovable boulders. Grain size and visual oiling descriptors were assigned to vertical layers within the pit using the standard SCAT terminology[1]. Grain size was described as the relative percent of bedrock, boulder, cobble, pebble, granule, sand, and mud/peat in the layer. Table 2.1 lists the oiling descriptors and their definitions. Because of the nature of the oiled sediments, the surface oil thickness descriptors (e.g., stain [ST], coat [CT], cover [CV]) were used to describe the subsurface oiling on individual clasts, along with an estimate of the percent cover of the oil on the clasts. However, percent cover estimates are not appropriate for oil type descriptors for the different degrees of oil residues (OR), partially filled pores (PP), and oil-filled pores (OP). The same two-person team described and photographed all the pits. Figure 2.1 shows representative photographs of the different types of subsurface oiling.

Because the pits were randomly located within each oiled zone, the oil type and thickness of oiled sediments described in the pits are considered to be accurate representations of the likely amount of oil present. The pit oiling data were processed in the following manner:

The oiling descriptors were combined into three categories, listed in order of decreasing amount of oil:

a. $\geq$LOR and >50% cover – this category includes LOR, MOR, HOR, OP, and PP descriptors of subsurface oil.
b. <LOR and 10–50% cover – this category includes ST, CT, CV, TB, and OR.
c. <LOR and <10% cover – this category includes ST, CT, CV, TB, and OR.

The volume of oiled sediments for these three oiling categories, and for all categories, was estimated for each zone surveyed. This was accomplished by considering all pits within a zone to be random samples (0.5 m x 0.5 m x 0.5 m or 0.125 m^3) of the entire sediment volume of the zone (considered to be the zone surface area x 0.5 m). The average proportion of oiled sediment to total sediment volume within excavated pits was calculated, and multiplied by the total volume of sediment for that zone, to provide an unbiased estimate of total oiled sediment volume in that zone. Also, all of the data for each zone were reviewed, including pit descriptions and photographs, field sketches, and the summary graphics showing the locations and oiling of the pits. The results of the oiled sediment data analyses for the 24 zones are shown in Table 2.2. The subsurface oiling results for all segments are presented in Figures 2-2 through 2-16 by zone and segment, along with the locations of the mussel and passive array (PEMDs) sampling points, overlain onto 1983 aerial photographs to provide a visual summary of the data. The figures also indicate the pits where sediment samples were collected.

The elevation of the seaward edge, the center and the landward edge of each zone was determined by measuring the elevation above the waterline at the time of the survey with hand level, laser, and stadia rod. Tide height was estimated based on predicted heights at the nearest tidal monitoring station at the time of survey. All elevations were corrected to meters above MLLW. Vertical elevations of all pits were then estimated as linear interpolations of the tidal elevations of either the seaward edge and center, or center and landward edge of a given zone, based upon the horizontal distance seaward or landward of the zone centerline.

Results

Sediment Oiling by Segment and Zone

In this section, the sediment oiling results are briefly described for each segment and zone surveyed in 2008. Figures 2.2 through 2-16 present visual summaries of the surface and subsurface oiling found at each pit within a segment and zone.

In Pumicestone Bay, PTN-03-A was selected for assessment in 2008 because it was near a harlequin duck trap site. It had no visible subsurface oil in the 80 pits excavated along the 6 x 400 m zone (Fig. 2.2) and a trace (<1%) of surface oil in a 10 centimeter (cm) band at the seaward edge of the vegetation for about 300 m. The narrow pebble-cobble beach near the head of the bay showed evidence of reworking, and the oil had not been deposited much above the high-tide line.

The M/V *Selendang Ayu* grounded just south of the entrance to Skan Bay, and the shorelines in Skan Bay were among the most heavily oiled (Fig. 1.1). In north Skan Bay, there are three segments and six zones. SKN-05-A is the pebble beach at the head of the bay where extensive sediment reworking and relocation was conducted in 2005 and 2006 as part of the cleanup efforts because some of the oil was as much as 2 m below the surface[3]. Therefore, in 2008 pits were dug as deep as physically possible, with most pits 60-80 cm deep and the deepest pit 140 cm. Subsurface oil was observed in 17 of 80 pits along the 19 x 400 m zone (Fig. 2.3). All of the oiled pits were in the high storm berm in the supra-tidal zone. In 2008, 3% of the sediment volume in the zone was estimated to be oiled. The oiling on 95% of these sediments was described as <1-10% cover. SKN-05A was the site of an extensive storm berm relocation in July 2005, where the oiled sediments in the supratidal storm berm were mechanically relocated to the middle intertidal zone[3]. An intermittent subsurface lens of oil occurred along the north end of the segment. Depths and thicknesses varied for the fragmented lens; for instance, in a 125-cm pit dug on the north end, a HOR layer of 50% coverage was found at 98-107 cm.

SKN-11-A is located at the southern end of a mixed sand and gravel beach, where it grades into boulder rubble. In 2008, there was no visible subsurface oil in the ten excavated pits along the 9 x 30 m zone (Fig. 2.4); there was weathered surface oil coat and cover on the sheltered sides of the boulder rubble in a band 1-4 m wide by 17 m long.

There were four zones in SKN-15 that did not meet cleanup endpoints in 2006. Zones B (9 x 30 m) and C (8 x 25 m) are short zones where the oil occurred in the large and angular boulder rubble at the base of talus slopes in the supra-tidal zone. Figure 2.5 shows that subsurface oil was observed in six of ten pits in SKN-15-B; 21% of the sediment volume was estimated to be oiled (Table 2.2). About 60% of the oiled sediments were described as stain, coat, cover, or oil residue at 1-3% distribution. There was one pit with 10 cm of heavily oiled residue and one pit with partially filled pores (the oil included a lot of oiled organic matter) at 30-45 cm. Surface oil occurred as 1% cover of coat and stain splatter in a 3-10 m band up to the edge of the grass. At SKN-15-C, all ten pits had visible subsurface oil (Fig. 2.5), and clean sediments were reached in only two pits. It was estimated that 89% of the sediment volume in this zone was oiled (Table 2.2). Half of the oiled sediments were described as having <10% oil distribution. However, one-third of the oil on the clasts was relatively thick, being described more as oil residue and globules, and often at 20% distribution. Heavily oiled residues were found deep (>20 cm) in three pits. Surface oil occurred as coat and cover on boulders with occasional tarballs between the boulders in a band 5-10 m wide and 2-5% distribution.

SKN-15-D is a 19 x 60 m zone located along a thin cobble storm berm between headlands on a rock platform. The gravel was sub-rounded. Many of the 40 pits could not be excavated to 50 cm because bedrock was encountered. Subsurface oil was found in 8 of 40 pits, in the middle of the zone (Fig. 2.6). The oiled sediments were mostly in the top 5-10 cm; thus, only 7% of the sediment volume was estimated to be oiled (Table 2.2), and most of that was stain or coat with a few globules at less than 5% cover. Surface oil occurred as a 3-10 m band with 2-3% cover of coat and stain up to the edge of the grassy vegetation.

SKN-15-E is 19 x 60 m zone located along a pebble-cobble-boulder beach and storm berm fronted by a rock platform, also bordered by rock outcrops. The gravel was sub-rounded. Subsurface oil was observed in 19 of 40 pits (Fig. 2.5), mostly in the face of the storm berm and in the northern half of the zone. The subsurface oil was quite variable in thickness and depth, with layers of oiled sediments ranging from 0-40 cm to 30-50 cm. In 2008, 29% of the sediment volume was estimated to be oiled (Table 2.2). More than 80% of the oiled sediments had <1-5% distribution of stain, coat, cover, and oil residue. Patches of moderately and heavily oiled residue 8-20 cm thick were found in four pits; only two were adjacent but at different depths. Most of this heavier oil (representing about 10% of the estimated oiled sediment volume) occurred in pebbles and cobbles at depths of 30-50 cm below coarser sediments. Surface oil occurred as 3-10 m band averaging 2-3% stain, coat, and cover up to the edge of the vegetation fringe.

Two zones in south Skan Bay were surveyed in 2008. SKS-04-A is an exposed pebble-cobble beach with multiple cuspate high-tide and storm berms. The sediments were well-rounded. Cleanup methods included mechanical mixing and relocation[3], thus pits were dug as deep as 70 cm along a 5 x 235 m zone. Widely spaced subsurface oil was observed in 4 of 40 pits (Fig. 2.7). Only 1% of the sediment volume was estimated to be oiled (Table 2.2). In three pits, the oil occurred as a single pebble or piece of debris with a spot of oil; in one pit, the oil occurred as 5%

cover and oil residue at 30-35 cm. Surface oil occurred as a discontinuous band of <1% weathered stain and coat 1-5 m wide between the storm berm and the vegetation fringe.

SKS-12-A is located at the head of south Skan Bay and is sheltered from direct wave exposure. The zone starts on a sloping rock shelf and ends on an angular pebble-cobble beach. It is near a harlequin duck trap site, and cleanup methods included mechanical dry mixing[3]. No subsurface oil was observed in any of the 40 pits along a 4 x 250 m zone (Fig. 2.8); ten of the pits were located on bedrock or in a stream drainage across the beach and were not excavated. Surface oil occurred in two areas: a 0.5 x 0.5 m patch of 1% coat and cover on bedrock and a 1 x 100 m band with <1% coat and cover against the vegetation fringe between the bedrock and the stream.

In Humpback Bay, three zones in segment HMP-05 were near harlequin duck trap sites. HMP-05-B is a rock platform with a veneer of angular boulders, somewhat sheltered by Cathedral Point. Bedrock was encountered at depths of 15-40 cm. Subsurface oil was reported as 5 cm thick patches of oiled fine gravel under boulders in two of ten pits along a 4.5 x 60 m zone (Fig. 2.9); 5% of the sediment volume was estimated to be oiled (Table 2.2). Surface oil occurred as a 5-10 m wide band with <1% cover of oil stain, coat, and cover as splatter and drips.

HMP-05-C is also a rock platform but with a thicker veneer of sub-rounded boulders; bedrock was encountered at depths of 30-40 cm. Subsurface oil was observed in 8 of 40 pits along a 7.5 x 160 m zone (Fig. 2.9); 38% of the sediment volume was estimated to be oiled (Table 2.2). Most of the oiling was less than 5% stain, coat, and cover and occurred as 0-5 cm patches of oiled fine gravel under large boulders. Surface oil occurred as a 3-10 m band of <1% cover (though locally up to 10% cover) coat and cover on the boulders and minor asphalt pavements in crevices.

Zone HMP-05-D is a pebble-cobble beach where well-rounded sediments have accumulated against a rock headland. This 12 x 20 m zone had no surface or subsurface oil (Fig. 2.9). The sediments below the surface tended to contain 10-20% sand and granules and be mixed with organic wrack material.

Two segments in Makushin Bay were surveyed in 2008 because they had not reached cleanup endpoints in 2006: MKS-14 and MKS-16. Both segments are very exposed to direct wave attack. Within segment MKS-14, there are two zones. MKS-14-A extends equally across a supra-tidal band of rocky rubble with patchy vegetation and a pebble-cobble beach. The lower intertidal zone consists of an irregular and wide rock platform with tidal pools. Subsurface oil was observed in 18 of 36 pits along a 19 x 100 m zone (Fig. 2.10). In 2008, 30% of the sediment volume was estimated to be oiled; 85% of this oil was described as stain, coat, cover, or oil residue at less than 5% cover (Table 2.2). The three oiled pits in the beach on the northern end contained oil in the top 8-15 cm described as a single oiled pebble, two globs, or <1% cover. The southern half of the zone contained more and heavier subsurface oil, including three pits that had 5-10 cm of moderately oiled residue. Generally, subsurface oil was found where the surface sediments included boulders. Surface oil occurred as a 20 m wide band of 1-2% stain, coat, and cover, with very scattered tarballs. There was also a 0.5 x 4 m patch of surface asphalt pavement on the southern end of the zone.

MKS-14-B is bedrock surface covered by a thin veneer of angular, boulder-sized rubble that was partially vegetated with grasses (thus mostly in the supra-tidal zone), fronted by an irregular and wide rock platform. Subsurface oil was observed in 8 of 20 pits along a 19 x 50 m zone (Fig. 2.10). Most pits could only be excavated to depths of 25-30 cm before bedrock was reached; the pits included a lot of vegetation and soils. In 2008, 24% of the sediment volume was estimated to be oiled; about 55% of this oil was described as 1-7% stain, coat, and cover (Table 2.2). The heavier subsurface oil was patchy. Two adjacent pits had 10-20 cm of heavily oiled residue, and one pit had 15 cm of moderately oiled residue. These areas had large boulder rubble on the surface, and all the sediments were angular, indicating very low rates of reworking by waves. This zone had the second highest estimated volume of the more heavily oiled sediments (51.9 m^3; Table 2.2). Surface oil occurred on the boulders as 1-30% cover with occasional thicker patches in crevices.

