

# Using Satellite Radar Imagery to Detect Leaking Abandoned Oil Wells on the U.S. Outer Continental Shelf

Phase I – TECHNOLOGY DEMONSTRATION

Final Report

U.S. Minerals Management Service  
Solicitation #1435-01-99-RP-31018  
Purchase Order #0100PO17140

Prepared By

Advanced Resources International, Incorporated  
1110 North Glebe Road, Suite 600  
Arlington, Virginia 22201 U.S.A.

January 3, 2001

## DISCLAIMER

The material in this Report is intended for general information only. Any use of this material in relation to any specific application should be based on independent examination and verification of its unrestricted applicability for such use and on a determination of suitability for the application by professionally qualified personnel. No license under any Advanced Resources International, Inc., patents or other proprietary interest is implied by the publication of this Report. Those making use of or relying upon the material assume all risks and liability arising from such use or reliance.

## EXECUTIVE SUMMARY

Advanced Resources International, Incorporated, conducted an evaluation for the U.S. Minerals Management Service of radar satellite imagery for detecting leaking abandoned oil wells on the U.S. continental shelf. The test site for this project was an abandoned well in the Gulf of Mexico that was reported leaking in July 1997, and was re-plugged in January 1998.

Radarsat International agreed to donate two radar images to this project. Advanced Resources searched the image data archives and identified 25 images that covered the site prior to re-plugging. For each date of acquisition, surface wind speed histories were reconstructed using historical weather records from buoys and coastal weather stations. Because radar images of the sea surface are strongly affected by surface wind patterns, the wind speed histories were used to rate the suitability of each image for oil slick detection. Only 11 images survived the rating process; of these, two images acquired in August 1997 were selected.

The images were processed to emphasize the appearance of slicks and provide accurate location information, and were incorporated for analysis into a GIS database that included the locations of pipelines, platforms and shipping lanes in the Gulf.

Numerous small oil slicks caused by natural seeps on the seafloor were visible throughout both images. However, no oil slicks were apparent at the E-1 well site on either image, despite indications that conditions were generally favorable for slick detection. The appearance of a small oil slick emanating from a production platform in another area strongly supports the concept of using radar imagery to operationally detect small leaks, but another demonstration over a better-documented test site may be required to correctly assess this technology.

# TABLE OF CONTENTS

<b><u>DISCLAIMER</u></b> .....	<b>i</b>
<b><u>EXECUTIVE SUMMARY</u></b> .....	<b>ii</b>
<b><u>TABLE OF CONTENTS</u></b> .....	<b>iii</b>
<b><u>INTRODUCTION</u></b> .....	<b>1</b>
<b><u>METHODOLOGY</u></b> .....	<b>2</b>
<u>General Approach</u> .....	2
<u>Task 1: Construct GIS</u> .....	3
<u>Task 2: Define Demonstration Site and Time Period</u> .....	3
<u>Task 3: Data Evaluation and Acquisition</u> .....	3
<u>Archive Evaluation</u> .....	5
<u>Image Selection</u> .....	8
<u>Task 4: Data Processing and Analysis</u> .....	8
<b><u>RESULTS</u></b> .....	<b>12</b>
<u>General Features</u> .....	12
<u>E-1 Well Site</u> .....	16
<b><u>CONCLUSIONS AND RECOMMENDATIONS</u></b> .....	<b>21</b>

## INTRODUCTION

Satellite radar imagery is routinely used as an exploration tool by energy companies for detecting small, persistent oil slicks on the sea surface. These slicks indicate the presence of natural oil and gas seeps on the underlying seabed, and are thus a useful guide for energy exploration on the continental shelf. This technique was developed and publicized during the early 1990s under concurrent projects operated by NASA's EOCAP program and The Geosat Committee's GOSAP program. Both projects focused on detecting surface oil slicks caused by natural seeps in the Gulf of Mexico.

Measurements of seepage flux, combined with numerical modeling of oil slick formation and attenuation, suggested that some of the natural slicks appearing on radar imagery of the Gulf were created by flux rates as low as two gallons per hour. It is reasonable to assume that small leaks of crude oil from other fixed-point sources on the seafloor would create slicks at the sea surface that could be detected using the same radar imaging technique.

The U.S. Minerals Management Service is concerned that some abandoned oil wells in the Gulf may be leaking crude oil. Advanced Resources proposed a two-phase project to use satellite radar imagery for detecting oil slicks caused by leaking abandoned wells. Phase 1, Technology Demonstration, would acquire historical radar imagery over the site of a formerly leaking well to demonstrate the feasibility of the technique. Phase 2, Leak Detection, would apply the technique to the Central and Western Planning Areas of the Gulf using new imagery to detect actively leaking wells across the continental shelf.

This report describes the efforts and results of the Phase 1 technology demonstration.

## METHODOLOGY

### General Approach

A variety of phenomena can create the signature of small slicks on radar imagery of the sea surface, including shoals or shallows, biological surfactants (fish oils, coral spawn), algal blooms, cold-water upwelling, mats of floating vegetation, and human-caused spills from oil platforms, leaking pipelines, or passing vessels. Many of these phenomena can be eliminated from consideration based on the appearance of the slick (size and shape), its location relative to surrounding features, and its orientation relative to prevailing wind and current conditions. Therefore, an important aid to correctly interpreting the significance of slicks is an accurate Geographic Information Systems (GIS) database that includes the locations of pipelines and platforms, major shipping lanes, and bathymetry. The GIS provides a framework for analysis.

A large archive of historical satellite radar imagery exists for the Gulf, stretching back to 1991. However, not all of these images are useful for showing oil slicks. The suitability of radar imagery for slick detection is largely a function of the local weather and sea-state conditions at the time of image acquisition. Detection hinges on a significant difference in sea-surface texture between the area covered by oil and the surrounding, “clean” water. This occurs when a uniform wind of sufficient strength blows across the surface, raising small capillary wavelets in the absence of oil. If the wind blows too strongly, however, it overwhelms the surface-tension effects of a thin film of oil, and the oiled area becomes as rough as the surrounding seas. Precipitation can also break apart or obscure thin oil slicks. The wind history for 24 hours prior to acquisition is also important: if the wind blows too hard for a sustained period, it will break apart a thin oil slick. At a minimum, several hours of fair conditions are subsequently required for a new slick of detectable size to accumulate. Data buoys operated by the National Data Buoy Center (NDBC) provide detailed, historical observations of surface wind conditions throughout the Gulf, so the weather suitability of archived imagery may be assessed.

The tasks described below were conducted during Phase 1 to address these issues.

### **Task 1: Construct GIS**

A GIS database for the Gulf was compiled using data from several sources. Vector shoreline data were obtained from the Digital Chart of the World (DCW) database. Bathymetric contours were digitized from NOAA nautical charts. Vector pipeline routes, platform locations, protraction area boundaries, and major shipping fairways were obtained from the Minerals Management Service. These datasets were compiled using ArcView GIS software, and were placed into a geographic projection using the Clarke 1866 ellipsoid. Figure 1 displays the GIS information used for this study.

### **Task 2: Define Demonstration Site and Time Period**

A test site for this demonstration was provided by the Minerals Management Service. An abandoned well (designated “E-1”) was reported to be leaking in July 1997. The well had been originally plugged and abandoned in July 1992. In January 1998, E-1 was re-entered and re-plugged. The well is located along the western edge of Block 75 in the South Timbalier protraction area, approximately 30 km due south of Isles Dernieres, Louisiana (Figure 1). The exact coordinates provided by MMS for this location are 28.76749804 degrees North latitude, 90.74314728 degrees West longitude. The water depth in this area is fairly shallow, probably less than 100 meters.

Several major pipelines are nearby, and a fixed production platform was installed directly over the site sometime after the leak was reported (a platform or large drillship is clearly visible at the location on December 28, 1997). No other information regarding this test site was provided.

### **Task 3: Data Evaluation and Acquisition**

Radarsat International (RSI) agreed to provide two satellite radar images for this project. We conducted a search of RSI’s data archive to compile a list of all images acquired over the test site prior to January 1998, when the well was re-plugged. The RADARSAT-1 satellite became operational early in 1996.

