U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Effects of produced waters at oilfield production sites on the Osage Indian Reservation, northeastern Oklahoma

by

James K. Otton, Sigrid Asher-Bolinder,
Douglass E. Owen, and Laurel Hall
U.S. Geological Survey
MS939, Box 25046
Denver, Colorado 80225-0046

Open File Report 97-28

February 1997

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

ABSTRACT

The authors conducted limited site surveys in the Wildhorse and Burbank oilfields on the Osage Indian Reservation, northeastern Oklahoma. The purpose was to document salt scarring, erosion, and soil and water salinization, to survey for radioactivity in oilfield equipment, and to determine if trace elements and naturally occurring radioactive materials (NORM) were present in soils affected by oilfield solid waste and produced waters. These surveys were also designed to see if field gamma spectrometry and field soil conductivity measurements were useful in screening for NORM contamination and soil salinity at these sites.

Visits to oilfield production sites in the Wildhorse field in June of 1995 and 1996 confirmed the presence of substantial salt scarring, soil salinization, and slight to locally severe erosion. Levels of radioactivity on some oil field equipment, soils, and road surfaces exceed proposed state standards. Radium activities in soils affected by tank sludge and produced waters also locally exceed proposed state standards. Laboratory analyses of samples from two sites show moderate levels of copper, lead, and zinc in brine-affected soils and pipe scale. Several sites showed detectable levels of bromine and iodine, suggesting that these trace elements may be present in sufficient quantity to inhibit plant growth. Surface waters in streams at two sampled sites exceed total dissolved solid limits for drinking waters. At one site in the Wildhorse field, an EM survey showed that saline soils in the upper 6m extend from a surface salt scar downvalley about 150 m.

In the Burbank field, limited salt scarring and slight erosion occurs in soils at some sites and low to moderate levels of radioactivity were observed in oil field equipment at some sites.

The levels of radioactivity and radium observed in some soils and equipment at these sites are above levels of concern as defined in regulations proposed by the Conference of Radiation Control Program Directors. The volumes of material involved appear to be relatively small for most sites. The lead levels observed in soils affected by tank sludge wastes are about one half of the US Environmental Protection Agency (USEPA) interim remedial action levels used for Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and Resource Conservation and Recovery Act (RCRA) sites (400 ppm).

Field gamma spectrometry proved useful in delineating areas where radium has been added to the natural soil by oilfield solid waste and produced water, although the technique does not meet standards of assessment used in the state of Louisiana which require core sampling of 15 cm intervals and radiochemical analysis in the laboratory. Further work is needed to develop field gamma spectrometry as a substitute for the more expensive coring and laboratory analysis. The ratio of radium-228 to radium-226 may hold promise in evaluating the relative ages of NORM contamination at a site.

INTRODUCTION

Investigations on the Osage Indian Reservation (Fig. 1A) are part of a study of the effects of produced waters on soils, shallow bedrock, surface waters, and shallow ground waters being conducted by the U.S. Geological Survey. Produced waters in oil and gas fields are often extremely briny (as much as 35 weight percent total dissolved solids, Collins, 1975). Original formation waters throughout Osage County were very briny with most waters ranging from 75,000 to 250,000 ppm TDS (Wright and others, 1957). In addition to high concentrations of dissolved sodium and chloride, and lesser concentrations of other major elements, these produced waters and solids formed from them can contain varying amounts of naturally occurring radioactive materials (NORM, principally radium-226 and radium-228) and trace elements such as arsenic, barium, selenium, cadmium, chromium, copper, lead, nickel, silver, zinc, mercury, lithium, and boron (Collins, 1975). The effects of the surface disposal of produced waters can include the death of vegetation, soil erosion and siltation of streams, lakes, and reservoirs, and contamination of soil, ground water and surface water by salts, hydrocarbons, trace elements, and NORM.

The USEPA estimates that 30 percent of oil and gas production operations in the U.S. may have levels of NORM in brine and brine solids sufficiently elevated to be of concern (USEPA, 1993). One industry estimate suggests that if strict regulatory requirements for assessment and cleanup of NORM were put in place in the U.S., 20 percent of oil production and 8 percent of gas production would become uneconomic (Smith and others, 1995).

As in many producing areas of the U.S., in the early 1900s Osage County produced waters were often dumped on the surface or in nearby washes and streams. This practice later gave way to the use of brine evaporation ponds. Still later, companies injected produced waters for waterflooding and for maintaining field pressures. As regulations governing brine discharges were put into place, injection disposal wells became extensively used. Many injection, waterflooding, and pressure maintenance wells encountered problems with equipment failures, leakage across geologic structures, and leakage up improperly plugged and abandoned older production wells. This history suggests that salt scarring and past contamination of soils and ground and surface waters are likely to be common in the county. Previous deep geophysical surveys had mapped the presence of brine plumes in the subsurface in the Burbank field area (Fitterman, 1985; Raab and Frischknecht, 1985).