The second segment surveyed in Makushin Bay, MKS-16, has three zones. MKS-16-B is a very steep pebble-cobble beach with a high storm berm and well-rounded gravel. There is a flat rock platform offshore, but offshore breakwaters occur only on the ends of the beach, so waves can break directly on most of the beach. Subsurface oil was observed in 19 of 40 pits along a 14 x 100 m zone (Fig. 2.11); it should be noted that almost all the oiled pits were located in the storm berm, above normal high tides as indicated by the presence of vegetation. In 2008, 25% of the sediment volume was estimated to be oiled (Table 2.2); over 80% of the oil was described as 1-7% stain, coat, cover, and oil residue from 5-43 cm thick. A 10-15 cm thick layer of moderately oiled residue (a cohesive layer of oil, pebbles, and organic matter) was found in four pits, at depths of 5-23 cm. Surface oil occurred in a 9 m wide band of <1-3% distribution of coat and cover on the gravel and into the vegetation fringe. Also, a 0.5 x 10 m layer of oiled gravel with 15% coat and cover was exposed in a small erosional scarp in the berm at the northern end of the zone.

MKS-16-C is just south of and topographically lower than MKS-16-B, located along the high-tide pebble berm. No surface or subsurface oil was observed along a 4.5 x 18 m zone (Fig. 2.11).

MKS-16-F is on the southern end of the segment, where a rock slide deposited large boulder rubble onto the pebble beach. Subsurface oil was observed in four of ten pits along the 8 x 50 m zone (Fig. 2.12). Although 11% of the sediment volume was estimated to be oiled (Table 2.2), none of the oiling was greater than 1% in distribution. Often the oil was described as splotches or smears on a few individual clasts. Surface oil occurred as <1% coat, mostly on the back sides of the boulder rubble.

The shoreline south of Kof Point, at the northeast entrance to Skan Bay, was very heavily oiled and had deep oil penetration into the storm berms. Because of access restrictions along this highly exposed shoreline with extensive offshore rock outcrops, only manual cleanup methods were conducted in 2005; however, mechanical tilling and relocation was conducted in 2006 in some of the zones. There are seven zones within KFP-01 that did not meet cleanup endpoints in 2006. All of the zones are located in the supra-tidal zone on steep storm berms composed of rounded cobbles with varying amounts of pebbles and boulders.

The gravel beach at KFP-01-A has a very steep depositional storm berm composed of very rounded cobbles. The 6 x 100 m zone extended over the berm face and berm top. Subsurface oil was observed in 12 of 20 pits (Fig. 2.13); 28% of the sediment volume was estimated to be oiled (Table 2.2). All of the oiled sediments were described as no more than 1% stain, coat, cover, and oil residue. The depth and thickness of this trace oiling varied widely, from a 5 cm thick layer at the surface, to a depths of 35-40 cm, to the entire interval of 0-55 cm. Surface oil was similar, with less than 1% coat and cover on the gravel.

The gravel beach at KFP-01-B consists of a steep, eroded storm berm behind large offshore rock outcrops. The sediments are rounded but less well sorted, with variable amounts of pebbles, cobbles, and boulders. The 5 x 24 m zone extended from the high-tide line to the base of the scarp in the grassy vegetation. Subsurface oil was observed in five of ten pits (Fig. 2.13); 23% of the sediment volume was estimated to be oiled (Table 2.2). All of the oiled pits were along the upper part of the zone. Two pits in the northern end had 10 cm thick bands of oiled sediments described as oil-filled pores or partially filled pores at depths of 26 and 34 cm. The three pits in the southern half had oiled sediments with 1-25% oil residue; the southernmost pit had 4% oil residue from 0-50 cm and 25% oil residue from 50-80 cm. Surface oil occurred as a 2 m wide band of 1-20% coat and cover adjacent to the vegetation.

The gravel beach at KFP-01-C consists of a steep, eroded storm berm behind large offshore rock outcrops, just north of and similar to KFP-01-B. Subsurface oil was observed in nine of ten pits (Fig. 2.13); 70% of the sediment volume in this 6 x 30 m zone was estimated to be oiled (Table 2.2). One pit had a layer of moderately oiled residue mixed with organic material at 36-50 cm, and one pit had sediments with 20% oil residue at 40-50 cm. The rest of the pits had sediments with <1-5% distribution of stain to oil residue up to 55 cm thick, representing 93% of the oiled sediment volume. Surface oil occurred as 1% distribution of stain and coat.

KFP-01-D is the southern part of a tombolo composed of pebbles and cobbles deposited behind a very large rock outcrop. This zone was mechanically tilled and oiled sediments relocated to the intertidal zone. The north part of the zone extended across the vegetated berm top. Subsurface oil was observed in eight of ten pits (Fig. 2.13); 26% of the sediment volume was estimated to be oiled (Table 2.2). Of this volume, 92% was described as 1-5% stain to oil residue that ranged in thickness from 5-30 cm. One pit had a 10 cm thick band of sediments with 20% coat, cover, and oil residue. Surface oil occurred as a 3-10 m wide band of 1-2% coat and cover above the berm and patches of asphalt pavement consisting of shell hash and granules.

The gravel beach at KFP-01-E has a high, steep storm berm composed of rounded cobbles and boulders and covered by patchy vegetation. The 29 x 50 m zone extended from the high-tide line to the storm berm top. Pits were dug to 70 cm deep. Subsurface oil was observed in 28 of 40 pits (Fig. 2.14); 45% of the sediment volume was estimated to be oiled (323 m^3; Table 2.2), which is the largest estimated volume of oiled sediments of all zones surveyed in 2008. Of this volume, 85% was described mostly as having no more than 1% stain, coat, and oil residue (in 18 pits); in four pits, the oil distribution on the sediments was 2-7%. About 8% of the oiled sediments were described as 10-15% coat and cover; in one pit, the entire 60 cm depth was described as such. Four pits contained a deep layer (40-48 cm below the surface) of mostly pebbles described as having heavily or moderately oiled residue. The measured thickness of the layer was 6-23 cm;

however, it was not possible to reach clean sediments below this layer in every pit. Three of the pits with this oil layer were clustered together in approximately the middle of the zone on the lower face of the storm berm. Surface oil occurred as a 3-10 m wide band of 1% coat and cover on the storm berm face and top.

The gravel beach at KFP-01-F includes a high storm berm composed of sub-rounded pebbles, cobbles, and boulders, with multiple pebble-cobble berms on it. The north end of the zone extends into an area of rocky rubble and patchy vegetation. Offshore, there is an irregular rock platform with a large sea stack on the north end. This zone was mechanically tilled, and oiled sediment was mechanically relocated to the intertidal zone in 2006 as part of cleanup activities. The 7 x 150 m zone is located on the face of the storm berm, well above normal high tides. Pits were dug 45-101 cm deep. Subsurface oil was observed in 38 of 40 pits (Fig. 30); 57% of the sediment volume was estimated to be oiled (Table 2.2). The oiling was lighter and thinner on both the northern and southern ends of the zone, where the subsurface sediments were finer-grained with a significant granule fraction. This zone had the highest estimated volume of the more heavily oiled sediments, representing 18% of the volume of oiled sediments (54.9 m^3; Table 2.2). In the middle of the zone, these heavier oiled sediments (described as moderately and heavily oiled residues) occurred in two clusters: around pits 9, 11, 14, and 16, with 5-36 cm of oiled sediments, including one pit with moderately oiled sediments from 0-36 cm; and around pits 31, 32, and 33, with 30-56 cm of oiled sediments at depths of 20-45 cm below the surface. Surface oil ranged from 1-20% distribution of stain, coat, and cover, with patches of asphalt pavement on the southern end.

KFP-01-G is a complex zone that has dimensions of 14 x 200 m (Fig. 2.15). The westernmost quarter is a thin layer of angular, boulder-sized rubble on bedrock. Oiling occurred as patches of fine gravel with 1-20% oil residue between the boulder rubble 5-10 cm thick. The next section to the east is angular cobble/pebble-sized rubble with extensive vegetation; subsurface oil was found in one pit at <1% distribution. In the third section to the east, which is about 75 m long, the rubble is larger and unvegetated. Of 31 pits in this section, 5 pits had no subsurface oil, 21 had sediments with 5% or less oiling, and five pits had sediments with 10-25% oiling at thicknesses of up to 40 cm. The last 25 m of this zone was bedrock and large boulder with no subsurface oil (Fig. 2.15). As shown in Table 2.2, 21% of the sediment volume in this entire zone was estimated to be oiled, though this is likely an overestimate because of the large amount of irregular bedrock where the oil occurred as patches of oiled sediments in crevices. Surface oil occurred as a 8-15 m wide band of <1-3% coat and cover, mostly on the bedrock and boulders.

Tidal Elevation and Depth of Residual Oil

Normal spring high tides in Skan and Anderson Bays are +1.3 to +1.4 m relative to MLLW. Of the 735 pits excavated, 123 (17%) were located below +1.4 m MLLW, meaning that they were at elevations within normal spring tidal flushing. Of the 373 pits that contained any oiling, 18 (5%) were within the range of normal spring tides. Of the 262 pits that contained subsurface oiling, only 2 (<1%) were located within the range of normal spring tides.

Figure 2.16 shows the distribution of subsurface oiled layers (for all oiling categories and for different groups of oiling categories) by tidal elevation (note that these are counts of oiled layers, not pits, so separate subsurface oiled layers within the same pit are counted independently). Within these pits, there were 342 distinct oiled layers (the total of the Fig. 2.16 counts), of which 2 (<1%) were located at pits below +1.4 m MLLW. Most (61%) of the subsurface oiled layers occurred at +2-5 m MLLW, although there was some subsurface oil as high as +9 m MLLW. The heaviest subsurface oiling was generally at +3-4 m MLLW (Fig. 2.16), well above the influence of tidal flushing, even at depth.

Figure 2.17 shows the distribution of oiled sediment with depth, for all oiling categories (including surface and subsurface oil) and for different groups of oiling categories, as observed in pits. Most of the lighter oiling (lighter oil descriptors and <10% cover) occurred at shallower depths, compared to the heavier oiling. This pattern is what one would expect; both sediment reworking and tidal flushing would be less effective at physical removal with depth.

Discussion

The *Selendang Ayu* spill was unique in that the majority of the oil was believed to have been released during an intense storm on 8 December 2004, with waves up to 9 m so that oil was stranded very high on the shoreline (up to 4 m above the normal high tide zone[3]). The lack of similar-sized storms the rest of the winter of 2004/2005 triggered the decision for use of aggressive cleanup methods in the summer of 2005 including mechanical removal, sediment mixing, and relocation to lower intertidal zones on eight (mostly exposed) beaches[3]. In 2008, nearly all of the oiling remaining on the shoreline occurred at elevations of +3-6 m above MLLW (Fig. 2.16). Thus, the oil persists above the zone of normal tidal flushing.

To evaluate the effects of intense storms on oil persistence, available NOAA buoy data on significant storm wave heights over the period of December 2004 through March 2009 were obtained from two buoys in the Bering Sea, for wind direction from 200 to 340 degrees, to reflect the direction from which waves would be most likely to enter the oil-impacted bays on Unalaska Island (Fig 2.18):

12/2004-5/2005 from buoy 46035 (http://www.ndbc.noaa.gov/station_page.php?station=46035)
5/2005-4/2009 from buoy 46073 (http://www.ndbc.noaa.gov/station_page.php?station=46073)

These buoys are about 640 and 320 km respectively from Unalaska Island to the west. Buoy location maps can be found at: http://www.ndbc.noaa.gov/

At-sea significant wave heights exceeded the 8 December 2004 storm (6.9 m) about 15-20 times between the spill and March 2009. There have been at least four very intense storms with significant waves of almost 10 m during this period. It appears that the oil remaining on the beaches of Unalaska Island will be physically reworked only by a very intense storm event, one that is strong enough to rework the storm berms.

It was estimated that the 24 zones surveyed in 2008 contained 2,336 m^3 of oiled sediments (Table 2.2). Of that volume, 81.5% was described as oiled with 0.1-10% cover of stain, coat, cover, tarballs, or oil residue. These oil residues mostly occurred as patches of oil on individual clasts. In addition, 9.5% was described as oiled with 10-50% cover of stain, coat, cover, tarballs, or oil residue. These oil residues occurred as thicker accumulations as well as in higher concentrations. However, 9% of this total volume was described as oiled with >50% cover of moderately and heavily oiled residue, partially filled pores, and oil-filled pores, representing free oil in the pore spaces between the gravel that would be more likely to be mobilized by flushing during storms.

The 24 zones surveyed in 2008 can be classified into four habitat types: 1) pebble/cobble beaches with multiple berms or tombolos; 2) steep cobble/boulder storm berms; 3) boulder rubble on bedrock; and 4) transitional edges between beaches and bedrock or mixed sediments. Table 2.3 shows the habitat assignments.