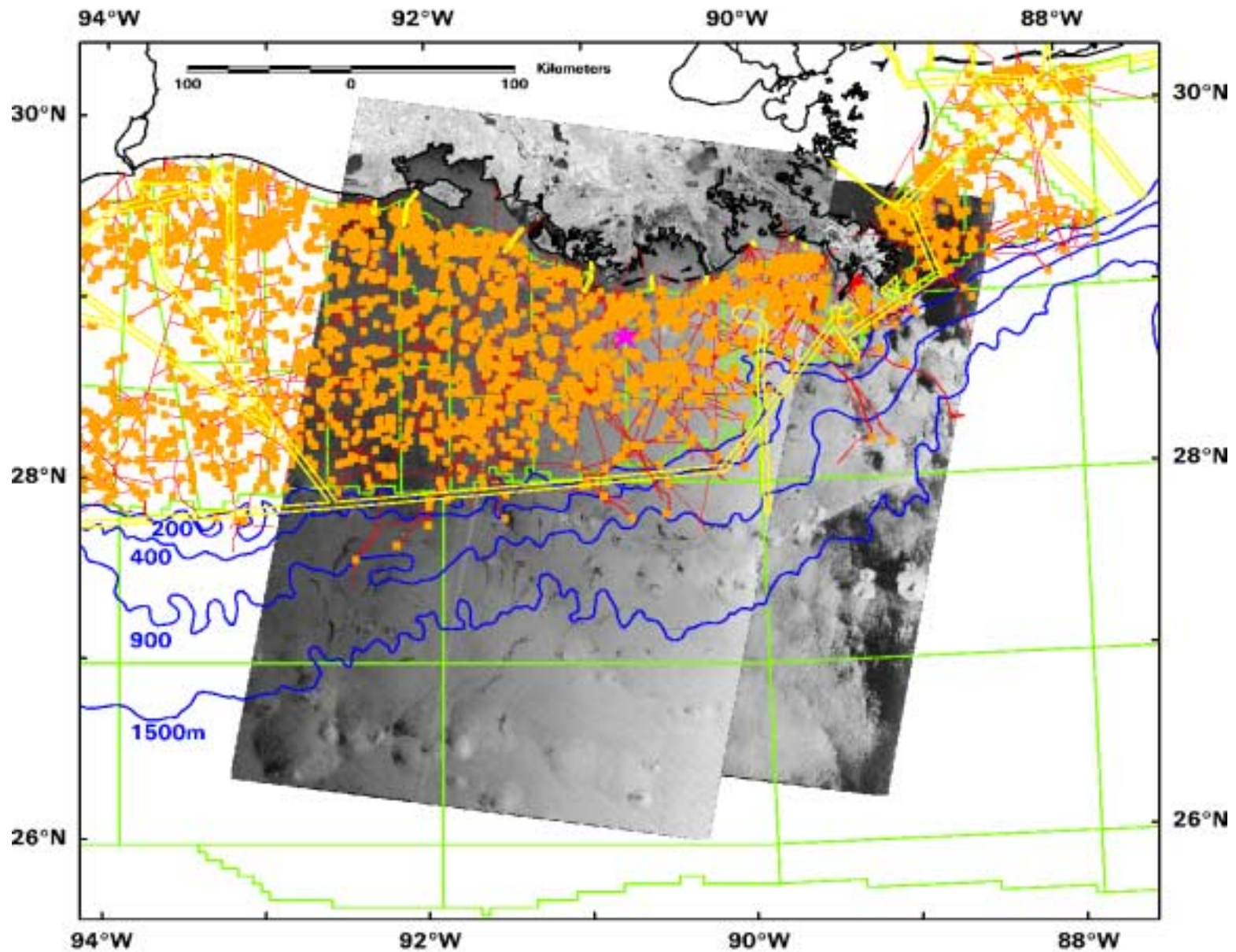


Figure 1. Gulf GIS and two RADARSAT images assembled for this project. Protraction area boundaries in green; bathymetric contours in blue; major shipping fairways in yellow; pipelines in red. Platforms shown as orange squares. Well site E-1 marked by star.



Twenty-five images were found in the data archive, ranging in date from May 28, 1996 to December 28, 1997 (Table 1). To evaluate their suitability for slick detection, we compiled historical weather observations from NODC stations. Two manned coastal stations (C-MAN stations GDIL1 and BURL1) and three remote data buoys (42040, 42001 and 42002) were operational in the Gulf during that period. The buoy stations and their identification codes are presented in Figure 2.

### ***Archive Evaluation***

NODC data stations record wind speed, wind direction, barometric pressure, temperature, dewpoint, wave height and frequency, and a variety of other physical observations. These observations are collected as ten-minute averages. For each image, we compiled the data from the five nearest stations spanning the 24-hour period prior to the time of the satellite's overpass. Images were rejected from consideration if they met any of these criteria:

- Wind speed at the time of image acquisition was less than 2 or greater than 8 meters per second (out of bounds for imaging thin oil slicks).
- At any time during the prior 24 hours, the wind speed exceeded 10 meters per second (likely to have dissipated a thin oil slick).
- The average wind speed during the prior 24 hours exceeded 5 meters per second (likely to have prevented formation of a thin oil slick).

Thirteen of the images were rejected; an additional image was eliminated from consideration because the well site was too close to the edge of the image. The remaining 11 images (Table 2) were qualitatively ranked based on their favorability for slick detection. Ideal conditions were considered to be a wind speed at acquisition time of 3-4 meters per second, with a maximum wind speed well below 10 meters per second and average speed well below 5 meters per second during the prior 24 hours.

Precipitation data were not available from the NODC buoys.

**TABLE 1. List of available RADARSAT-1 images covering well site E-1 prior to January 1998.**

<b>Acquisition Date</b>	<b>Imaging Mode</b>
5/28/96	Standard-6
8/07/96	ScanSAR Narrow-A
8/18/96	Standard-3
8/25/96	Standard-5
9/04/96	ScanSAR Narrow-A
9/11/96	Wide-2
11/15/96	Wide-1
12/09/96	Wide-1
5/16/97	ScanSAR Narrow-A
6/02/97	ScanSAR Narrow-A
6/09/97	ScanSAR Narrow-A
7/03/97	ScanSAR Narrow-A
7/22/97	ScanSAR Narrow-A
8/06/97	ScanSAR Narrow-A
8/13/97	ScanSAR Narrow-A
11/06/97	Standard-3
11/10/97	Wide-1
11/17/97	Standard-3
11/19/97	ScanSAR Narrow-A
11/30/97	ScanSAR Narrow-A
12/04/97	ScanSAR Narrow-A
12/11/97	Standard-3
12/13/97	ScanSAR Narrow-A
12/24/97	Standard-3
12/28/97	ScanSAR Narrow-A

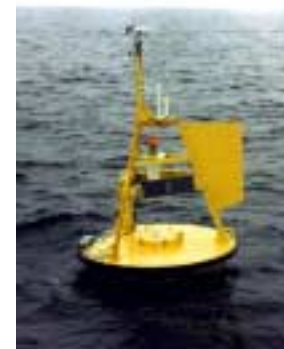
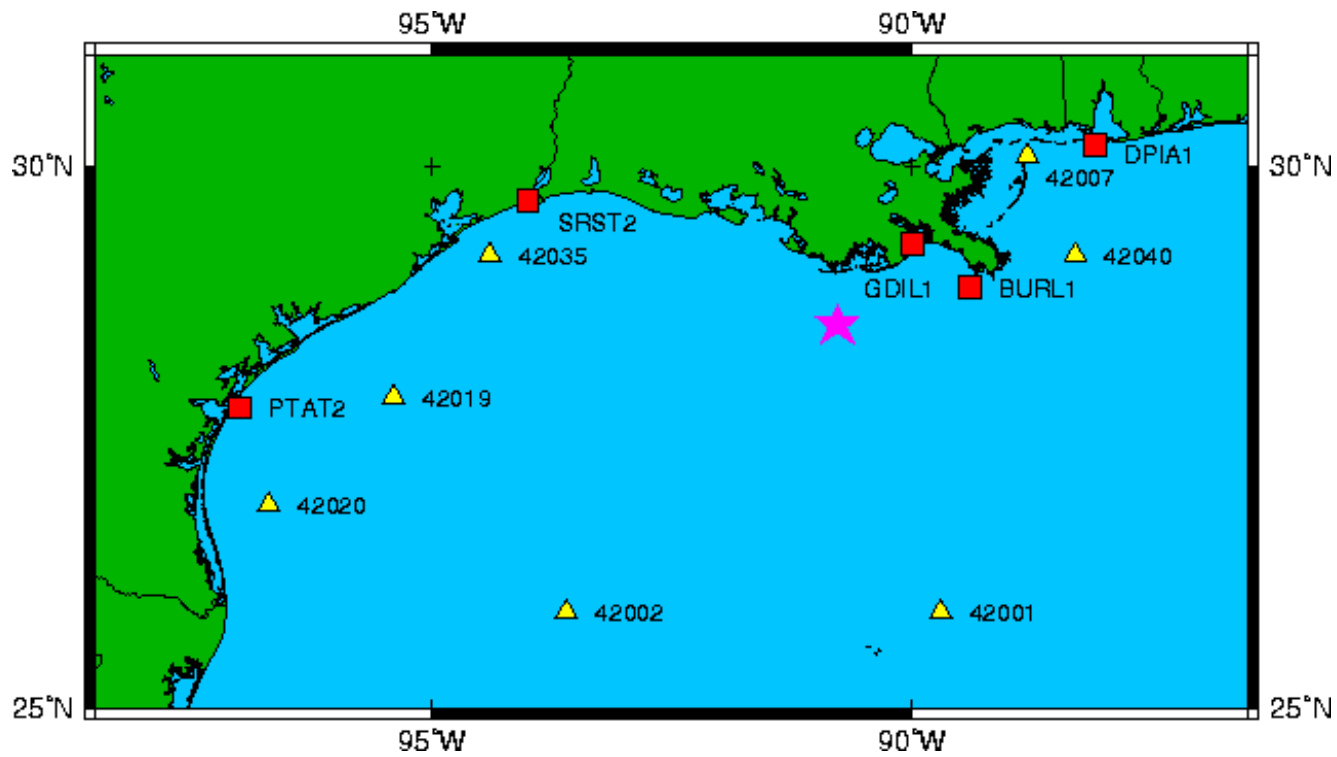