A 1989 American Petroleum Institute (API) survey of radioactivity in active U.S. oil production and gas processing equipment included oil production equipment at 115 sites in Osage County (Otto, 1989). The average radioactivity across the county was 87 microRem per hour (μR/hr) above background and the median and 75th percentile values were 4 and 32 μR/hr above background, respectively. The maximum observed value was 3391 μR/hr above background. Slightly more than 25 percent of the oilfield equipment measured in Osage county exceeded the USEPA

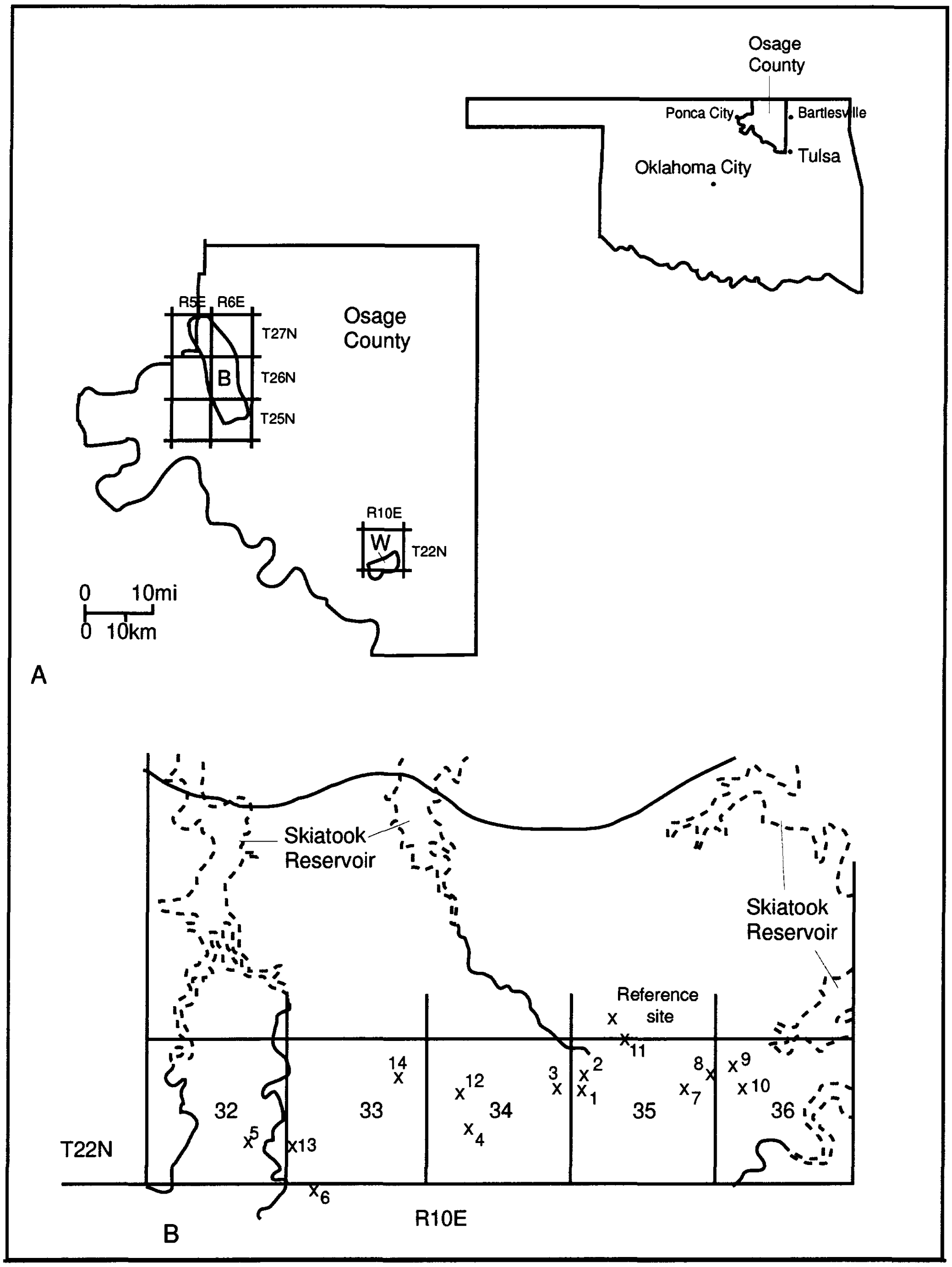


Figure 1- A- Map showing the location of the Wildhorse (W) and Burbank (B) fields in respect to the township and range grid system, Osage County, northeastern Oklahoma. B- Map showing the location of sample sites and other features in the Wildhorse area, Osage County, Oklahoma.

radioactivity standard used in uranium mine tailings reclamation sites (25 μR/hr above background). High values observed in the API survey occur mostly on separator tanks, water storage tanks, and water lines where brine scale and tank sludge accumulate.