The five zones classified as pebble/cobble beaches had the lowest percent volume of oiled sediments in the zone, averaging 6% when including the tombolo in KFP-01-D, and 0.8% when excluding this zone. Pebble/cobble beaches are composed of finer gravel that is more likely to be reworked by wave action, particularly where the oil is deposited within the zone of normal wave action[5-7]. The finest gravel is eroded from the beach and transported seaward during storms, allowing for abrasion and removal of oil attached to the sediments. Clean sediments are returned to the beach during the post-storm recovery period. This process appeared to be effective at releasing most of the stranded oil remaining after cleanup efforts were terminated at HMP-05-D, PTN-03, and SKS-04-A (this zone also was also treated by mechanical mixing and relocation). At SKN-05-A, the persistent oil had been stranded in the storm berm, above the normal zone of wave action since the spill occurred, thus very extensive mechanical mixing and relocation was conducted in the summer of 2005[3]. The oil remaining after four years in the storm berm along this pebble beach occurred mostly as tarballs and one pit with a patchy layer of OP. At KFP-01D, the persistent oil occurred in a tombolo, above the zone of normal wave action.

Steep cobble/boulder storm berms were surveyed at two exposed sections of shoreline–Kof Point (KFP-01) and the entrance Makushin Bay (MKS-16-B/C). The seven zones in this habitat type had the highest percent volume of oiled sediments in the zone in 2008, averaging 35% (of which an average of 29% was less than 10% cover). All of the KFP-01 zones were located in areas with very difficult access, thus mostly manual cleanup methods were used, with the exception of mechanical work at KFP-01-F. Manual dry mixing was conducted at MKS-16. Storm waves normally build up, or do not modify, storm berms except during very strong storms[5]; therefore, it is not surprising that the largest amount of persistent subsurface oil is in these high storm berms. The remaining oil deeply penetrated into these high storm berms is likely to persist for a very long period.

Eight of the zones selected for study in 2008 were classified as boulder rubble on bedrock (Table 2.3). The sediments on these shorelines are accumulations of rocky debris transported by gravity downslope; these clasts are very large and angular, with no evidence of reworking by wave action. An average of 25% of the sediment volume in these zones was oiled. These zones had the highest percentages of sediment volumes with oiling descriptors greater than 50% cover (Table 2.2); three zones had 9-11% of the sediment volume with greater than 50% cover. Only manual removal methods were conducted in these zones. Where the rubble was thick and located in the supratidal zone, patchy layers of MOR and HOR have persisted nearly four years after the spill. Because the oil has penetrated into sediments that show little or no potential for physical reworking by wave action and are above the normal tidal flushing elevations, there is little chance for this oil to be removed by physical processes.

Four zones were classified as transitional/mixed sediments. An average of 12.5% of the sediment volume in these zones was oiled. These zones are usually partially sheltered by offshore rock platforms or adjacent rocky headlands, thus they tend to have a reduced potential for sediment reworking by wave action.

Summary

Nearly four years after the *Selendang Ayu* oil spill (July/August 2008), surveys were conducted at 24 shoreline zones within the spill area that were selected subjectively because they: 1) had not reached cleanup endpoint status and likely had persistent oil; 2) were subject to alternative treatment techniques during cleanup, such as berm relocation; 3) were near harlequin duck trap sites; and/or 4) were sites where subsistence samples showed evidence of oil exposure. As of the summer of 2008, there was very little surface oil on these 24 zones. Subsurface oil was found on 21 of the 24 zones. Nearly all of the subsurface oil occurred very high in the supratidal zone, where it had been initially deposited during an intense storm, and where it remains above the zone of normal tidal flushing and sediment reworking. Most (81.5%) of the subsurface oil was described as 0.1-10% cover on individual clasts; however, 9% occurred as thick accumulations. The heaviest oiling increased with depth and occurred mostly at 20-50 cm. The zones classified as sheltered boulder rubble accumulations and exposed storm berms had the highest fractions of the sediment volume that was estimated to be oiled (25-35%). Boulder rubble sediments have little potential for sediment reworking, and storm berms tend to build up over time (until a storm large enough to move them landward occurs). Thus, the subsurface oil remaining on the shorelines of Unalaska Island from the *Selendang Ayu* oil spill is not likely to be removed by physical processes for decades.

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Table 2.1. Visual oiling descriptors used to describe *Selendang Ayu* oiled sediments in 2008.

Oiling Thickness:

ST	Stain (visible oil, which cannot be scraped off with fingernail)
CT	Coat (visible oil <0.1 cm, which can be scraped off with fingernail)
CV	Cover (oil or mousse from >0.1 cm to <1 cm on any surface)
PO	Pooled Oil or Thick Oil (fresh oil or mousse >1 cm thick)

Oiling Type:

TC	Tar (highly weathered oil, of tarry, nearly solid consistency)
TB	Tar balls (discrete accumulations of oil <10 cm in diameter)
PT	Patties (discrete accumulations of oil >10 cm in diameter)
AP	Asphalt Pavements (cohesive, heavily oiled surface sediments)
OP	Oil-Filled Pores (pore spaces are completely filled with oil)
PP	Partially Filled Pores (the oil does not flow out of the sediments when disturbed)
HOR	Heavy Oil Residue (sediments are visibly oiled with black/brown coat or cover on the clasts, but there is accumulation of oil within the pore spaces)
MOR	Moderate Oil Residue (sediments are visibly oiled with black/brown coat or cover on the clasts, but little or no accumulation of oil within the pore spaces)
LOR	Light Oil Residue (sediments are visibly oiled with a light stain on the clasts)
OF	Oil Film (sediments are lightly oiled with an oil film, or stain on the clasts)
TR	Trace (discontinuous film or spots of oil, or an odor or tackiness)
NOO	No Oil Observed

Table 2.2. Summary statistics on pit oiling by zone on percent (%) of the sediments oiled and the estimated total volume of oiled sediments.

ZONE	CLAST OILING DESCRIPTORS <LOR (TB,CT,CV,ST, or OR) and 0.1 - 10 % COVER		CLAST OILING DESCRIPTORS <LOR (TB,CT,CV, or ST + OR) and 10 - 50 % COVER		CLAST OILING DESCRIPTORS >LOR (LOR,MOR,HOR, PP, or OP) and > 50 % COVER		ALL OILING DESCRIPTORS	
	% TOT. VOL.	EST TOT. VOL. (m^3)	% TOT. VOL.	EST TOT. VOL. (m^3)	% TOT. VOL.	EST TOT. VOL. (m^3)	% TOT. VOL.	EST TOT. VOL. (m^3)
HMP-05-B	5%	10.1	0%	0.0	0%	0.0	5%	10.1
HMP-05-C	37%	223.4	0%	2.3	0%	0.0	38%	225.8
HMP-05-D	0%	0.0	0%	0.0	0%	0.0	0%	0.0
KFP-01-A	28%	84.3	0%	0.0	0%	0.0	28%	84.3
KFP-01-B	9%	8.2	10%	8.3	4%	3.4	23%	19.9
KFP-01-C	65%	58.4	2%	1.8	3%	2.5	70%	62.6
KFP-01-D	24%	44.3	2%	3.7	0%	0.0	26%	48.0
KFP-01-E	38%	276.0	4%	26.0	3%	21.4	45%	323.4
KFP-01-F	40%	207.6	7%	35.5	10%	54.9	57%	298.0
KFP-01-G	16%	225.5	4%	62.8	0%	0.0	21%	288.3
MKS-14-A	25%	211.1	3%	21.6	2%	17.0	30%	249.8
MKS-14-B	13%	63.4	0%	0.0	11%	51.9	24%	115.3
MKS-16-B	20%	141.8	2%	14.0	2%	16.5	25%	172.3
MKS-16-C	0%	0.0	0%	0.0	0%	0.0	0%	0.0
MKS-16-F	12%	24.7	0%	0.0	0%	0.0	12%	24.7
PTN-03-A	0%	0.0	0%	0.0	0%	0.0	0%	0.0
SKN-05-A	3%	118.8	0%	6.7	0%	6.0	3%	131.5
SKN-11-A	0%	0.0	0%	0.0	0%	0.0	0%	0.0
SKN-15-B	12%	16.3	0%	0.0	9%	11.6	21%	27.9
SKN-15-C	46%	45.7	31%	31.3	12%	12.3	89%	89.3
SKN-15-D	6%	18.7	1%	3.1	0%	0.0	7%	21.9
SKN-15-E	23%	104.4	2%	10.5	3%	13.9	29%	128.8
SKS-04-A	1%	4.4	0%	0.0	0%	0.0	1%	4.4
SKS-12-A	2%	9.9	0%	0.0	0%	0.0	2%	9.9

Table 2.3. Shoreline classification for the 24 segments surveyed in 2008.

Pebble/Cobble Beaches with Multiple Berms or Tombolos	Boulder Rubble on Bedrock	Steep cobble/boulder storm berms	Transitional/Mixed Sediments
HMP-05A	HMP-05B	KFP-01A	MKS-16F
KFP-01D	HMP-05C	KFP-01B	SKN-15D
PTN-03A	KFP-01G	KFP-01C	SKN-15E
SKN-05A	MKS-14A	KFP-01E	SKS-12A
SKS-04A	MKS-14B	KFP-01F	
	SKN-11A	MKS-16B	
	SKN-15B	MKS-16C	
	SKN-15C		

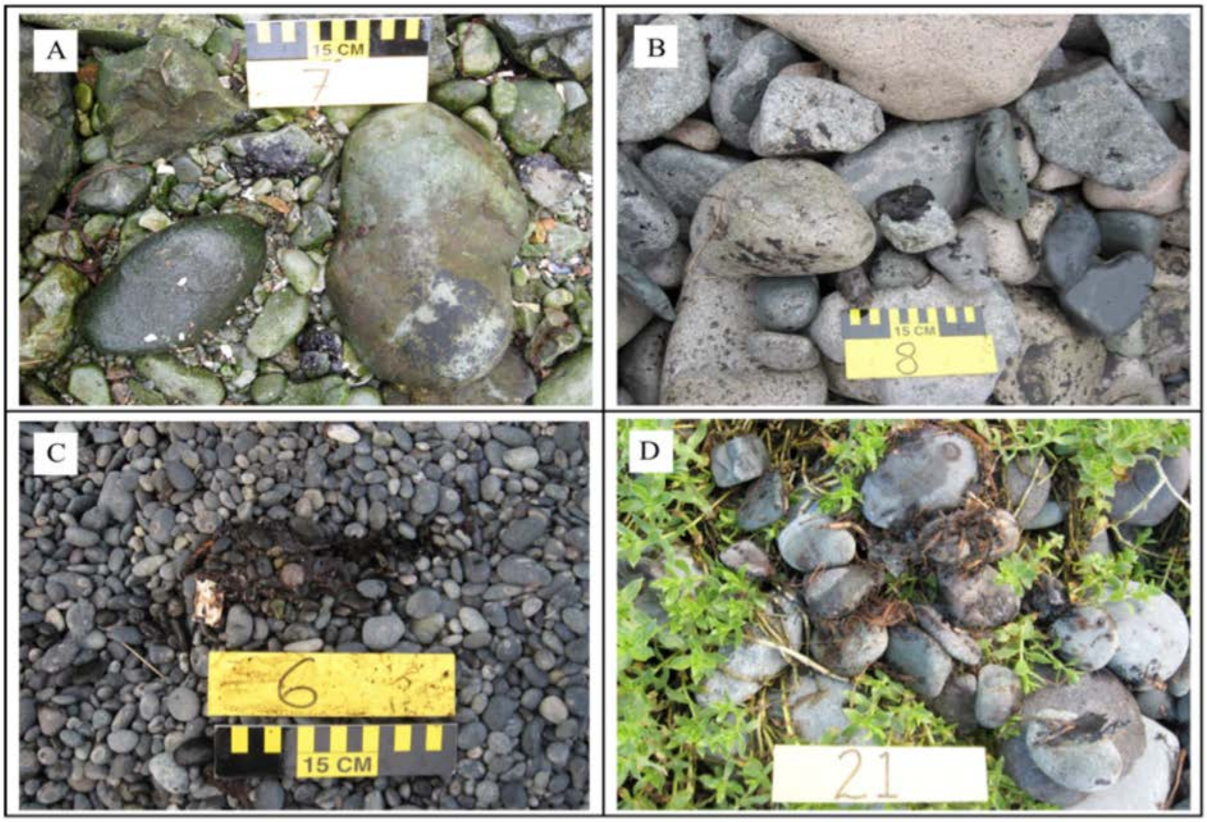

Figure 2.1. Photographs of the different types of subsurface oil observed in 2008 on the oiled zones. A) Moderately oiled residue from 0-5 cm at HMP-05B; B) Coat/cover on individual clasts from 0-10 cm at KFP-01E; C) Tarball from 55-60 cm at SKN-05A; and D) Coat/cover/pooled oil from 15-40 cm at MKS-16B. The number indicates the pit number.