Figure 2. Top: locations of NODC weather stations in western Gulf of Mexico. Abandoned well E-1 marked by star. Bottom, left to right: BURL1 C-MAN station; 10-meter discus buoy at stations 42001 and 42002; 3-meter discus buoy at station 42040.

**TABLE 2. RADARSAT-1 images meeting minimal weather criteria.**

<b>Acquisition Date</b>	<b>Imaging Mode</b>	<b>24hr avg</b>	<b>24hr max</b>	<b>@ Acquisition</b>
8/18/96	Standard-3	3.1	5.7	3.4
8/25/96	Standard-5	3.4	7.0	2.6
9/04/96	ScanSAR Narrow-A	3.1	7.4	4.0
9/11/96	Wide-2	2.7	6.5	2.2
5/16/97	ScanSAR Narrow-A	3.9	8.1	3.1
6/02/97	ScanSAR Narrow-A	4.8	8.4	2.9
7/03/97	ScanSAR Narrow-A	5.0	6.9	5.5
8/06/97	ScanSAR Narrow-A	3.6	8.4	3.9
8/13/97	ScanSAR Narrow-A	3.5	7.2	2.2
11/06/97	Standard-3	4.9	9.3	8.5
11/10/97	Wide-1	3.2	5.7	4.6

### *Image Selection*

Based on the evaluation process described above, several images were considered highly favorable for slick detection over the study area. Only four were acquired after the leak was reported. Two of those were acquired in November 1997, typically a time of gusty and unstable wind conditions. The other two were acquired very soon after the well was reported to be leaking, on August 6 and August 13, 1997. These images were chosen for Phase 1, and were provided by RSI. Both are ScanSAR-Narrow “A” mode images (SCN-A), acquired during the satellite’s descending (southward) orbit, looking off-vertical toward the west. The RADARSAT-1 system operates in a variety of beam modes, trading spatial detail for broader coverage. The ScanSAR mode covers about a 300 km x 300 km area at a spatial resolution of approximately 50 meters, and has been demonstrated as one of the most cost-effective modes for natural oil slick detection.

### **Task 4: Data Processing and Analysis**

The image data, provided on CD-ROM, were loaded onto a Windows NT v.4.0 workstation using Erdas Imagine v.8.3.1 image processing software. Corner point locations, derived from definitive (post-pass) satellite orbital ephemeris, were provided with the images. These

control points were applied to derive a simple one-dimensional polynomial equation, using least-squares regression, that was used to digitally transform the image data to fit a standard map projection (Universal Transverse Mercator projection, North American Datum of 1927, Clarke 1866 ellipsoid, UTM Zone 15 North).

Image brightness and contrast were manipulated using the contrast tools in Imagine to optimize the discrimination of slicks. Land areas appear very bright in the resulting images, as do vessels and production platforms. In the Gulf, slicks appear dark gray to black, while surrounding waters are generally light gray.

Because fixed platforms have such a strong radar signature, we were able to assess the positioning accuracy of the map-projected images by directly overlaying the GIS platform locations obtained from MMS and graphically measuring the differences. A random check of 47 platforms yielded an average error of 196 meters for both of the images.

The processed images were incorporated into the Gulf GIS, and visually interpreted on-screen by an experienced oil slick analyst. Analytical efforts were focused on overall assessments of image quality and suitability for slick detection, identification of possible oil slicks in the immediate vicinity of well E-1, and comparison of slick patterns between the two dates of imagery.

The images were annotated with conventional map information and printed on semi-gloss paper using a large-format Hewlett-Packard HP2500CP DesignJet printer (Figures 3 and 4). The full-size 1:500,000 scale image maps accompany this report as rolled separates.

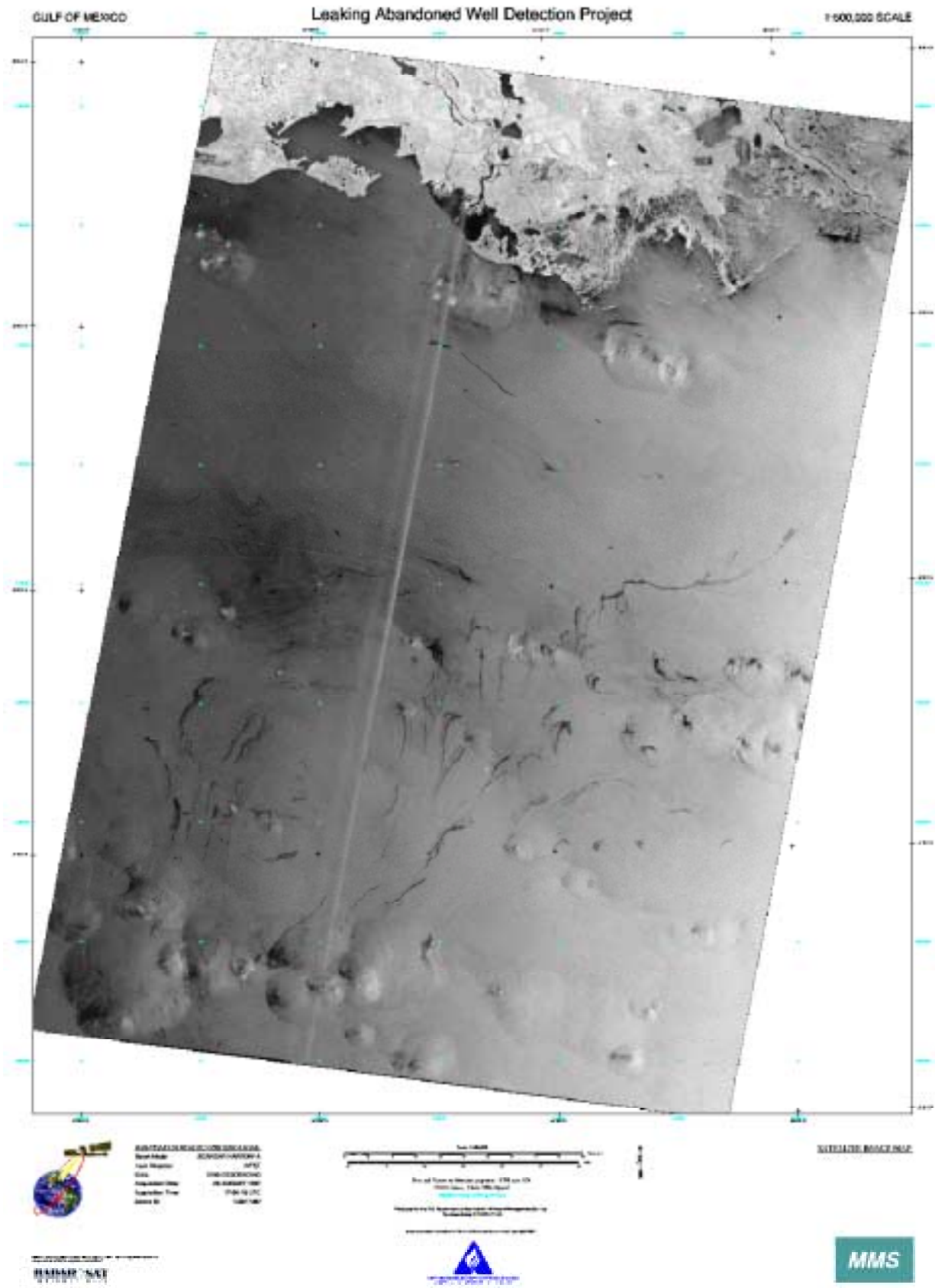


Figure 3. August 6, 1997 RADARSAT image map of study area.