An aeroradiometric survey of Osage County was conducted as part of the National Uranium Resource Evaluation (NURE) survey of the Department of Energy (Texas Instruments, 1978). East-west flightlines spaced at a nominal 6 miles (10 km) were flown across the county. These data show that equivalent uranium values for the eastern part of the county (an area underlain mostly by sandstone and shales) generally range from 1.0-2.0 ppm (0.33-0.67 pCi/g radium-226). In the western part of the county (an area underlain mostly by limestone) equivalent uranium values are generally somewhat higher (1.5-2.5 ppm, 0.5-0.8 pCi/g radium-226). Some anomalies in the profiles are related to the presence of uranium-enriched black shales; however, some substantial equivalent uranium anomalies occur (as much as 10 times background) that have no geologic explanation. The NURE report interpreted these anomalies as caused by "possible Ra-rich oilfield brines". The largest of these anomalies (about 5 pCi/g Ra-226 maximum) occurs over the Wildhorse oilfield.

In the soil survey of Osage County, Bourlier and others (1979) identified "oil-waste land" as one of the soil map units and indicated that 1927 acres (0.1 percent) of the county is underlain by this unit. Our studies of aerial photos and our field inspection of the Wildhorse oilfield suggest that 1) a large number of small areas of active salt scars are not mapped in the soil survey; and 2) extensive areas of probable older salt scars, now revegetated with grasses, were not included in this soil map unit. This suggests that considerably more Osage County acreage is underlain by active and historic salt scars.

This report describes salt scarring and erosion at selected sites in the Wildhorse oilfield, provides information regarding the presence of trace elements in soils in the Wildhorse oilfield, provides survey information for NORM at operations in the Wildhorse and Burbank oilfields, and documents shallow soil salinization at one site in the Wildhorse field.

REGULATIONS AND REGULATORY PROPOSALS RELEVANT TO RADIOACTIVITY, NORM, AND TRACE ELEMENTS AT OIL AND GAS PRODUCTION SITES

The USEPA has not issued regulations limiting NORM contamination and radioactivity in oil and gas production operations, however, they are assessing the extent of the problem in a wide number of industries that generate NORM and they and the Department of Energy are evaluating the health risk associated with NORM exposure in oil and gas operations. At uranium mill tailings sites, NORM contamination of soils and other solid materials is limited to 5 pCi/g above background in surface layers in the Code of Federal Regulations (40 CFR 192). Consistent with 40 CFR 192, the Conference of Radiation Control Program Directors (CRCPD) has suggested state regulations (E. Kray, CRCPD, written commun., 1995) that would limit NORM contamination at oil and gas operations to 5 pCi/g in surface materials (upper 15 cm) and radioactivity to 25 μR/hr. Six states (Louisiana, Texas, Michigan, Mississippi, Arkansas, and New Mexico) currently have regulations that affect some aspect of NORM in the oil and gas industry. In these regulations, NORM concentration thresholds for soils and other media are either 5 pCi/g or 30 pCi/g dependent mostly on the assumed rate of radon emanation from the radium present. Limits of radioactivity in equipment are either 25 μR/hr or 50 μR/hr. Whether these radioactivity levels are reported as above background or including background varies from state to state. Proposed state regulations in Oklahoma would limit NORM levels in soils to 30 pCi/g and radioactivity on equipment to 50 μR/hr above background (Gene Smith, oral commun., 1995).

Oil and gas production operations are presently exempt from RCRA and CERCLA regulations, thus no limits are presently placed on toxic trace element levels in sludges and scales or in soils affected by sludge, scale, or produced waters. However, for lead, EPA has set a preliminary remediation goal of 400 ppm for CERCLA sites and RCRA corrective action facilities (USEPA, 1994). Soil screening levels for other trace elements are under consideration by EPA, but are not ready for publication. It is EPA's intent that screening levels trigger further remedial investigation or feasibility studies. These screening levels may or may not become response levels or cleanup standards for a site.

Drinking water standards have been established by the USEPA for public water supplies for radionuclides, organic compounds, major and trace elements, and total dissolved solids (TDS). Many of these contaminants occur in oilfield produced waters. In most cases of oilfield brine contamination, it is likely that the TDS standard (500 ppm) will be exceeded before other substances reach unacceptable levels.

Many tribes in Oklahoma and elsewhere are establishing their own environmental standards, typically adapting existing environmental regulations from other jurisdictions. (Pamela Snyder-Osmun, BIA, oral commun., 1995). For tribes with oil and gas production operations, some decisions will need to be made regarding environmental standards for NORM and trace elements.