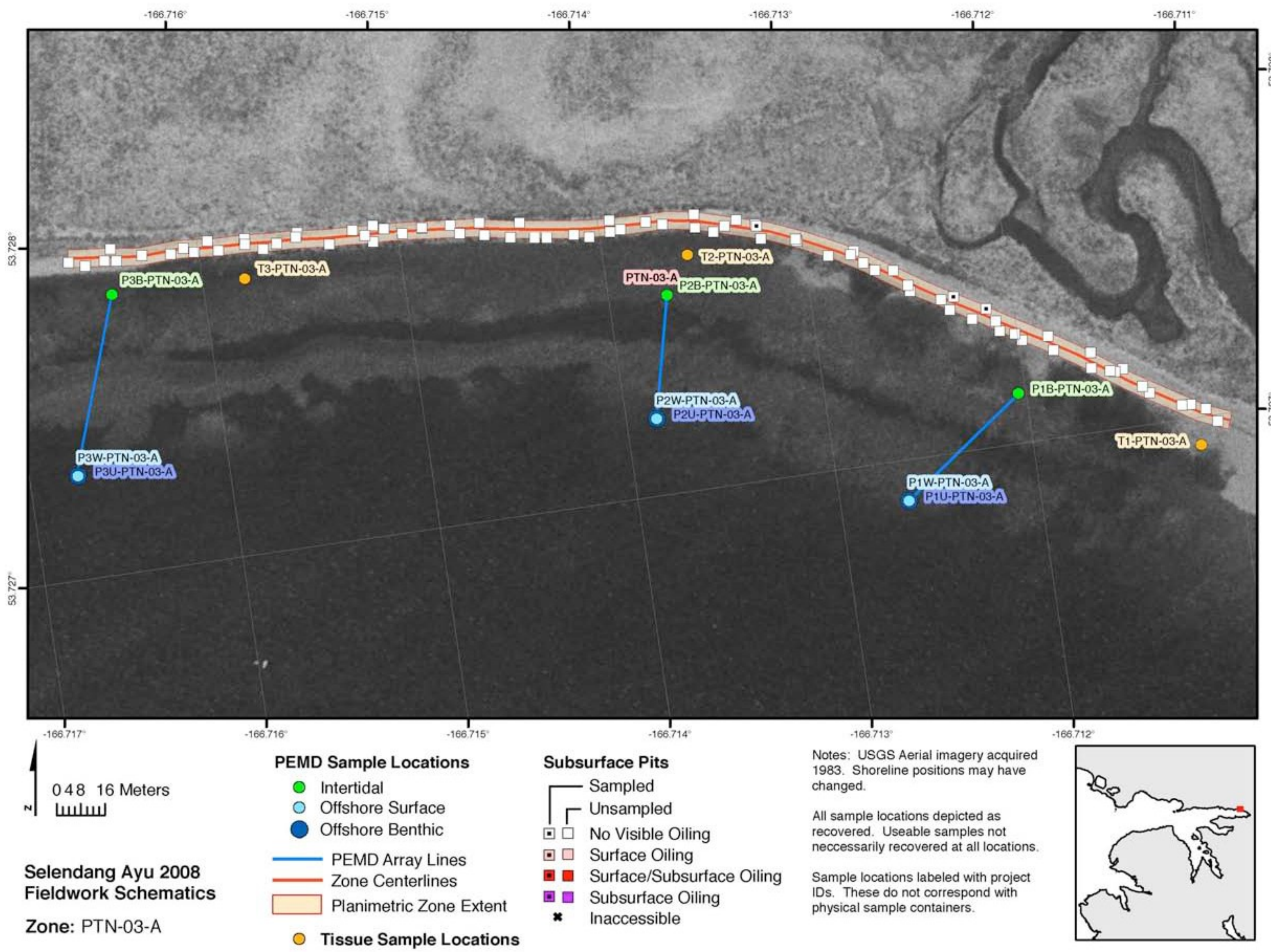

Figure 2.2. Segment PTN-03-A showing the location and oiling of pits and the location of PEMD and mussel sampling sites.

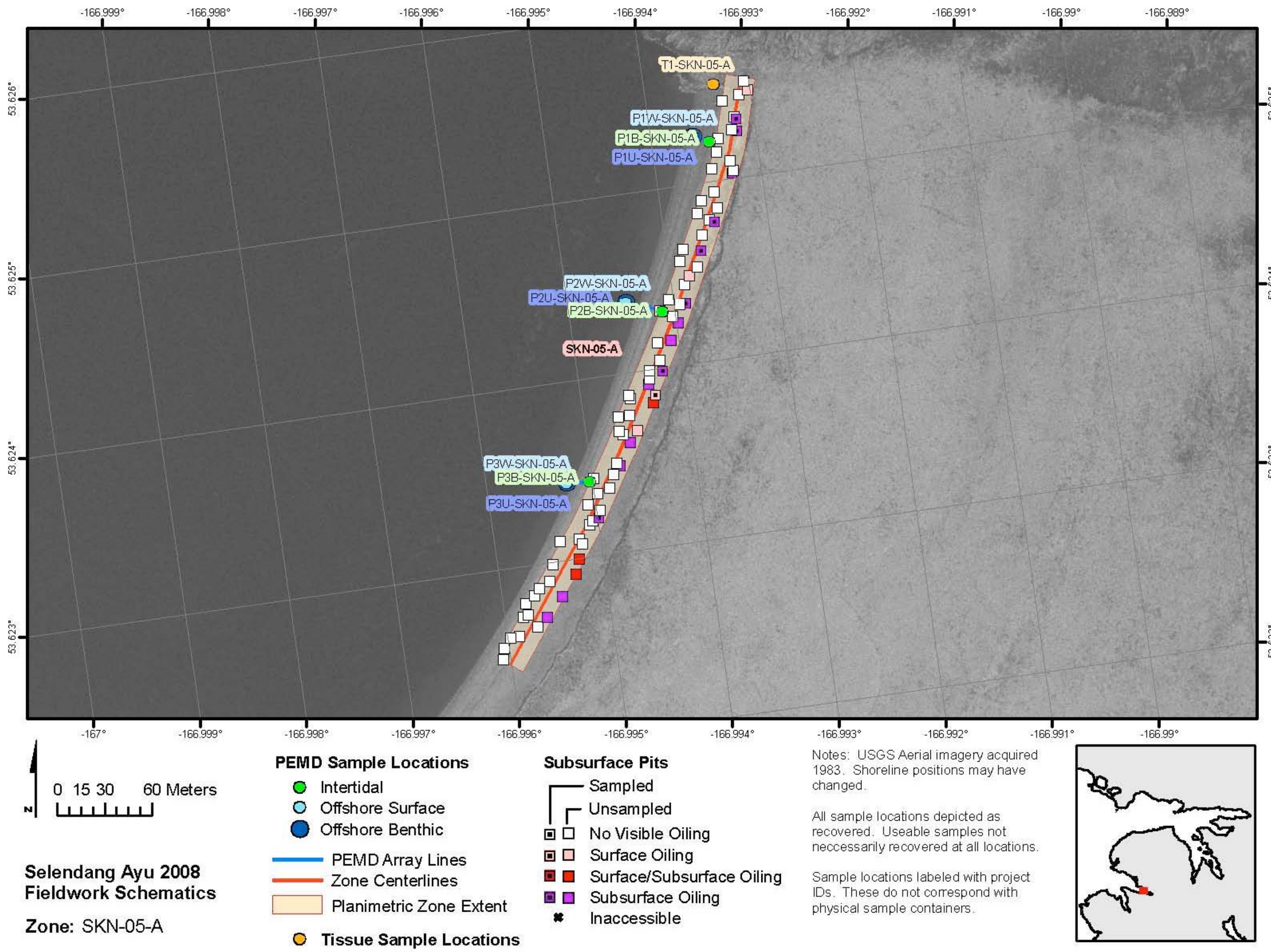

Figure 2.3. Segment SKN-05-A showing the location and oiling of pits and the location of PEMD and mussel sampling sites.

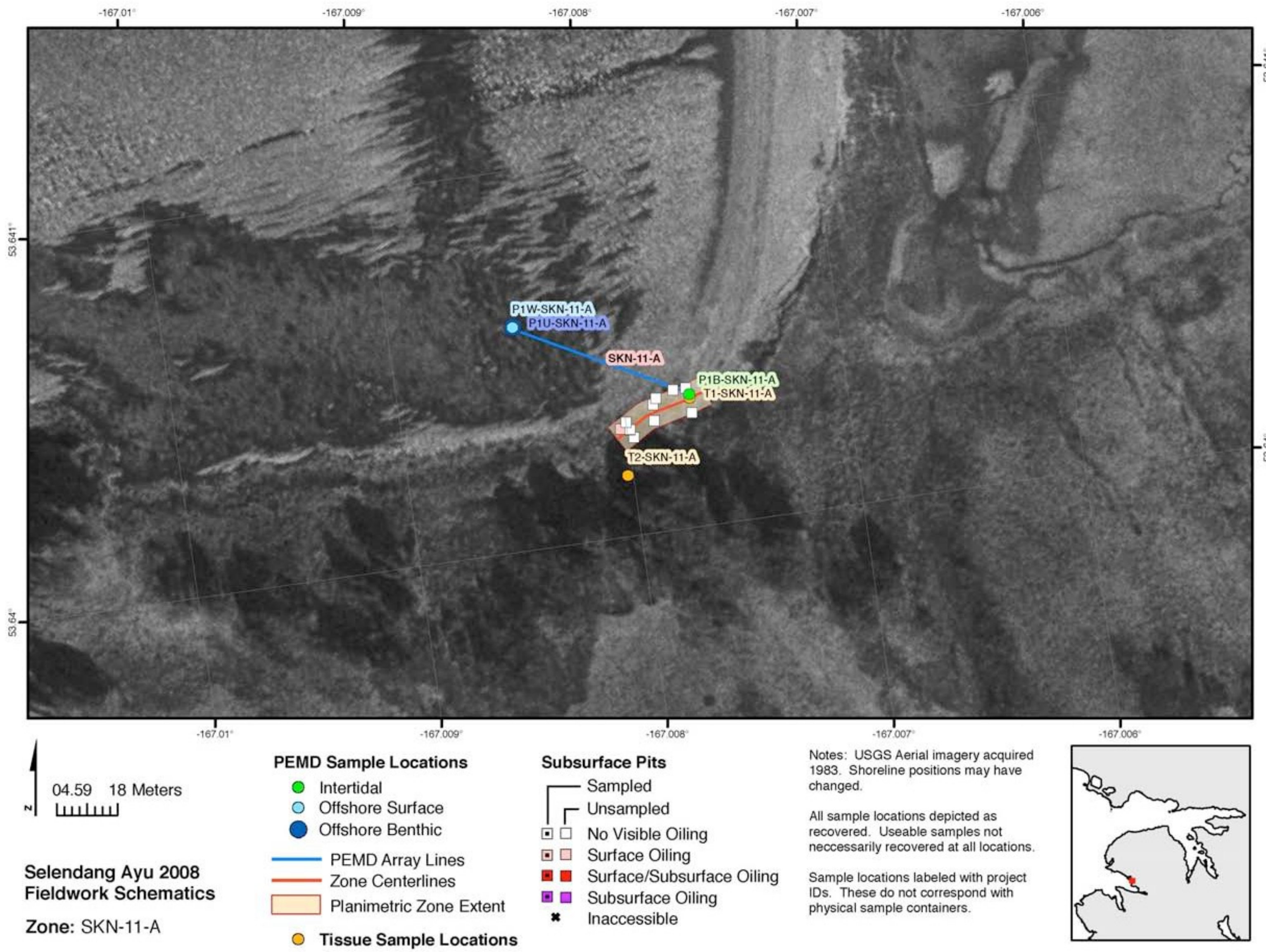

Figure 2.4. Segment SKN-11-A showing the location and oiling of pits and the location of PEMD and mussel sampling sites.