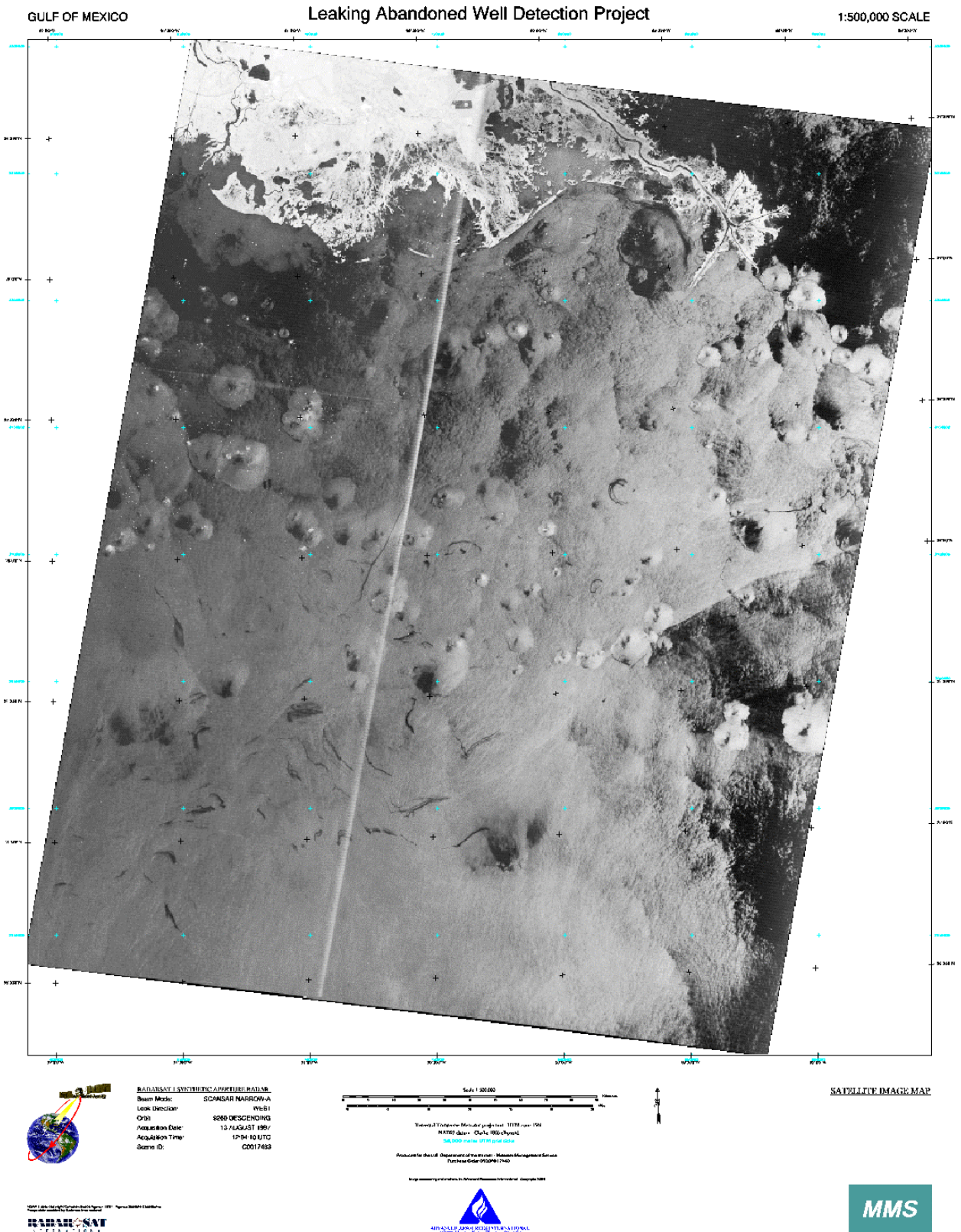
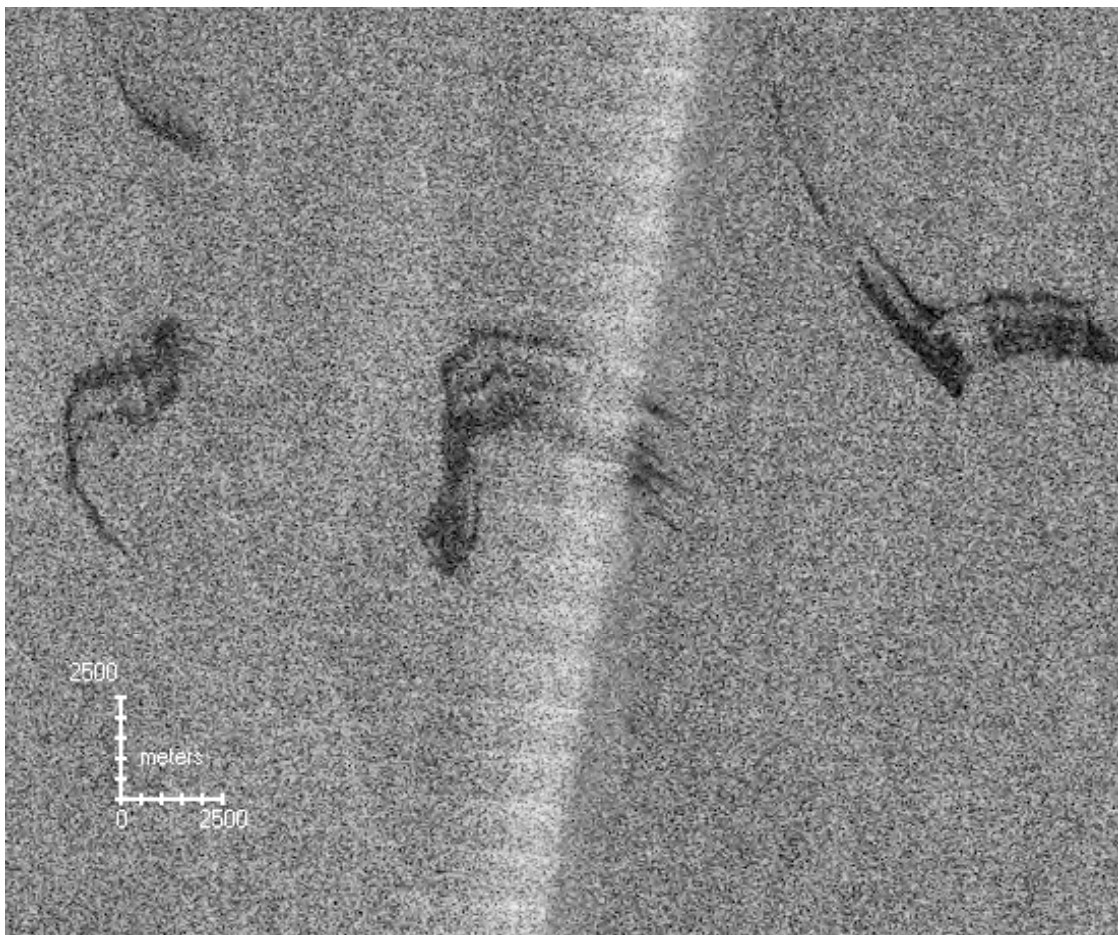


Figure 4. August 13, 1997 RADARSAT image map of study area.