SURVEY AND SAMPLING METHODS

Sample sites in the Wildhorse oilfield were selected based on the proximity of the site to the anomalous portion of the flightline profile that traversed the field and ease of access to the site on paved and unpaved roads. Sites in the south Burbank unit of the Burbank field were visited based on topographic map indications of the presence of a site and visual sighting of a prospective site from the road. As such these sites were not selected on a random basis and the sites evaluated do not necessarily represent all sites in the Wildhorse and South Burbank fields. These sites do not necessarily represent all sites in Osage County.

Detailed maps for sites OS95-3, OS95-4, OS95-5, and OS95-14 were created using tape and compass with supplemental distance and direction measurements made by pace and compass. The overview maps for OS95-4 (Fig. 5) and OS95-14 (Fig. 8) showing the location of the salt scars and other features were made from aerial photos provided by the Osage Indian Agency, Bureau of Indian Affairs, Pawhuska, Oklahoma. The depth of gullies was measured with a tape.

Estimates of erosional stage use definitions in a study of brine impacts in southern Illinois (Greater Egypt Regional Planning Commission, 1982). Sites in the early stages are characterized by advanced sheet and rill erosion, little outwash at the downslope edge, and peripheral expansion of the site along one or more edges. A site in the intermediate stage shows gully development, accumulation of outwash sediment, expansion of the barren area at the outwash edge, and development of sparse vegetation at the upslope periphery and on ridges between gullies due to leaching of salts. A site in the advanced stage shows deep gullying often including complete removal of the upper 0.6-1.5m of soil, extensive accumulation of outwash sediment at the downslope edge, and recolonization of plants on remaining soil on ridges and islands between gullies and at the periphery.

Each site was surveyed using a handheld Geometrics scintillometer (Model Exploranium, range 1-10,000 cps). Field calibration of the Geometrics scintillometer used during the survey with a calibrated Ludlum μR meter shows a nonlinear relation defined as $x(\mu R/hr) = 2.2 + 0.18492\ y - 1.3428 \times 10^{-5}\ y^2$ for values less than 10,000 cps where y is the scintillometer reading in counts per second (cps) (J.K. Otton, unpublished data, 1996). Produced water and oil storage tanks, separator tanks, flow lines, pumping wellheads, and injection wellheads were examined by placing the radiation detection instrument flush against the surface of the equipment. Soil surfaces, bedrock exposed in salt scars, and disturbed, oily, and discolored soils were also examined in a similar manner.

Soil at three of the sites was surveyed with a Scintrex GAD-6 gamma spectrometer. This instrument is a four-channel analyzer that records total gamma counts (over an energy range of 0.40-2.8 Mev) and gamma counts for three windows: a potassium window (1.35-1.60 Mev), a uranium window (1.60-1.85 Mev), and a thorium window (2.50-2.75 Mev). The potassium window brackets the 1.46 Mev potassium-40 peak, the uranium window brackets the 1.76 Mev bismuth-214 peak (a uranium-238 decay product), and the thorium window brackets the 2.62 Mev thallium-208 peak (a thorium-232 decay product). The raw count data for the bismuth-214 and thallium-208 channels can be used to determine equilibrium radium-226 and radium-228 activities respectively, unless there is evidence that substantial amounts of intervening radon (radon-222 or radon-220) decay products are lost from the material being measured. For oilfield brine solids, the emanation of radon from the solids is typically less than 5 percent (K.K. Nielson, oral commun., 1995); thus, radon loss is not considered significant. The gamma-spectrometer raw count data are more typically converted to equivalent uranium-238 (parts per million eU), and equivalent thorium-232 (parts per million eTh) using equations that account for the counting efficiency of the instrument and background gamma rays from cosmic sources. These equations are developed uniquely for each instrument by calibrating the instrument on concrete pads of known uranium, thorium, and potassium concentrations and by measuring background cosmic radiation at a site remote from sources of uranium, thorium, and potassium, typically at least 100 m from shore in the middle of a lake. The calibration equations for this instrument were developed from readings made at Department of Energy calibration pads at the airport in Grand Junction, Colorado. The cosmic background values used for this instrument were determined at Fairfax Lake, Fairfax County, Virginia (altitude about 100 m). eU and eTh are calculated assuming equilibrium with radium and its decay products. The instrument is further calibrated on a regular basis to make certain that the gamma-counting windows do not drift with time. This is done by using a thorium source and adjusting the thorium count to maximum values using a calibration dial on the instrument.

Gamma-spectrometer readings are of limited usefulness on production equipment because the equations that convert raw readings to potassium, uranium, thorium, and radium values are designed for planar soil or bedrock surfaces where an ideal hemispheric geometry applies. Corrections can be made for simple variations from that hemispheric geometry for an irregular soil or bedrock surface, but the corrections for the unusual source geometries and shielding that would apply to radium-bearing sludge layers in tank bottoms or cylindrical pipe scale sources require data that are not readily available under most field conditions (for example, thickness of the pipe scale or tank sludge layer and thickness of the pipe and tank wall). Gamma-spectrometer readings can be used as minimum values however, and if thickness data are available or can be estimated, radium concentration estimates can be made (Rogers and Nielson, 1995).