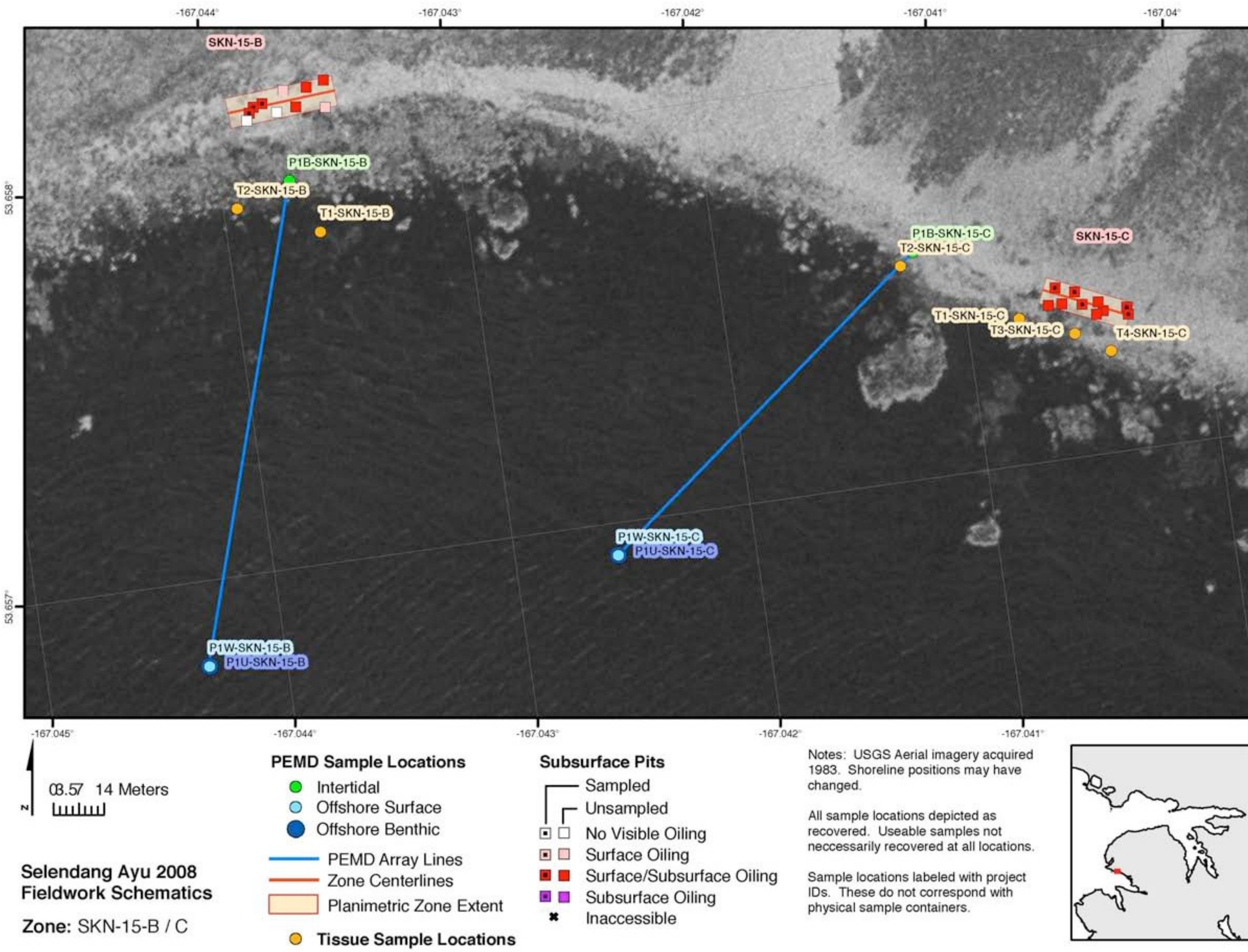

Figure 2.5. Segments SKN-15-B/C showing the location and oiling of pits and the location of PEMD and mussel sampling sites.

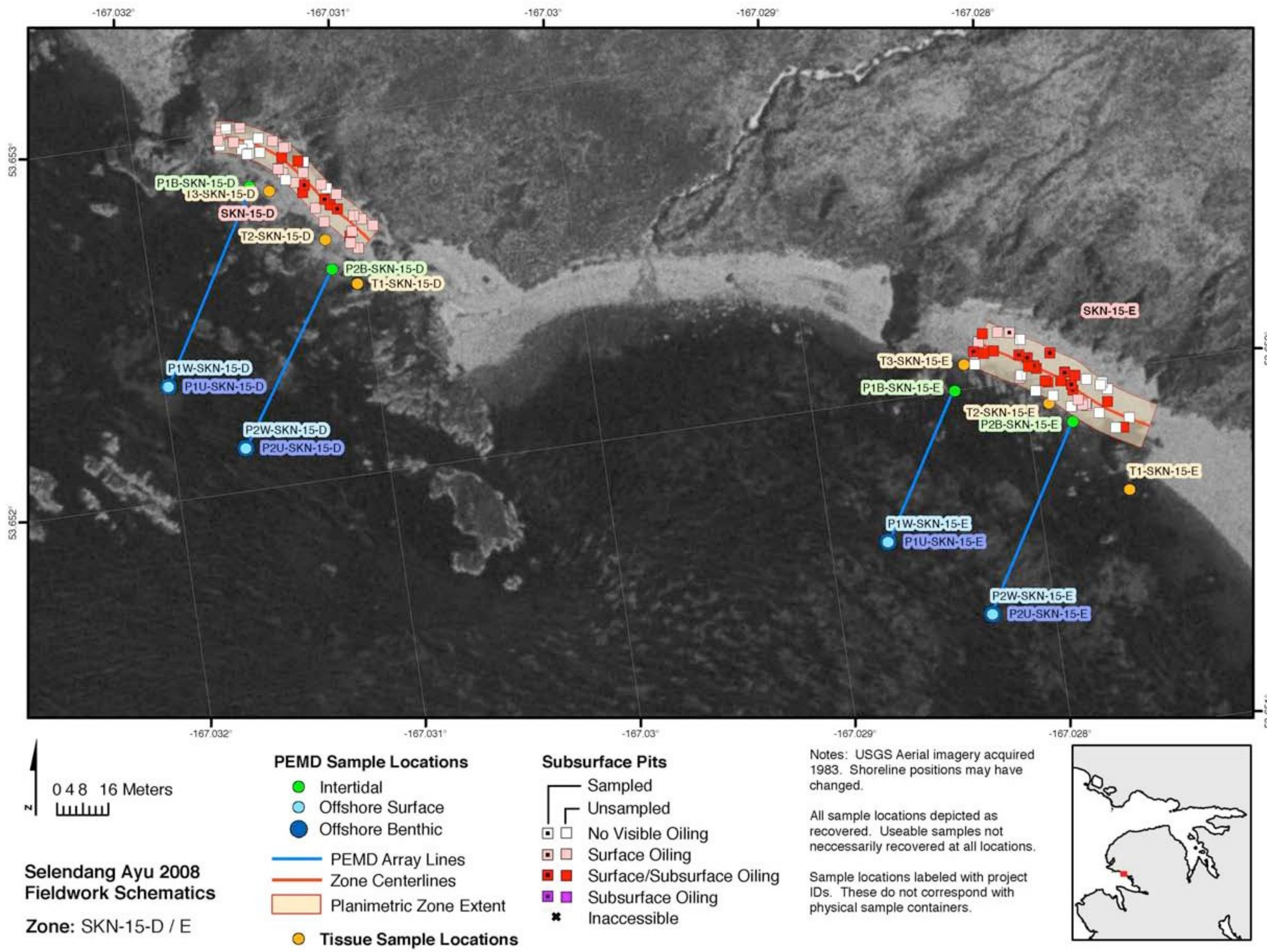

Figure 2.6. Segments SKN-15-D/E showing the location and oiling of pits and the location of PEMD and mussel sampling sites.

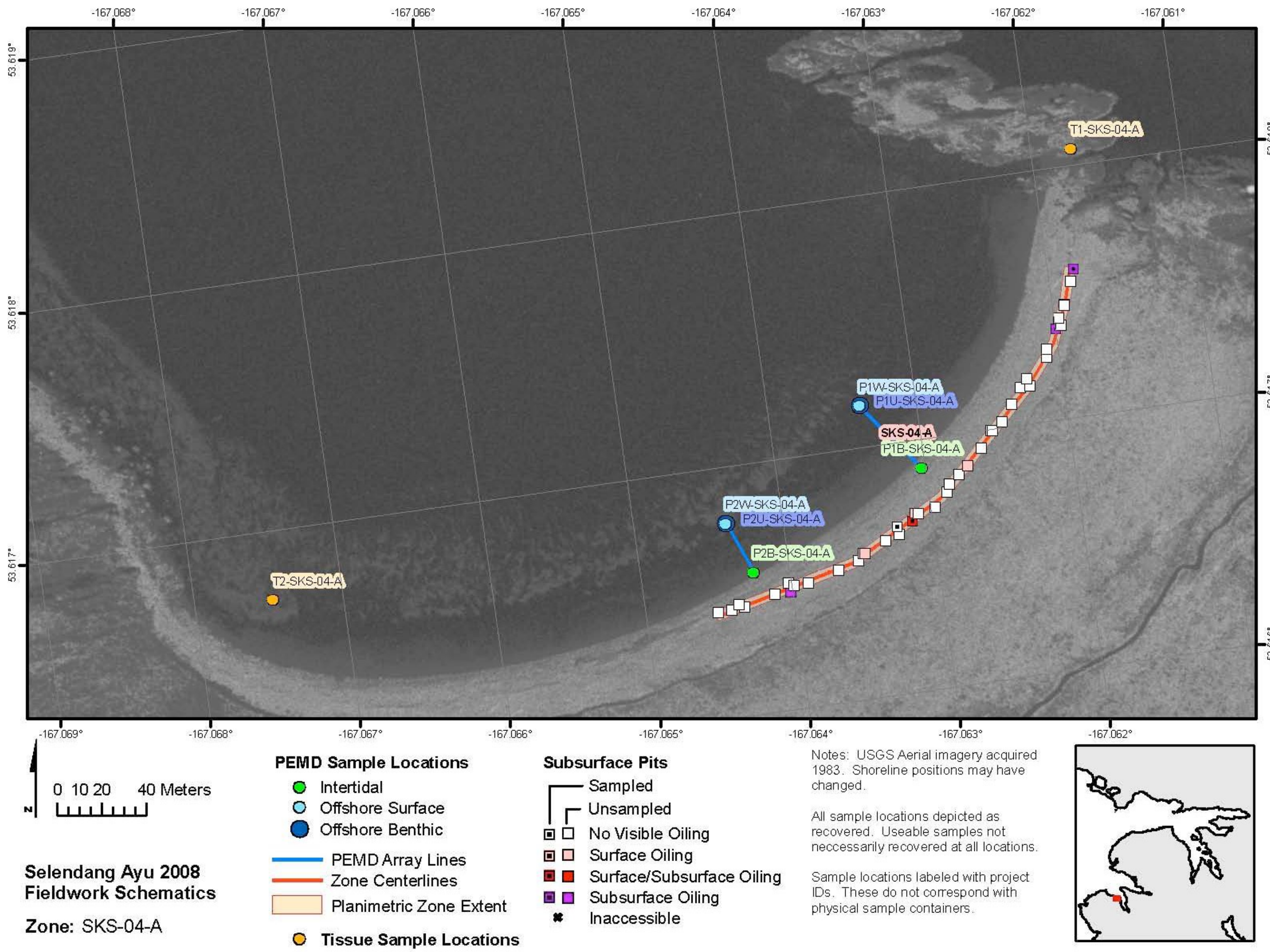

Figure 2.7. Segment SKS-04-A showing the location and oiling of pits and the location of PEMD and mussel sampling sites.

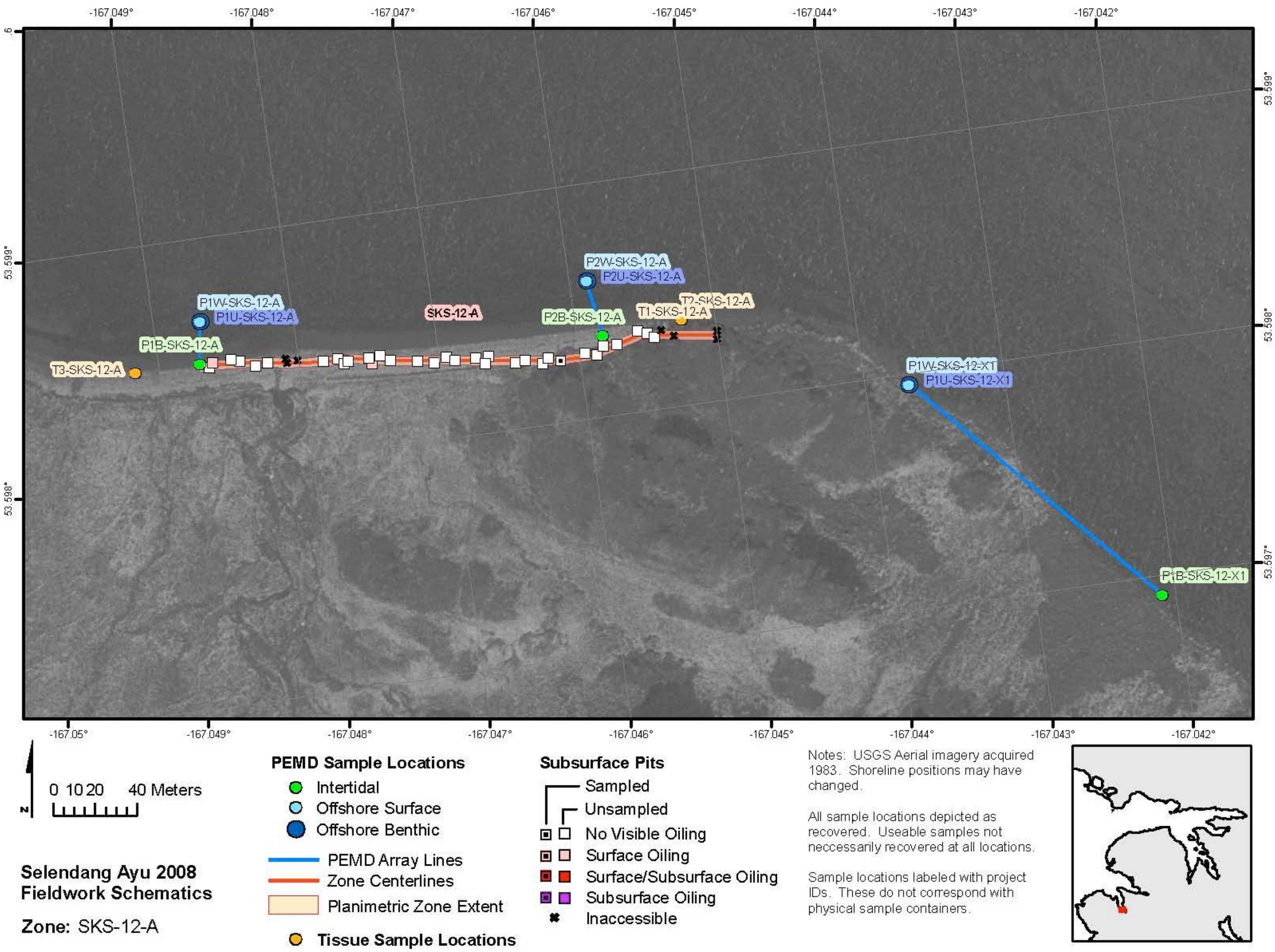

Figure 2.8. Segment SKS-12-A showing the location and oiling of pits and the location of PEMD and mussel sampling sites.