## RESULTS

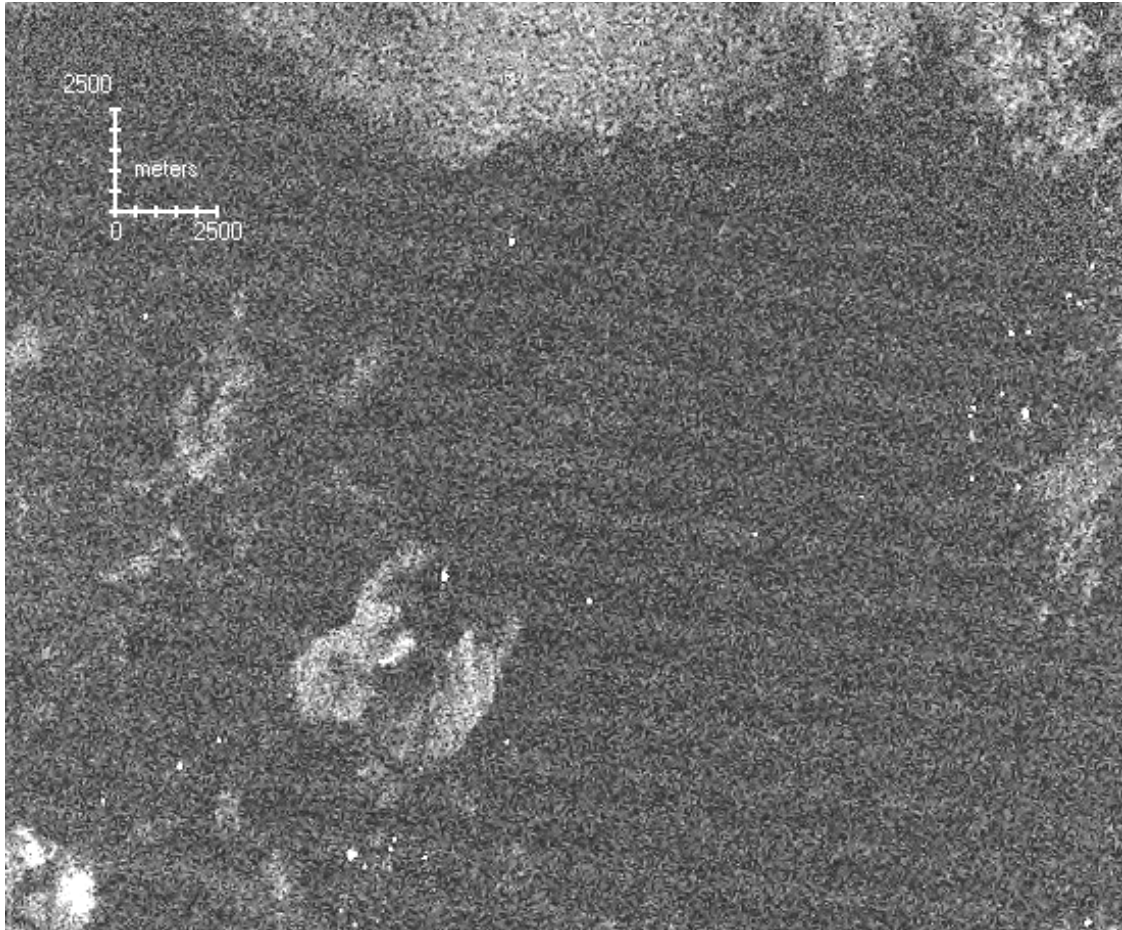
### General Features

Both images suffer from minor quality problems inherent to older ScanSAR imagery: slight calibration variations within the imaged area; faint east-west banding, called “scalloping”; and a bright line running north and south across the image, the “nadir anomaly,” caused by an errant radar echo bouncing up off the sea surface from directly beneath the satellite (Figures 5 and 6). In general, these artifacts pose little more than cosmetic problems.



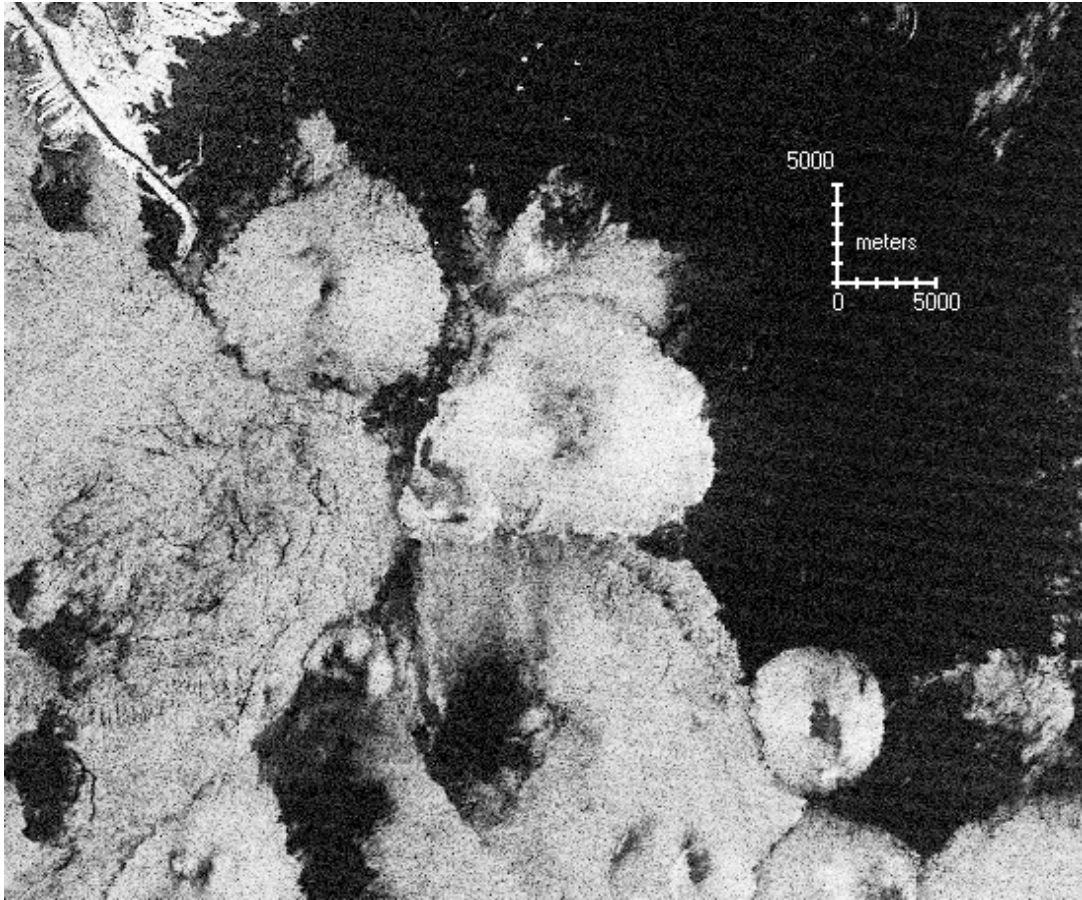
**Figure 5. Nadir anomaly (broad bright line parallel to satellite’s orbital path). Detail from southern portion of August 13 image. Dark patches are characteristic of wind-driven oil slicks caused by natural seafloor seeps.**