In typical field usage (detector placed against a planar, horizontal soil or rock surface), scintillometers and gamma-spectrometers receive most gamma rays from soil within a radius of 40±10 cm depending on the density of the soil and resultant attenuation of the gamma rays. The reported K, eU, eTh, Ra-226, and Ra-228 concentration values represent an average for that hemispheric volume of soil and do not provide a depthwise distribution. For example, if a thin surface layer of radium-rich material is underlain by radium-poor materials, the spectrometer readings will underestimate the radium content of the surface layer.

The terms "background" and "local background" as used in this report for scintillometer and gamma-spectrometer readings refer to readings taken at an uncontaminated reference site and to an average of readings determined by walking over uncontaminated rocks and soils at several spots adjacent to the individual study site. "Background" and variation in "background" values were not determined by an analysis of variance sampling. Where state regulations require cleanup of soils when they are 5 pCi/g above background, an accurate determination of background is important in determining the volume of soil designated for cleanup.

Use of gamma spectrometer data to delineate soils for remediation is not presently an approved method in those states where remediation is required. Louisiana presently requires that samples from 15 cm intervals at several core sites within a 10m square cell be analyzed for radium in a laboratory. The upper 15 cm interval may not exceed an average of 5 pCi/g for the samples within the 10 m cell. Subsequent 15 cm intervals must average less than 15 pCi/g. The gamma-spectrometer data do not directly provide information required to estimate the radium concentrations over these fixed thicknesses of soil.

Radium-226 in liquid samples was determined by the radon emanation technique (Broecker, 1965). An aliquot of the sample was placed in a radon bubbler and helium passed through it to remove all radon. The flask was then sealed to allow in-growth of radon-222 from the radium-226 in the sample. After a known time interval the radon was again removed from the flask and transferred to a counting cell coated with silver-activated zinc sulfide and placed on a photomultiplier tube to measure radon and daughter product activity. The efficiency of the radon collection, transfer and counting procedures was calibrated using National Institute of Standards and Technology (NIST) radium standards.

The radium-226 and radium-228 activity of solid samples was measured using gamma ray spectroscopy (Michel et al., 1981). Aliquots of samples were sealed in 10 ml polyethylene vials and placed in the well of a high-purity germanium detector which was calibrated with similar quantities of radium-containing barium sulfate precipitate prepared by adding $Ba(NO3)_2$ to NIST radium-226 and radium-228 standards and then adding H_2SO_4 to quantitatively precipitate $Ba(Ra)SO_4$. The $Ba(Ra)SO_4$ precipitate standards were stored to allow equilibration of daughter products of radium-226 and radium-228 before using the standards to calibrate the detector. $BaSO_4$ was chosen as the matrix to calibrate the detector because most of the high-activity samples in this study contain radium in a $BaSO_4$ precipitate, which is common in oil-field brine scales. This technique differs from the field gamma spectrometry in that a high resolution Ge(Li) crystal is used rather than a NaI (Tl) crystal. This allows for greater precision. The samples are much smaller and perhaps less representative of the soil at the site.

Three unfiltered water samples were collected in one liter polyethylene bottles that were prerinsed with sampled water prior to filling. Field pH and field conductivity measurements were made using standard techniques. Samples were stored under refrigeration. Upon return to the laboratory, alkalinity was determined by titration with standard acid. The remaining sample was filtered through a 0.45 micron cellulose acetate membrane. An aliquot of 125 ml was taken for anion analysis and the remaining solution was acidified to a pH <2 with ultrapure nitric acid and submitted for cation analysis. Cations were determined using standard flame atomic absorption spectrophotometry. The method of additions was utilized to compensate for matrix interferences. Anions were measured by ion chromatography following the method of Fishman and Pyen (1979). The cation-anion charge balance for two of the three water samples is within 10 percent. For sample OS95-3AW, the charge balance shows a difference of about 21 percent. Analyses for calcium, magnesium, and strontium show a mean deviation of 5 percent whereas potassium and sodium show a mean deviation of 10 percent.

Soil samples were collected from the 0-10 cm surface layer with a plastic scoop and placed in cloth sample sacks. The soil samples were analyzed, as received, for a limited suite of trace elements, using non-destructive, energy-dispersive X-ray fluorescence. The estimated precision of the technique is 10 percent. The samples were not pulverized and homogenized prior to analysis to permit quick turnaround on the analysis and to avoid exposure to radium in the samples. The results should therefore be considered semi-quantitative (±10-25 percent). The concentrations reported do not reflect the solubility or mobility of the elements reported and thus do not necessarily reflect any level of potential hazard to humans or the environment.