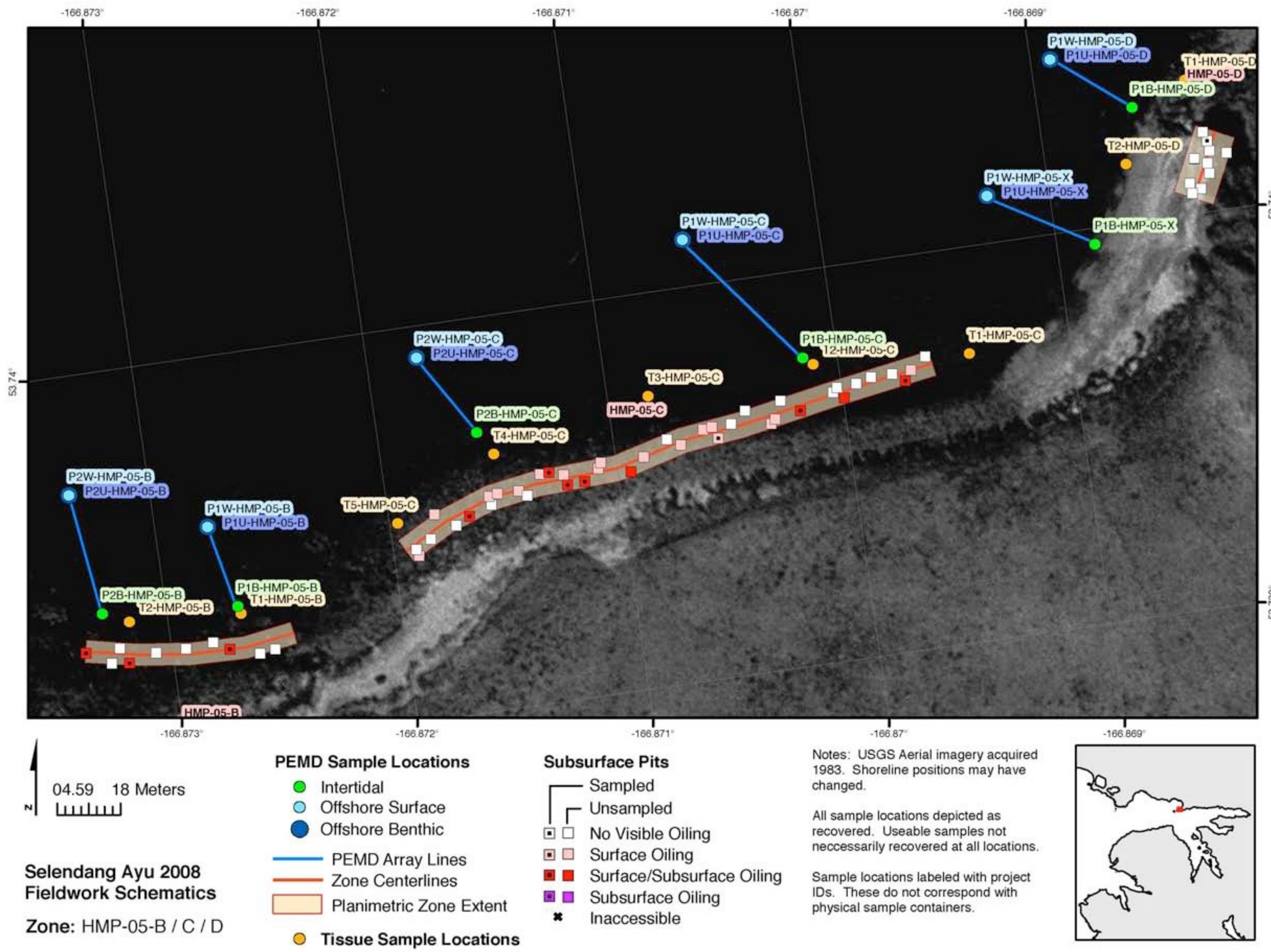

Figure 2.9. Segments HMP-05-B/C/D showing the location and oiling of pits and the location of PEMD and mussel sampling sites.

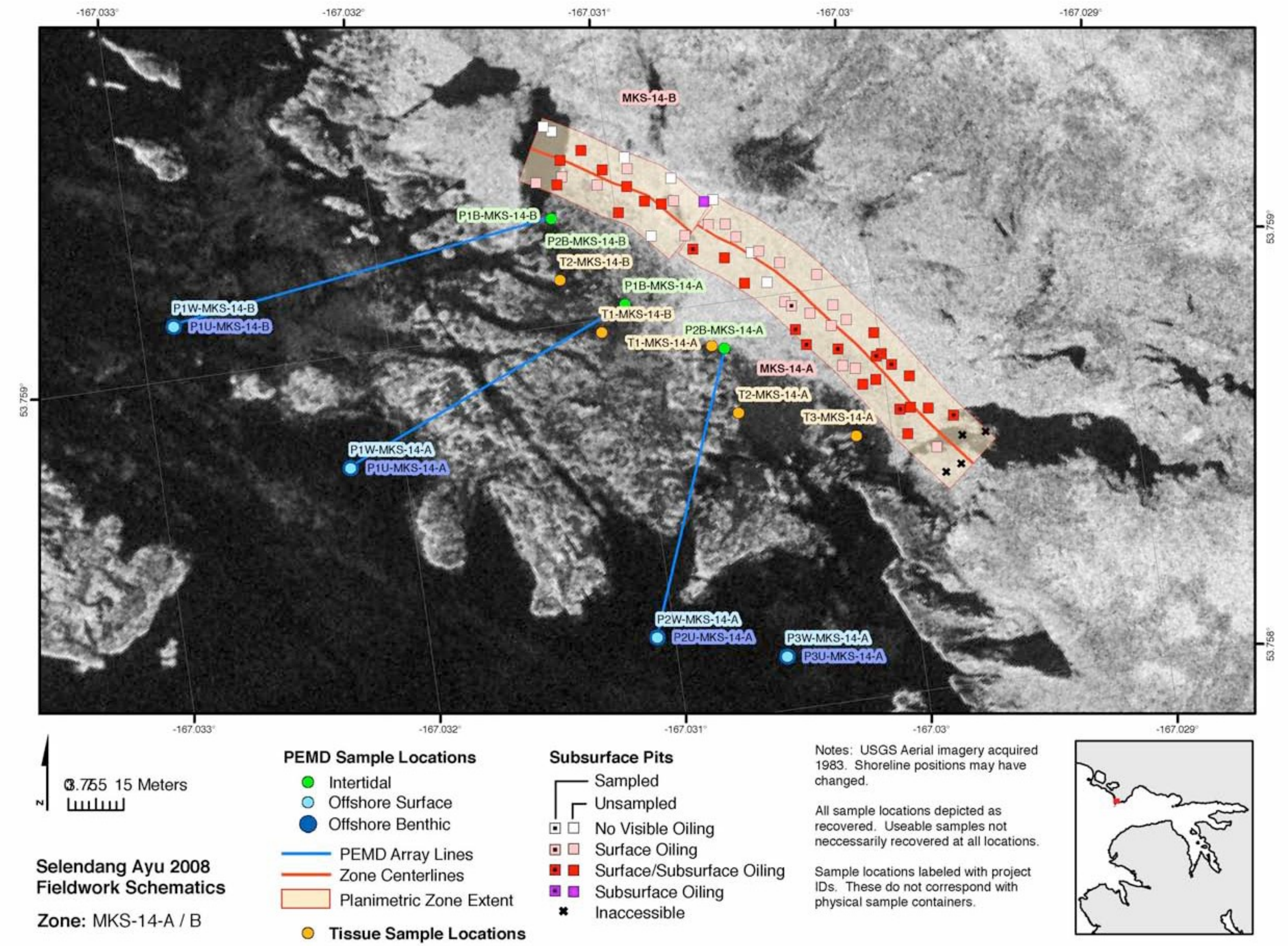

Figure 2.10. Segments MKS-14-A/B showing the location and oiling of pits and the location of PEMD and mussel sampling sites.

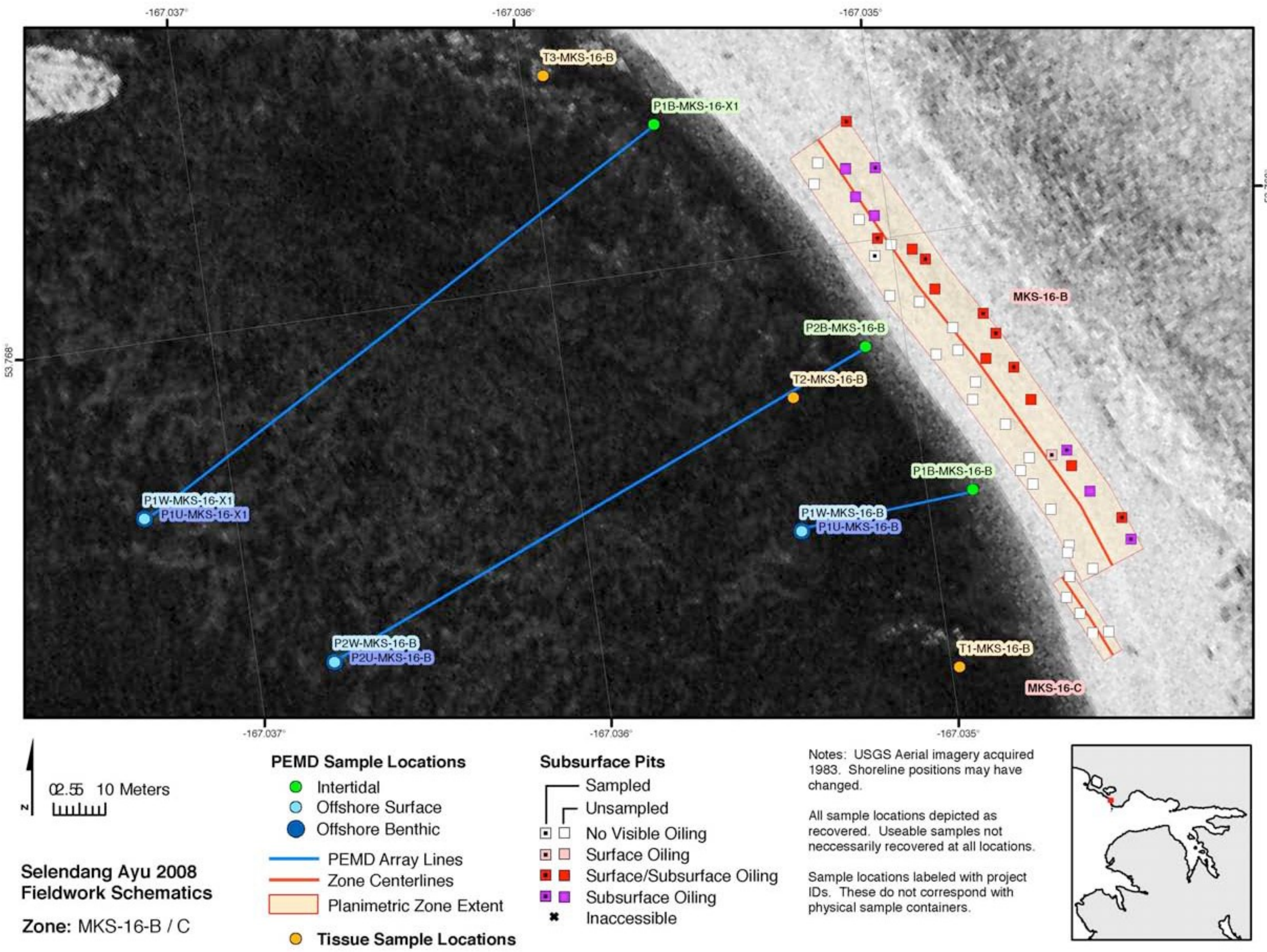

Figure 2.11. Segments MKS-16-B/C showing the location/oiling of pits and the location of PEMD and mussel sampling sites.