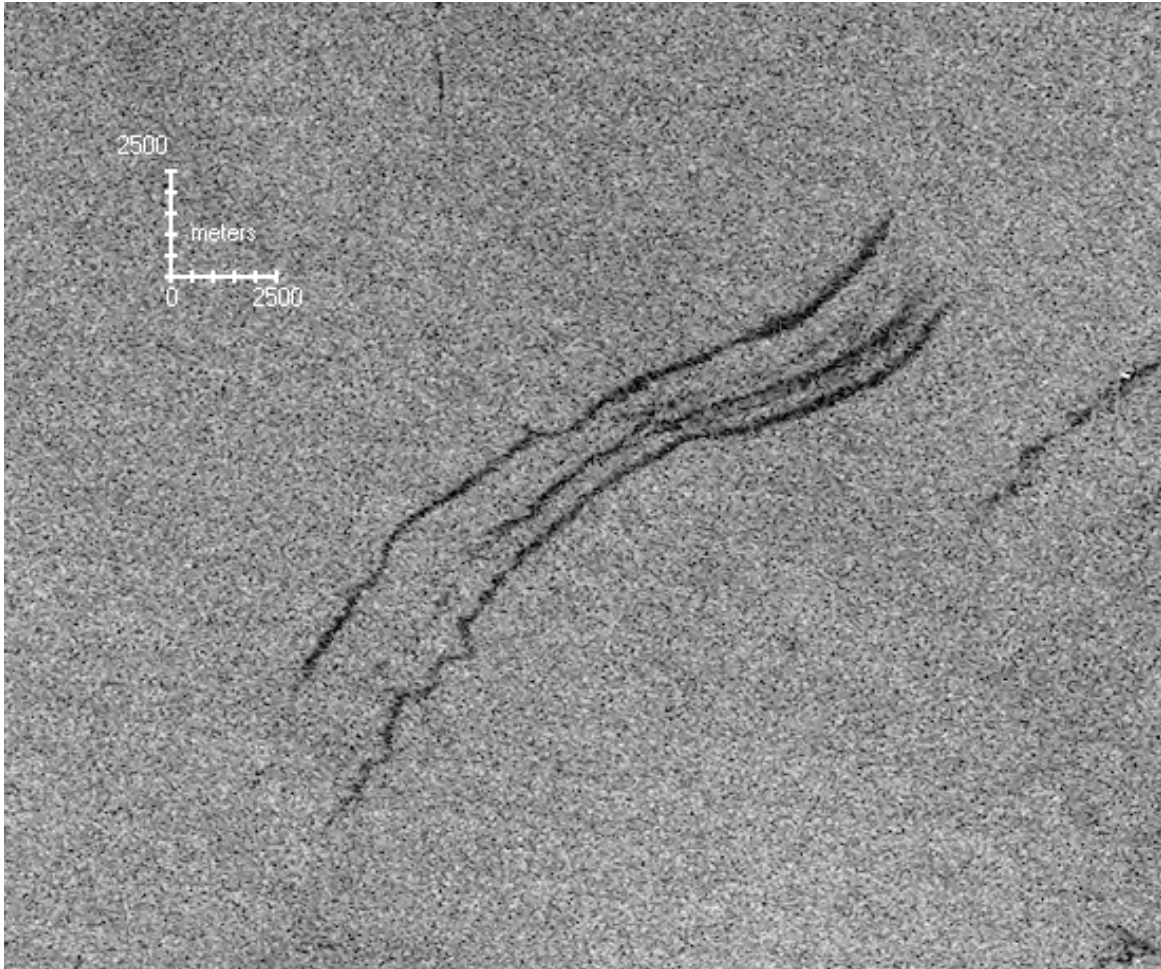
**Figure 6. Scalloping (faint banding perpendicular to satellite's orbital path). Detail from dark, low-wind region in northwestern portion of August 13 image. Production platforms are visible as discrete bright spots scattered throughout the image.**

A more serious problem is the effect of scattered thunderstorms and extensive dark, low-wind areas across the northern and western parts of the August 13 image (Figure 7). This weather pattern is not uncommon in the Gulf during the summer months, as intense solar warming of the sea surface generates convection cells in the lower atmosphere that rapidly strengthen during the late morning hours. Isolated patches of heavy rainfall are marked by dark circular patterns on the sea surface, effectively obscuring the signature of any oil slicks in the vicinity. Gusty, non-uniform wind fields around the areas of convection create surface texture anomalies that can hinder slick identification.



**Figure 7. Extremely variable sea-surface wind conditions. Black area to upper right is a broad region of very low wind speed (less than 1 meter per second). Circular bright patches near center indicate radial gusty winds beneath individual convection cells (probably isolated thunderstorms). Mottled are to lower left is a zone of moderate wind strength (light gray) with patches of heavy rain (black). Detail from northeastern portion of August 13 image; South Pass is visible as a thin dark channel in upper left corner.**

Despite these localized problems, both images were acquired under generally acceptable conditions for slick detection. Along the shelf break (200-1500 meter depth), numerous elongated slicks appear (Figure 5; Figure 8). These are characteristic of natural oil slicks caused by seafloor oil and gas seeps. In this area, well beyond the present oil and gas infrastructure and major shipping lanes, these slicks may be considered diagnostic of natural seeps. The clear discrimination of these slicks on both images provides strong evidence that imaging conditions were well within bounds for reliable oil slick detection.



**Figure 8. Cluster of elongated, wind-driven oil slicks characteristic of natural seafloor seeps. Point of origin is beneath the northern end of each slick. As wind and current drives the floating oil away from the point of origin, the slick becomes progressively thinner and narrower due to evaporation, biodegradation and mechanical dissipation, until it no longer exerts a radar-detectable influence on sea-surface roughness and effectively disappears; in this case, 19 kilometers from the point of origin. Detail from southeastern part of August 6 image.**

Platforms and vessels appear as bright spots (Figure 6), generally indistinguishable until the GIS platform locations are superimposed. A few vessels can be distinguished by the presence of short, faint lines that indicate a trailing bow or stern wake.

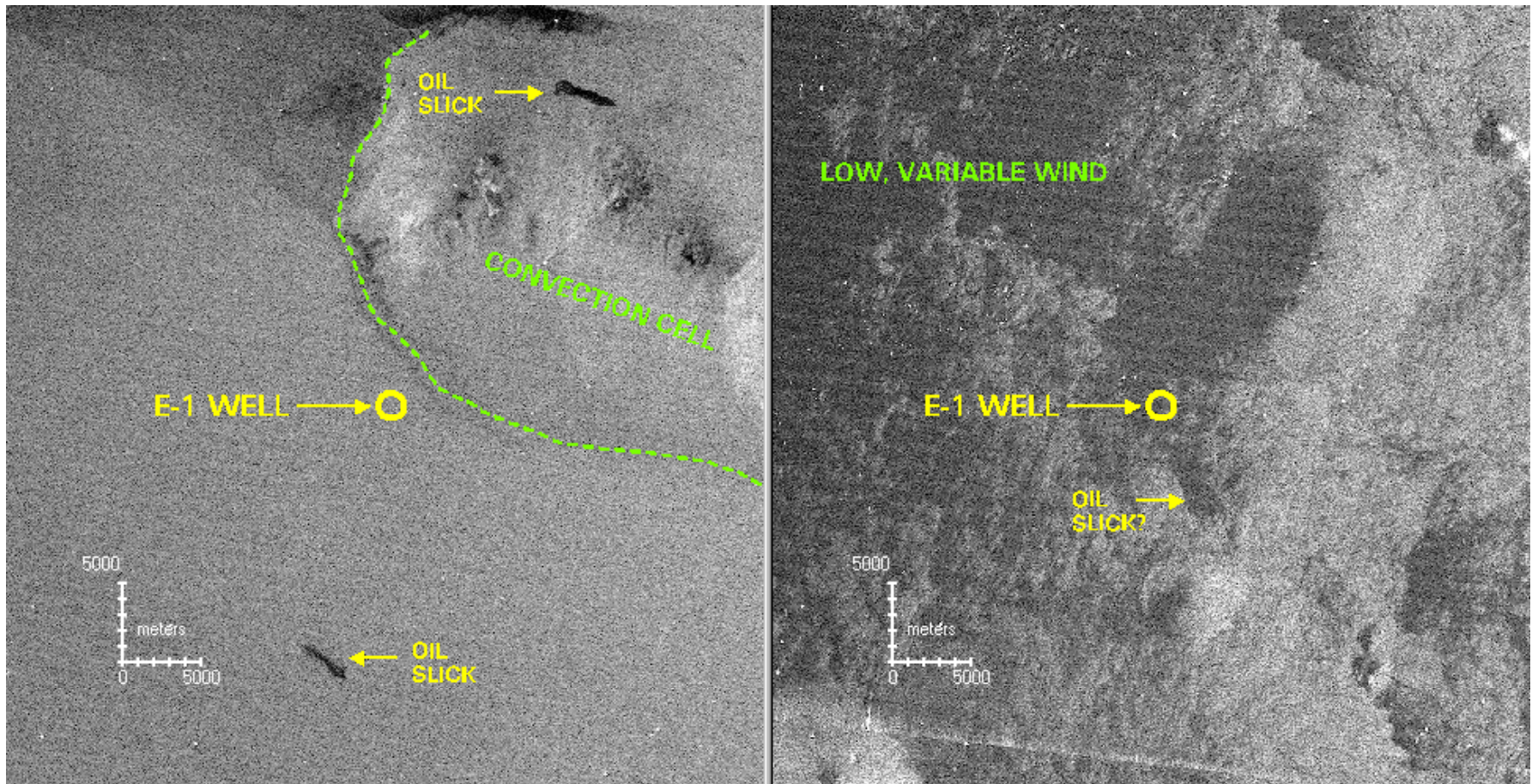
## E-1 Well Site

No slicks are apparent on either image that can be confidently attributed to a point source of leakage on the seafloor in the immediate vicinity of the E-1 well site. Figures 9 to 11 are a sequence of side-by-side comparisons of the August 6 and August 13 images. Each figure is zoomed in by 2x relative to the previous figure; Figure 10 represents a full-resolution enlargement (where one image pixel is represented by one hardware pixel on the display monitor of the image processing workstation).