Soil conductivity measurements were made at Site OS95-14 using an EM-31 Geonics Limited instrument (McNeill, 1980a, 1980b). Measurements were made in 4 orientations: 1) vertical dipole mode parallel to traverse line; 2) vertical dipole mode perpendicular to traverse line; 3) horizontal dipole mode parallel to traverse line; and 4) horizontal dipole mode perpendicular to the traverse line. In the vertical dipole mode, the instrument has an effective depth of exploration of about 6 m. In the horizontal dipole mode, the instrument has an effective depth of exploration of about 3 m.

WILDHORSE OILFIELD AREA

The Wildhorse field is located in the southeastern part of Osage County mostly in the southern part of T22N, R10E (Fig. 1B). The field was discovered in 1912. Production is shallow and comes from several units including the Bartlesville sand, Cleveland sand, Big Lime, Peru sand, Oswego Lime, Skinner sand, Burgess sand, and Mississippian Lime (all informal names). Precambrian granite occurs at 2217 ft in a well in the NE/4 sec 32, T22N, R10E. Water-flooding operations in the oilfield began in the early to mid-1950s (Johnson and Castagno, 1961).

The oilfield is located in a mixed grassland and oak forest area. Extensive salt scarring is present and erosion to underlying bedrock has occurred at most of the salt-scarred sites. Many open areas in forests may represent older salt scars that have been partly or mostly revegetated with grasses. Abandoned oilfield equipment is common. Streams draining the oilfield area flow northward into Skiatook Reservoir.

The area is underlain principally by sandstone and shale of the Pennsylvanian Barnsdall Formation (Bingham and Bergman, 1980). At the sites visited by us in the Wildhorse field, the ridge crests are typically underlain by thin to thickly bedded sandstone with minor shale partings on which sandy loam to fine sandy loam soils with minor sandy clay loam have formed (Darnell-Stephenville complex, Bourlier and others, 1979). Soils are typically thin (<20 inches). Hillslopes are underlain by interbedded sandstone and shale on which loams and silt loams often containing sandstone and shale fragments have formed (Steedman-Coweta complex, Bourlier and others, 1979). Soils are somewhat thicker, but generally less than 40 inches.

The Wildhorse field was visited in late June, 1995 and some sites were revisited in June, 1996. In 1995, heavy rains were recorded throughout the spring and early summer in this part of Oklahoma, but no rain fell for several days prior to our visit. Soils were generally dry in surface layers, but damp in the shallow subsurface. The weather was hot and humid during the survey period with bright sunshine and gentle winds.

Results

Fourteen sites were visited in the Wildhorse field (Fig. 1B). All the sites are located in sections 32-36, T22N, R10E except for a tank battery located in section 4, T21N, R10E. Radioactivity at a reference site in section 26, T22N, R10E was measured and data from this site were used as a general basis of comparison for other sites affected by oilfield wastes, however, local readings on apparently uncontaminated soils at some sites were sometimes lower than readings measured at the reference site.

Reference site

The reference site (Fig. 1B) is located along the east side of a narrow paved road about 1.4 miles south of Morgans Corner on Highway 20 between Skiatook and Hominy, Oklahoma (NE/4, SW/4, SW/4 section 26, T22N, R10E). This site was chosen because it was along a ridge crest like most of the tank battery and injection well sites studied, the soils were similar, and the site was not near oilfield equipment and appeared to be uncontaminated. This is a reference site only however, and actual background radioactivity in this area is subject to an unknown natural variability not documented here. If state regulations affecting NORM at a site required a comparison to background, a more thorough investigation would be required to establish background. This reference site is near the crest of a north-trending sandstone ridge. At this location, the road surface has been cut down into the soil and weathered bedrock, leaving a low road cut at the east edge of the road. Sandstone bedrock is partly exposed in the ditch at the edge of the road surface and in the field adjacent to the road. Thin sandy soil lies on top of the sandstone. Sparse vegetation grows on the site, although adjacent areas have abundant grasses and forbs. Field scintillometer and gamma-spectrometer readings for the site are given in Table 1.

Total radium at the reference site was 2.02 pCi/g and the radium-228/radium-226 value was 1.25. The total radium value is higher than the 1.35 pCi/g median value reported for the Barnsdall Formation (the principal surface geologic unit in the study area) in the NURE aeroradiometric dataset (Texas Instruments, Inc., 1978). The radium-228/radium-226 value is higher than the 0.72

Table 1- Radiometric data for the reference site in the Wildhorse field.
The eU-238 and eTh-232 values are calculated from raw gamma-spectrometer count data.
1 ppm eU= 0.33 pCi/g eRa-226. 1 ppm eTh= 0.11 pCi/g eRa-228.

				Wildhorse field reference site			
Location	Scintillometer	Values calculated from raw gamma-spectrometer readings					
	(cps)	eU (ppm)	eTh (ppm)	eRa-226 (pCi/g)	eRa-228 (pCi/g)	Ra-228/Ra-226	Total radium (pCi/g)
Background	22	2.7	10.1	0.90	1.12	1.25	2.02

median value for the Barnsdall Formation in the same dataset (Texas Instruments, Inc., 1978). The reference scintillometer reading is 22 cps.