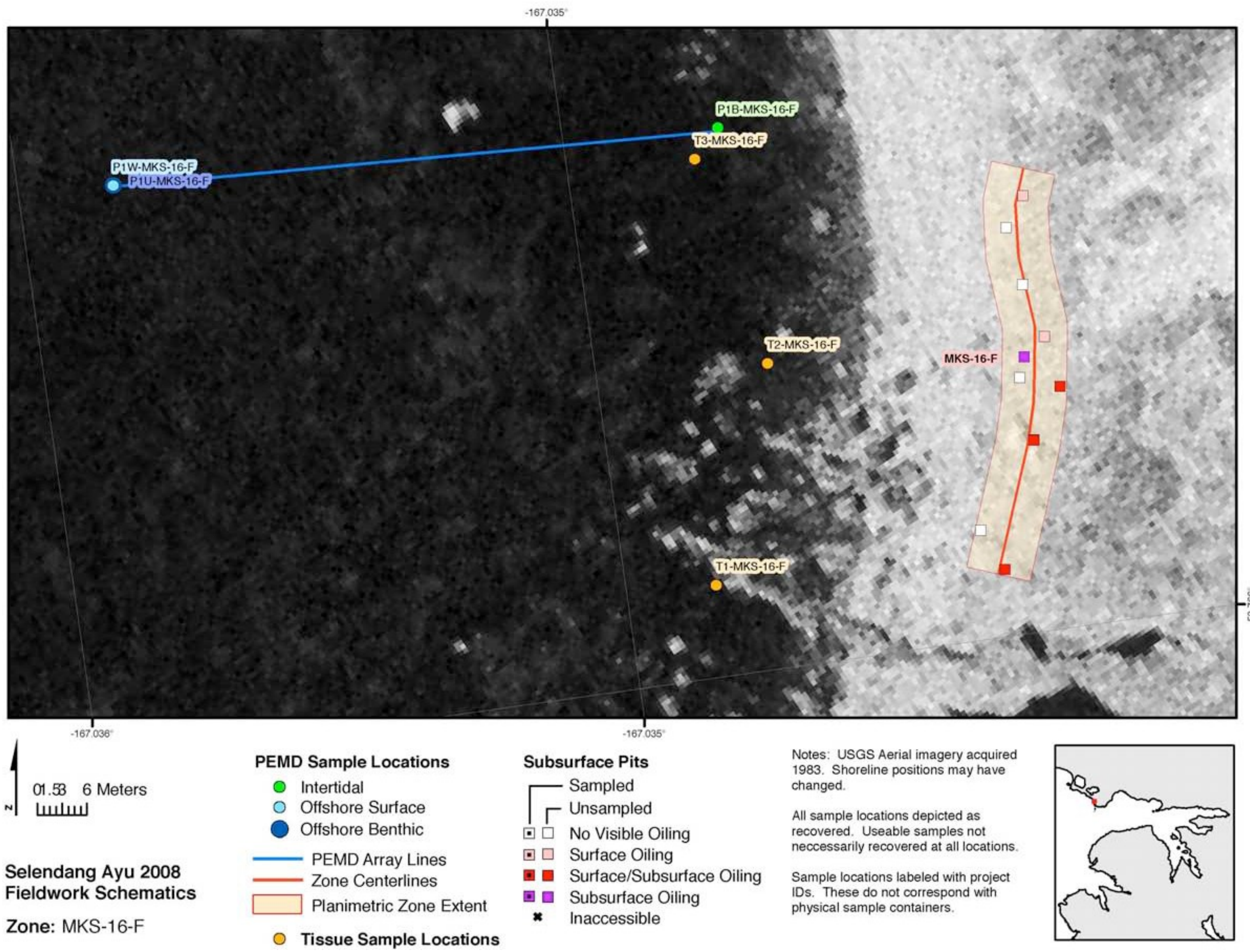

Figure 2.12. Segment MKS-16-F showing the location and oiling of pits and the location of PEMD and mussel sampling sites.

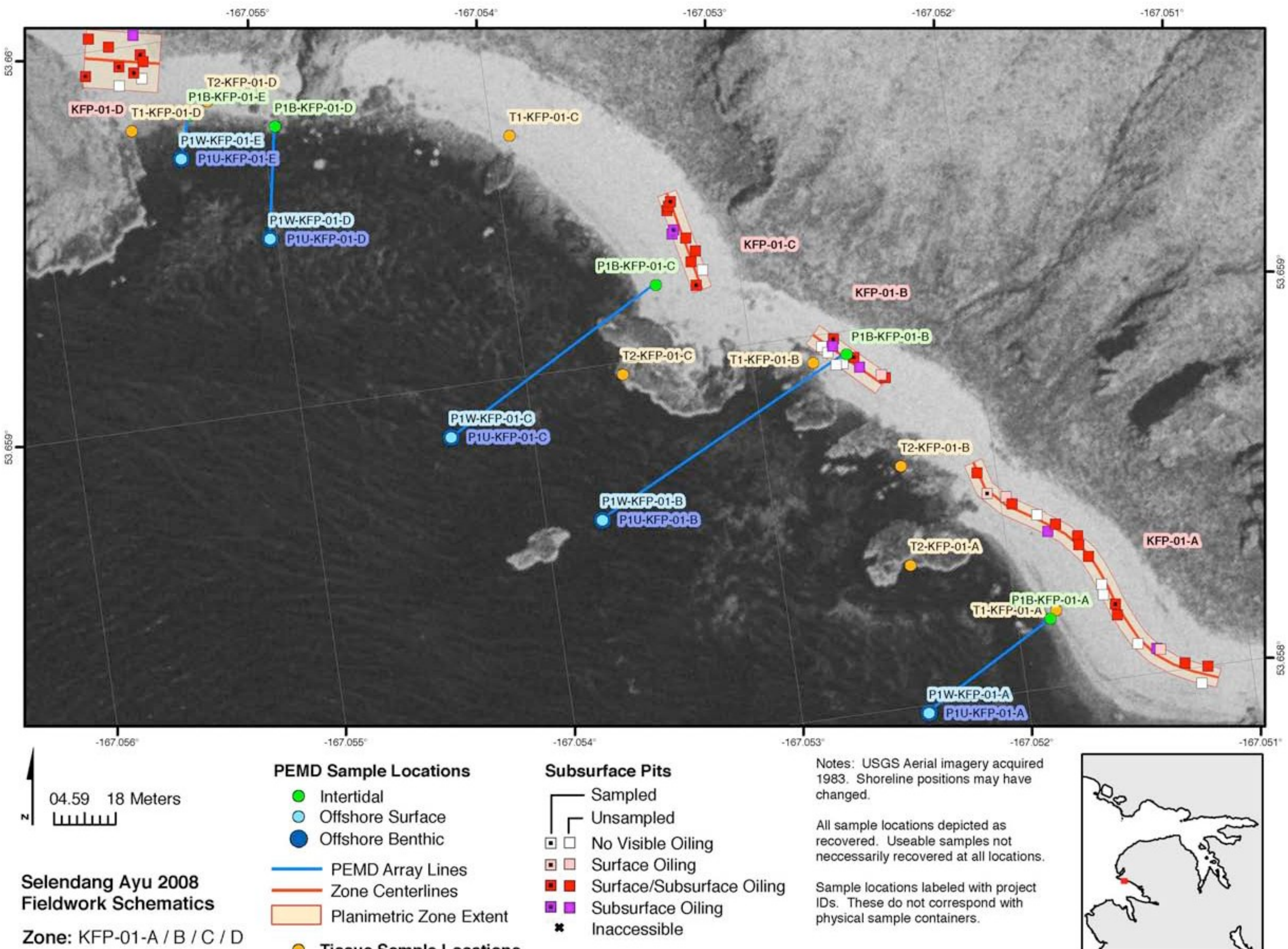

Figure 2.13. Segments KFP-01-A/B/C/D showing the location and oiling of pits and the location of PEMD and mussel sampling sites.

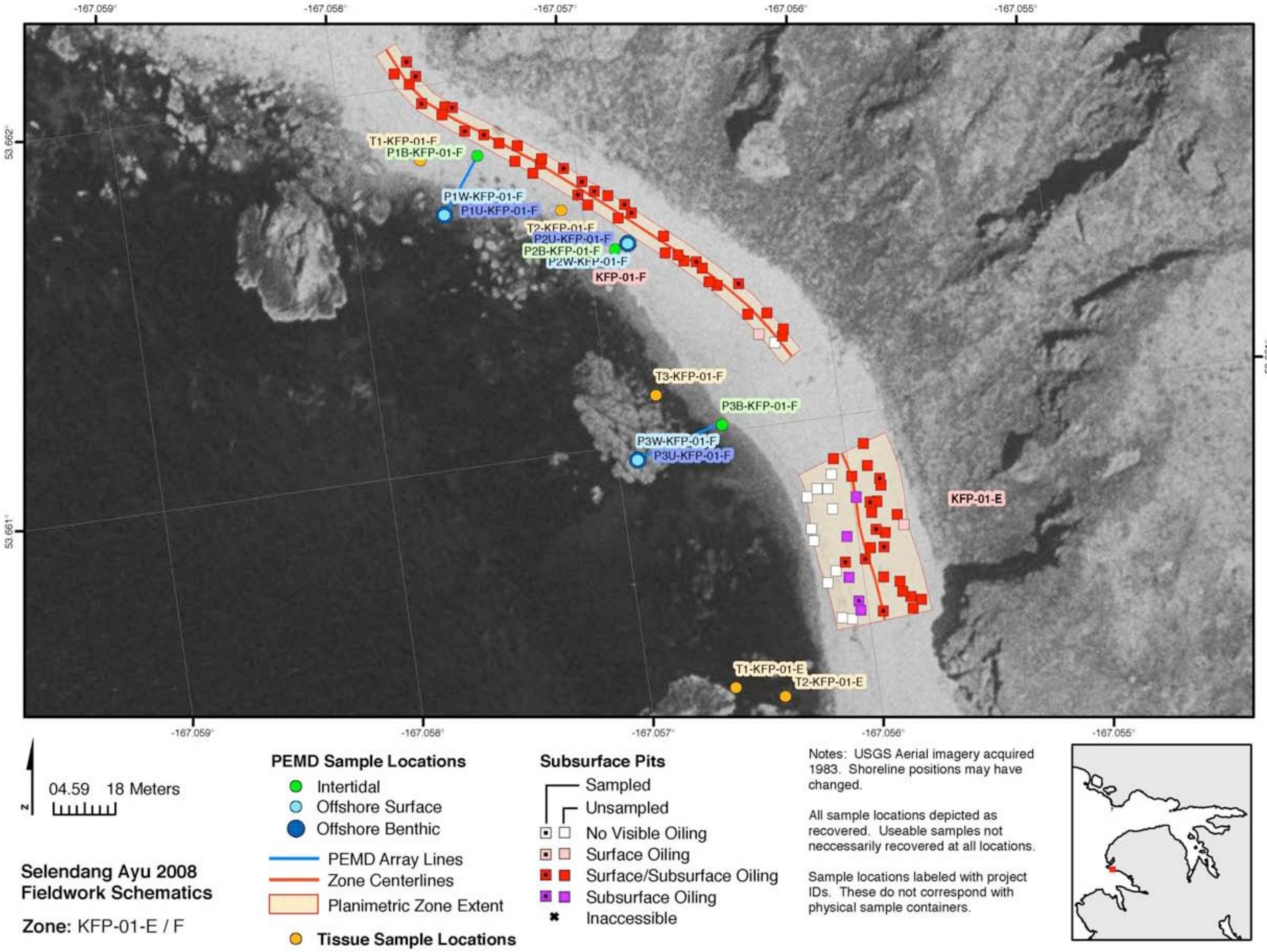

Figure 2.14. Segments KFP-01-E/F showing the location and oiling of pits and the location of PEMD and mussel sampling sites.