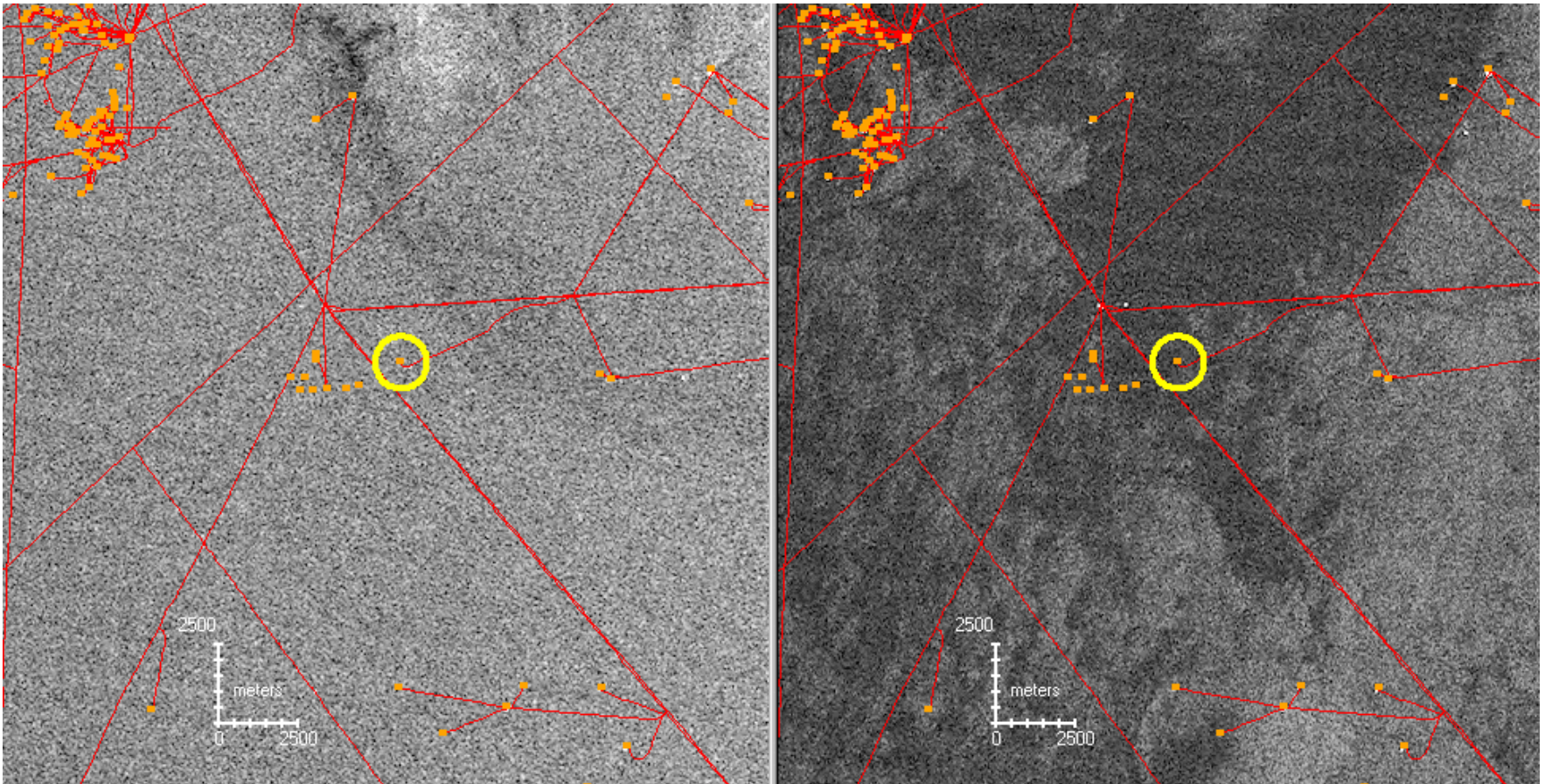
Figure 9 is marked with interpretive notes. The August 6 image exhibits the smooth, even grey tone that indicates a relatively uniform surface wind field, although the mottled circular pattern of a large but fairly weak convection cell occurs just north of the well site. The August 13 image, however, suffers from a highly variable wind field around the well. Low-wind regions appear as very dark patches throughout the area, including a large patch that covers most of the well site itself. An indistinct extension of this dark patch, stretching southeast from the well for about 7.5 kilometers, may represent a linear-wind-driven oil slick that is obscured by the low wind speed in the area. However, we consider this unlikely.

On the August 6 image two small but very prominent oil slicks appear, clear evidence that the wind conditions around the well site were ideal for detecting oil slicks on that date. One is located 16 kilometers south-southwest of the well site; the other is 23 kilometers to the north-northeast. Both slicks are approximately 3.5 kilometers in length, 600 – 800 meters in width, terminate abruptly on both ends, and trend northwest, roughly parallel to the shoreline. Neither appears on the August 13 image. These characteristics suggest that the slicks are ephemeral surface events from a moving source, probably minor spills from small passing vessels.

One additional feature of interest appears on the August 6 image. A platform in Ship Shoal South block 349, located at 28.062042 degrees North latitude, 91.062817 degrees West longitude, is obviously trailing a small, wind-driven slick that extends 11 kilometers to the southeast (Figure 12). The water depth in this area is approximately 200 meters.



**Figure 9. Well site E-1 (yellow circle) on RADARSAT images from August 6, 1997 (left) and August 13, 1997 (right). The even gray tone and appearance of two small oil slicks on the August 6 image indicate ideal surface wind conditions for slick detection. The dark, uneven tone and heavy mottling on the August 13 image indicate variable winds near the lower limit for slick detection, possibly obscuring the presence of any oil slicks. No slicks are confidently attributable to oil leaking from the E-1 site.**



**Figure 10. Well site E-1 (yellow circle) on RADARSAT images from August 6, 1997 (left) and August 13, 1997 (right). This is a 2x enlargement of Figure 9, with pipelines overlain in red and platforms marked by orange squares.**