Site OS95-1

Site OS95-1 (Fig. 1B) lies within grasslands near the edge of an oak forest and just to the north of a paved road (NW/4, SW/4, NW/4 sec 35, T22N, R10E). It consists of a pumping unit with a salt scar that trends north downslope from the pumping unit. Thin sandy soil overlying the shallow bedrock has been eroded from the salt scar and ledges of sandstone and shale are exposed. This site is in the advanced stage of erosion. East of the pumping unit and salt scar is an area several 100 m^2 covered with oil-saturated soil. The local background count was 20-25 cps (6-7 μR/hr). The wellhead was about 100 cps (21 μR/hr) and the oil-soaked soil around the wellhead was a few times background. Radioactivity over the exposed bedrock in the salt scar ranged from 35-50 cps (9-11 μR/hr) with higher values over the exposed shale. The oil-saturated soil to the east was at background.

Site OS95-2

This site (Fig. 1B) lies a few hundred feet north of site OS95-1 on the east side of a small wash (NW/4, SW/4, NW/4, section 35, T22N, R10E). It consists of a pumping unit with a large salt scar that trends west downslope from the pumping unit into the wash. Sandstone ledges are exposed in the salt scar. Abundant old piping lays about on the site. An area of dead oak trees covers part of the scarred area. This site is in the advanced stage of erosion.

The pipe on the site ranges from 40-3500 cps (10-500 μR/hr). Old, corroded pipe with a thick internal layer of scale has the highest count. The sandstone and the nearby soils are about 20-25 cps (6-7 μR/hr). Several other salt scars occur nearby.

Site OS95-3

This site (Fig. 1B) lies across a dirt road west of a large, active (June 1995 and June 1996) tank battery along the crest of a broad, north-trending ridge (SE/4, NE/4, sec 34, T22N, R10E). The active tank battery equipment was briefly surveyed; the oil storage tanks are mostly at 20 cps (6 μR/hr) , a heater/treater gave a maximum reading of 350 cps (65 μR/hr).

The part of the site studied in detail (Fig. 2) includes abandoned equipment and a discontinuous salt scar which occurs downslope to the west. The slope is covered by grasses and forbs except where the scars occur. The equipment includes an old oil storage tank laying on its side which has corroded through at one end; a separator tank; a second oil storage tank with an oil leak; and an adjacent wooden water storage tank (Fig. 2). Old pipe, much of it partly corroded with thick layers of pipe scale exposed, are scattered about the site. Two stacks of pipe are present. A small, water-filled pond with an oily surface film occurs just south of the largest scarred area. The westernmost salt scars are near the edge of a creek which has cut a steep-

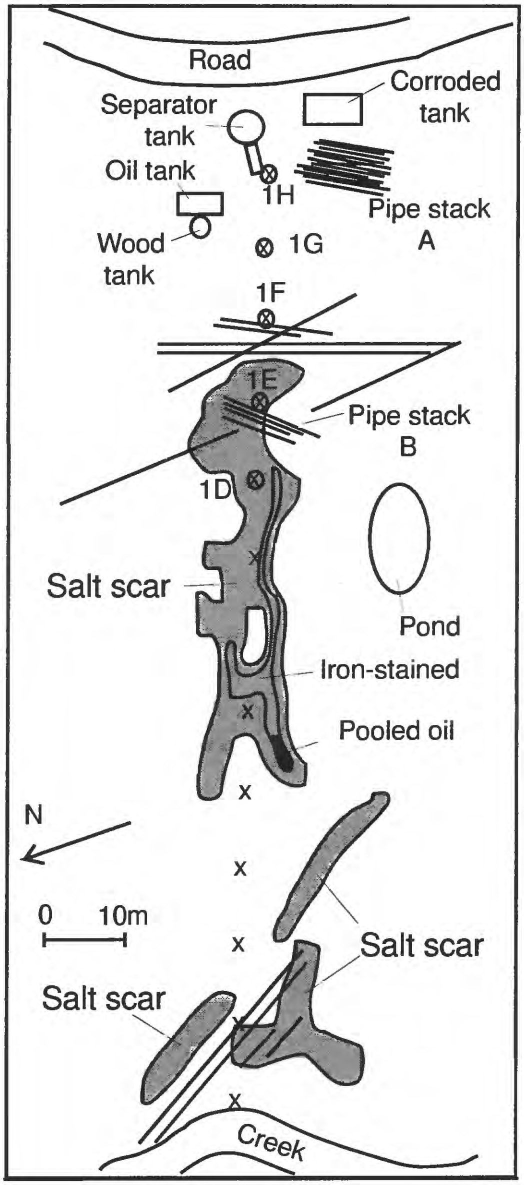


Figure 2- Map showing cultural and related features at site OS95-3. Wildhorse field, Osage County, Oklahoma. Shaded areas- salt scars. x- location of gamma-spectrometer survey stations. The 0 m station is at the top of the figure adjacent to the access stairs to the separator tank. The 120 m is at the edge of the creek. o- Soil sample sites (1D-1H). Unlabeled straight lines at various angles are isolated pieces of pipe. An area of iron-stained soil occurs within the larger salt scar. Pooled oil occurs at the lower end of this salt scar. See Fig. 1B for location.

walled channel about 1.6 m deep into the floor of the broad open valley.