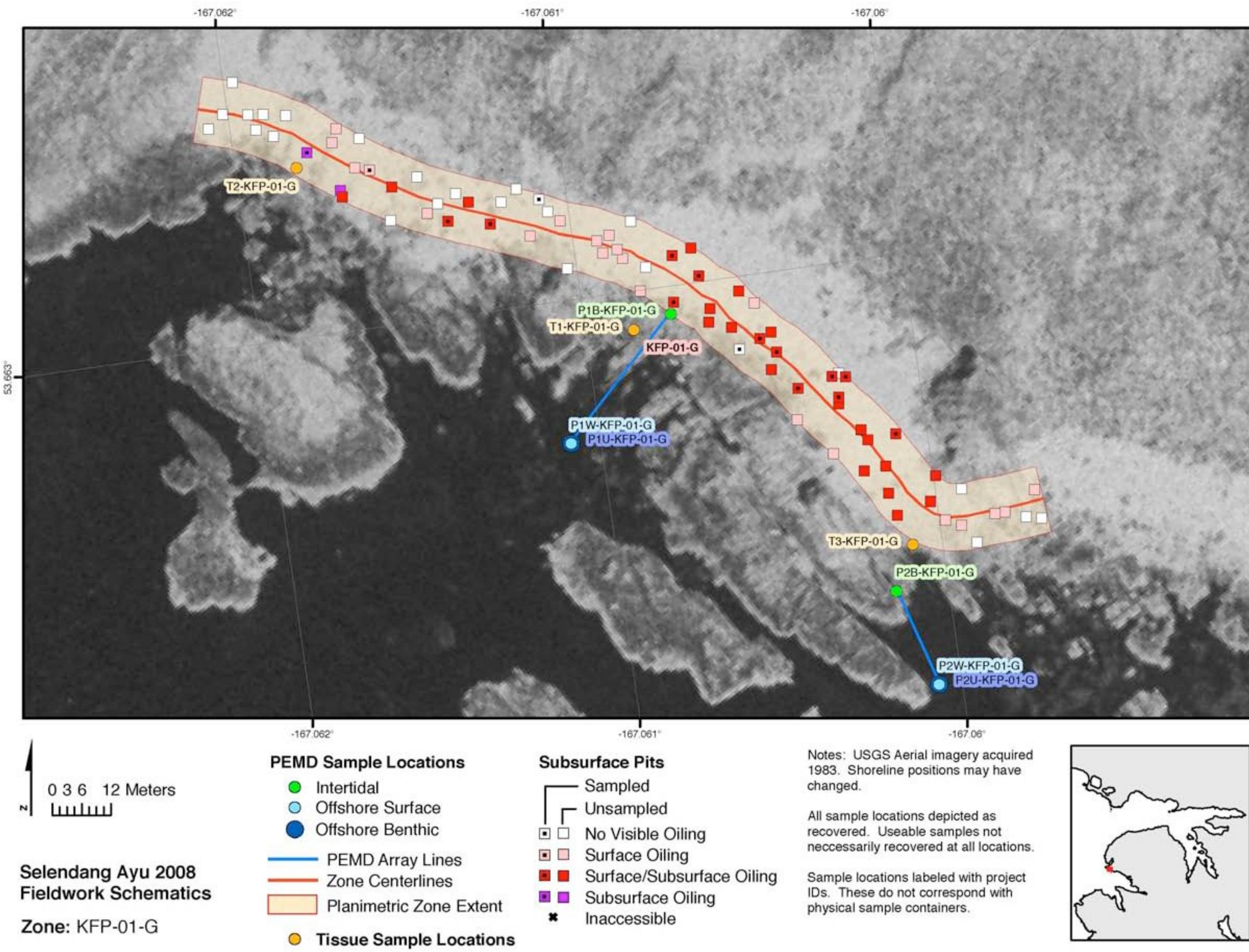

Figure 2.15. Segments KFP-01-G showing the location and oiling of pits and the location of PEMD and mussel sampling sites.

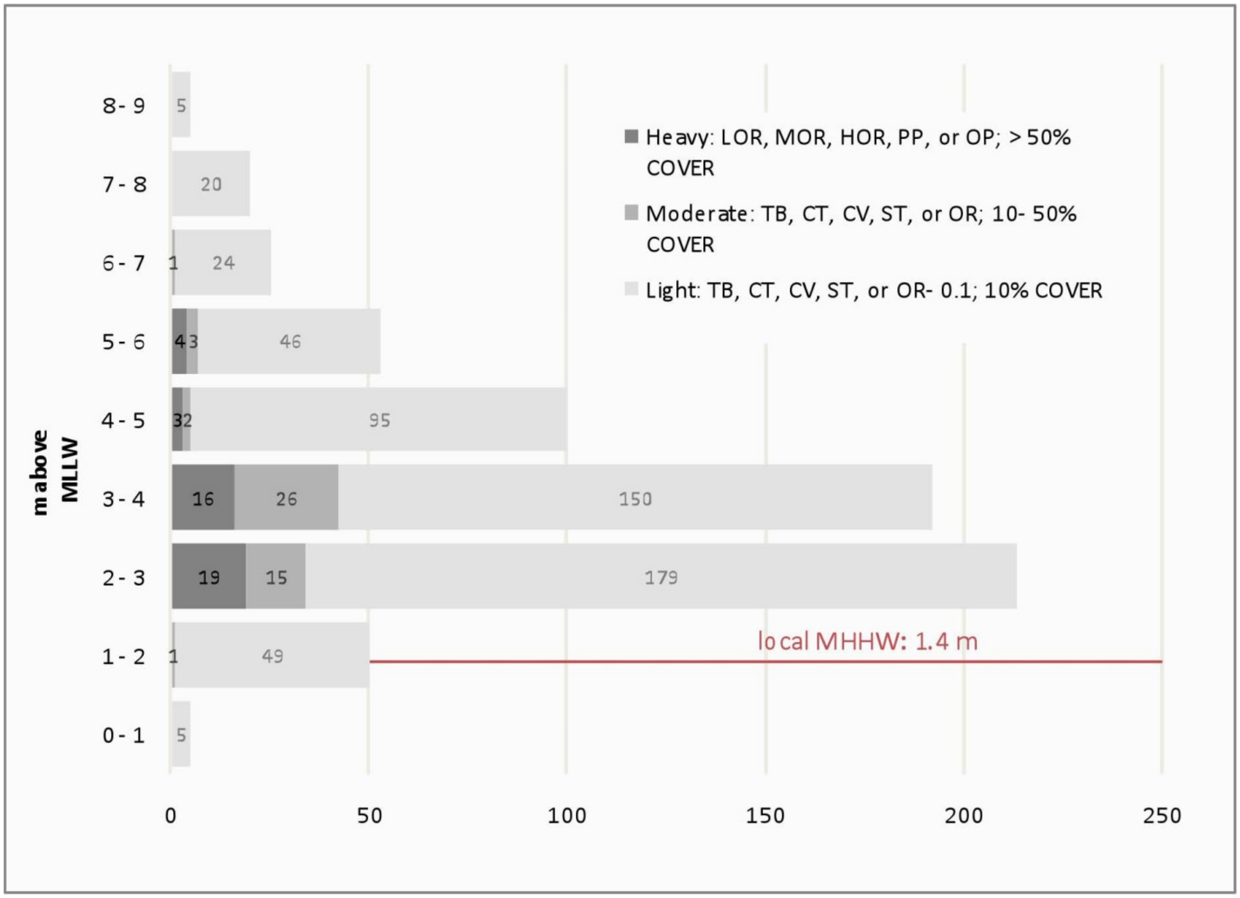

Figure 2.16. Counts of all oiled layers by oiling descriptor for various pit elevations in meters above MLLW.

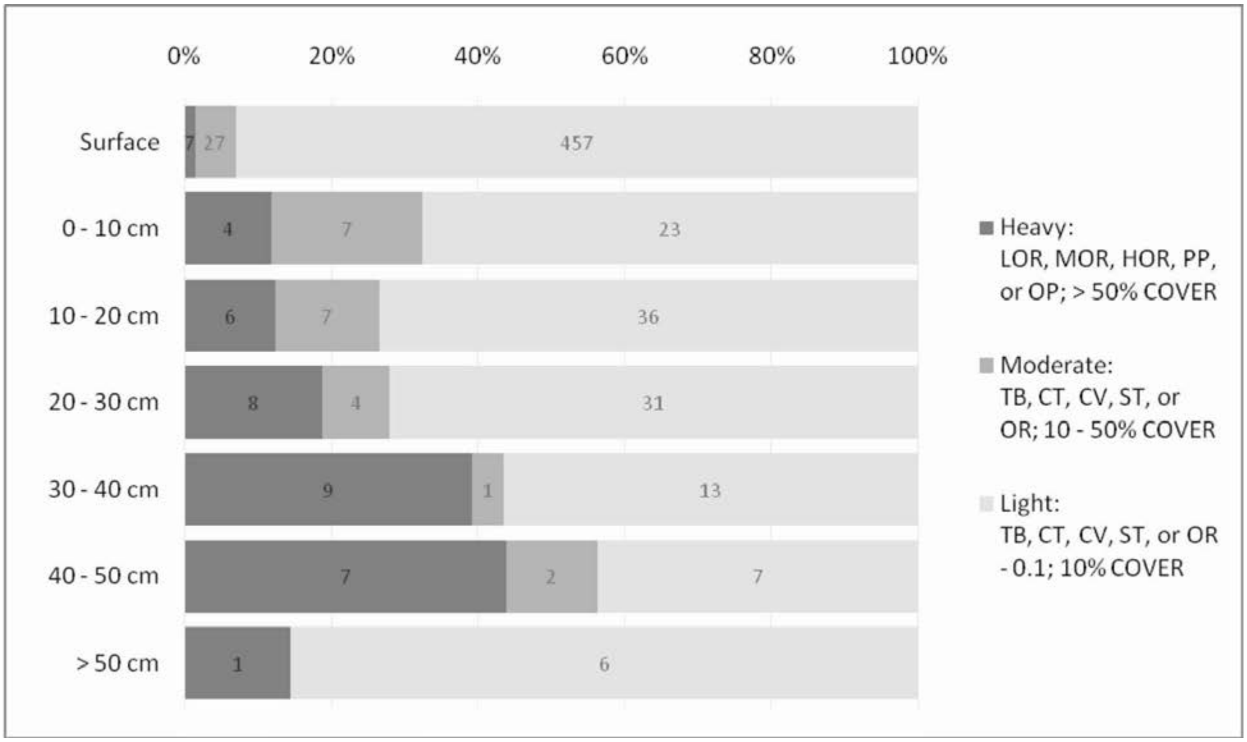

Figure 2.17. Percent composition of subsurface oiled layers by oiling descriptor for various burial depths.

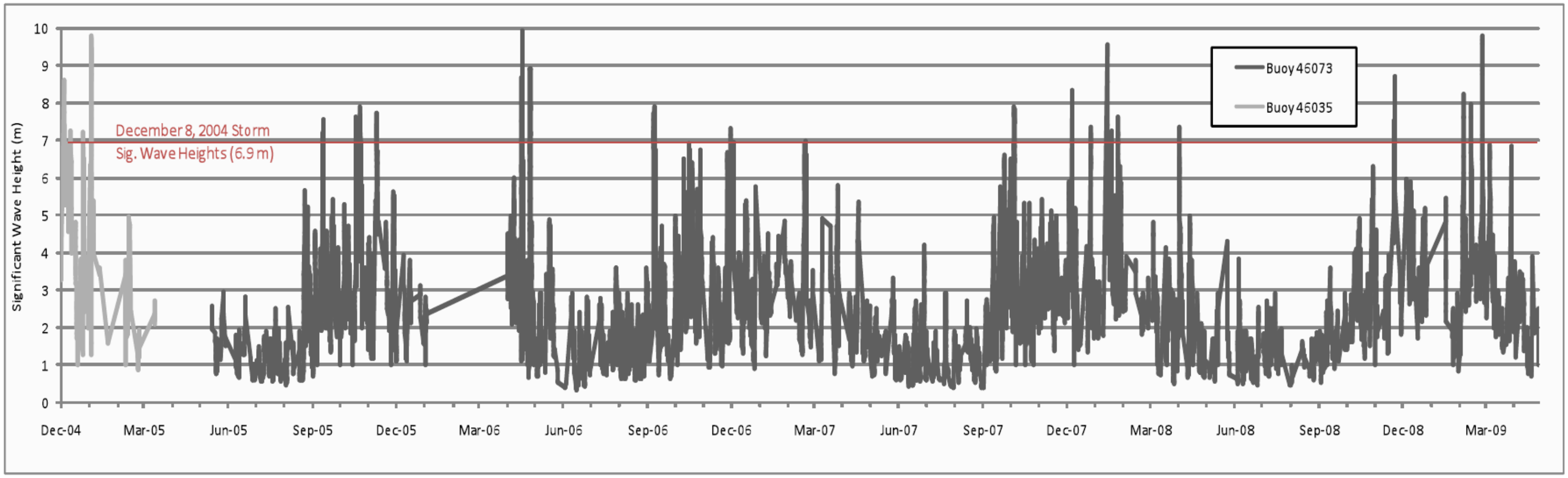

Figure 2.18. Significant storm waves for two NOAA buoys in the Bering Sea, for wind directions from 200 to 340 degrees. Gaps indicate lack of data between data collection periods of different buoys. Straight lines indicate periods where wind direction was not within 200 and 340 degrees.

Final
March 2010