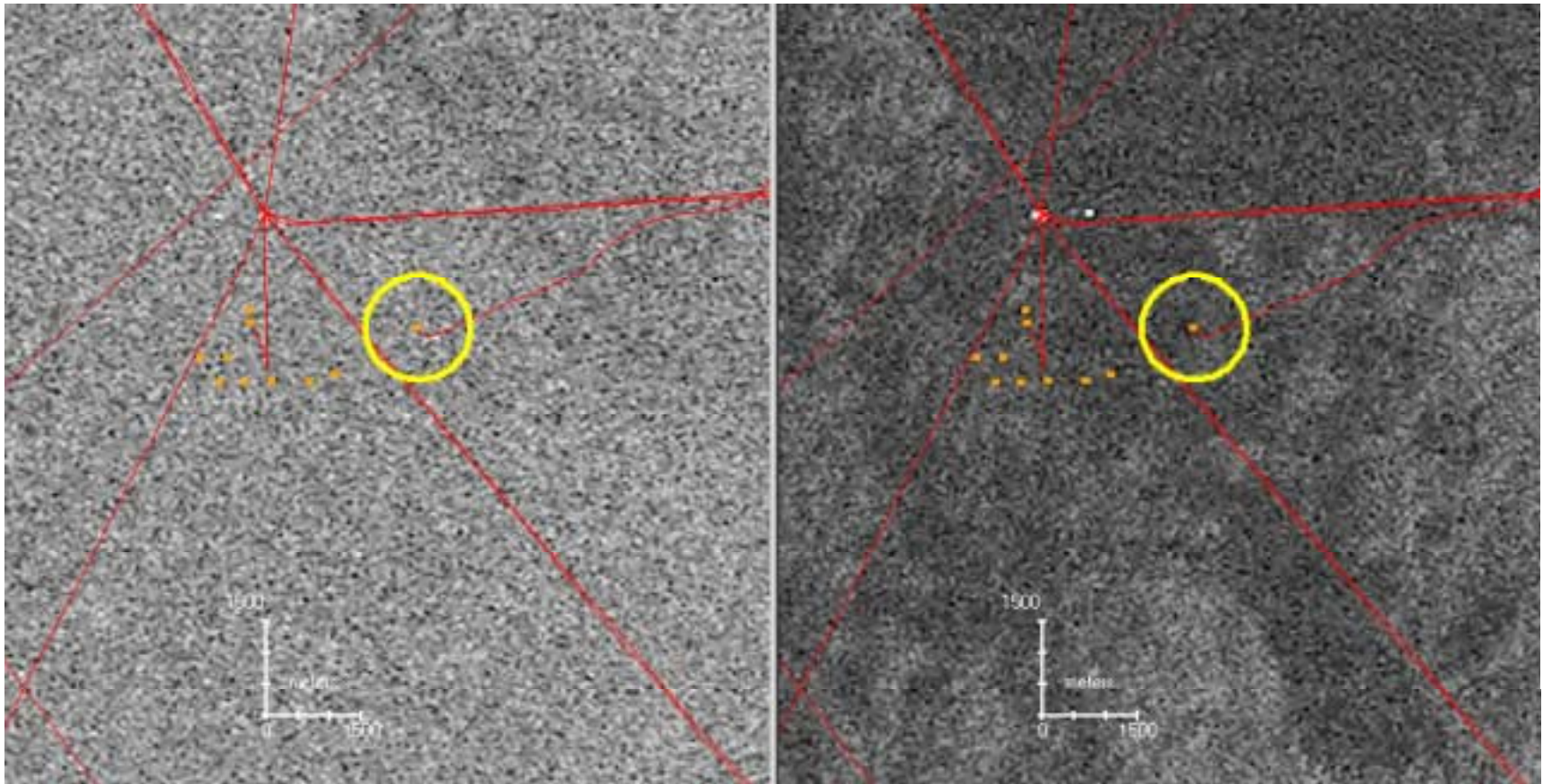


Figure 11. Well site E-1 (yellow circle) on RADARSAT images from August 6, 1997 (left) and August 13, 1997 (right). 2x enlargement of Figure 10.

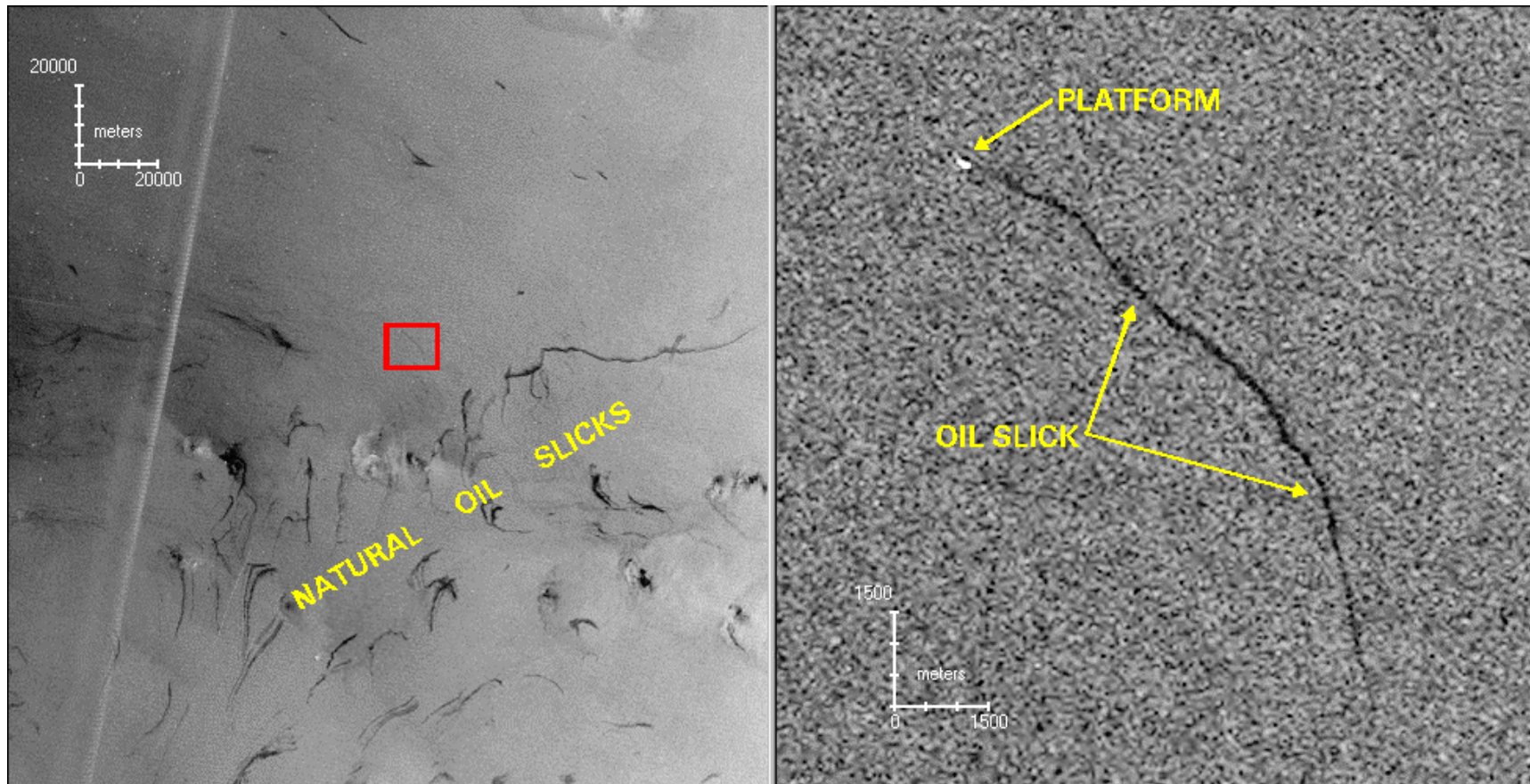


Figure 12. Oil slick emanating from production platform located in Ship Shoal South block 349, north of a large cluster of natural oil seeps on the continental shelf break. Red box marks area enlarged to the right. Detail from RADARSAT image acquired on August 6, 1997.



## CONCLUSIONS AND RECOMMENDATIONS

The results of Phase 1 are inconclusive and, in that regard, the Phase 1 effort has not successfully demonstrated the use of radar satellite imagery for remote detection of leaking abandoned oil wells. However, we think that the E-1 well site may not have been a suitable test case for demonstration purposes. Despite the appearance of small slicks bracketing the well location on the August 6 image – compelling evidence that wind conditions in that area were ideal for slick detection – nothing on the image suggests a leak from that location. Furthermore, the serendipitous discovery of a small slick originating from a platform in Ship Shoal South block 349 strongly suggests the ability of radar imagery to detect minor leaks and spills at sea. The lack of a slick at the E-1 site could be due to several possible factors:

- Reports that well E-1 was leaking were incorrect, or the location coordinates provided were inaccurate.
- Well E-1 was indeed leaking, but only intermittently, and the two radar images were acquired during periods of non-activity.
- Well E-1 was leaking persistently, but at such a low flux rate that no significant slicks formed on the sea surface above the well.

In the absence of any additional information regarding the test site, we are unable to confidently assess these possibilities. Therefore, we recommend that the Minerals Management Service consider the following actions before rendering a decision on whether or not to continue with Phase 2:

1. Collect additional information regarding the E-1 well site. Who reported that the well was leaking? How was the report verified? Were there multiple observations of oil slicks attributable to this well between the initial report in June 1997 and the re-plugging operation in January 1998? Were there direct observations of leakage from the wellhead at the seafloor? Was there any estimate of the rate of leakage, or the extent of the oil slicks that appeared above the well?
2. Investigate the oil slick noted from the platform in Ship Shoal South block 349. Was any pollution incident reported to the U.S. Coast Guard (Pollution Reporting Center) on or about August 6, 1997?

3. Select a new test site and repeat the technology demonstration. An ideal test site would have well-documented leakage noting specific dates of observation for surface oil slicks, as well as estimates of the slick extents and rates of leakage from the well on the seabed. Direct observations and measurements of leakage from the wellhead would also be helpful.

Satellite radar imagery is ideal for detecting small oil slicks, as shown by numerous natural oil slicks and suspected ship-related slicks that appear on both the images selected for this project. If an abandoned well persistently leaks crude oil at a rate comparable to the flux from natural seeps on the seafloor, then it should form a slick at the sea surface that will be plainly evident on radar imagery acquired under appropriate wind conditions. Selecting a better-understood test site may be required to correctly evaluate the potential of this powerful technology.