The large easterly salt scar is irregular, about 55 m long, and 10 m wide. Soil comprised of a sandy loam is exposed in most of this and the other three salt scars, but a small sandstone outcrop is exposed just west of sample site 1D (Fig. 2). Iron-staining occurs along the lower parts of the scar and the iron staining merges with pooled oil at the west end. Three smaller scars occur to the west. The immediate area of the site is in the intermediate stage of erosion, however the deep gully formed by the creek at the bottom edge of Fig. 2 reflects an advanced stage of erosion of nearby sites.

Gamma-spectrometer measurements were made at 13 stations along an east-west traverse starting at the abandoned separator tank and extending to the creek along the axis of the salt scar, a distance of 120 m (Fig. 2, Table 2). Soil samples were collected at the five stations closest to the old equipment (samples 1D-1H, Fig. 2, 0-40 m stations on traverse). Scale from the end of a corroded pipe that jutted out over the creek was also collected (Sample 1C). This locality is not marked in Fig. 2, but is on the west bank of the creek across from the end of the survey line. The sample from the east end of the profile (1H) was analyzed in the laboratory for radium-226 and radium-228. All six samples were analyzed for trace metals. Water samples were taken from the pond and the creek (Fig. 2).

The base of the heater/treater unit with the access stairs ranged from 300-450 cps (57-83 μR/hr). Pipe in stack A (Fig. 2) ranged from 200-2000 cps (40-320 μR/hr). Pipe in Stack B (Fig. 2) reads as much 6,700 cps (about 640 μR/hr). Individual pieces of pipe at the east end of the larger salt scar read from 100-1750 cps (20-285 μR/hr). At the north end of the corroded oil tank, large fragments of asphalt mixed with scale and corroded iron are exposed in the tank and have spilled out on the ground. This material gives readings that exceed 10,000 cps (>1,000 μR/hr). The broken-off corroded pipe from which sample 1C was taken read 1800 cps (290 μR/hr).

Total radium values calculated from the gamma-spectrometer data exceed 30 pCi/g (the proposed Oklahoma state standard) at the 0 m station and at the 30 m station near the head of the salt scar (Table 2, Fig. 3). The 30 m station lies adjacent to a highly radioactive pipe stack and the recorded value may have been influenced by radioactivity from the pipe. Downslope from the 30 m station values drop to between 1.9 and 7.5 pCi/g. Values for radium-228/radium-226 are very low at the first four stations (<0.07, Table 2, Fig. 4) at the upper end of the site, then increase in the active salt scar. West of the salt scar, the ratio is erratic, jumping to values >0.5 at two sites. All of the radium-228/radium-226 values are below the ratio of 1.25 observed at the reference site and the ratio of 0.72 in the aerorad data. These low ratios may develop through the addition of radium-226 alone to the brine-affected soils, however most brines contain both radium-228 and radium-226 in ratios of 0.6 to 2.0 with a median value of about 1.00 (T. Kraemer, oral commun., 1996). It

Table 2- Gamma-spectrometer data for stations along an east-west profile at site OS95-3, Wildhorse field.
1 ppm eU= 0.33 pCi/g eRa-226. 1 ppm eTh= 0.11 pCi/g eRa-228.

Location (m)	eU (ppm)	eTh (ppm)	eRa-226 (pCi/g)	eRa-228 (pCi/g)	Ra-228/Ra-226	Total radium (pCi/g)
0	127.1	11.2	42.37	1.24	0.0294	43.61
10	43.6	6.2	14.53	0.69	0.0474	15.22
20	34	6.2	11.33	0.69	0.0608	12.02
30	98.9	9.6	32.97	1.07	0.0324	34.03
40	8.3	5.9	2.77	0.66	0.2369	3.42
50	20.6	5.8	6.87	0.64	0.0939	7.51
60	9.9	5.6	3.30	0.62	0.1886	3.92
66	12	7.2	4.00	0.80	0.2000	4.80
70	7.7	5.4	2.57	0.60	0.2338	3.17
80	9.9	4.5	3.30	0.50	0.1515	3.80
90	3.9	6.1	1.30	0.68	0.5214	1.98
100	10.1	5.7	3.37	0.63	0.1881	4.00
110	10.7	7.2	3.57	0.80	0.2243	4.37
120	3.9	6.2	1.30	0.69	0.5299	1.99

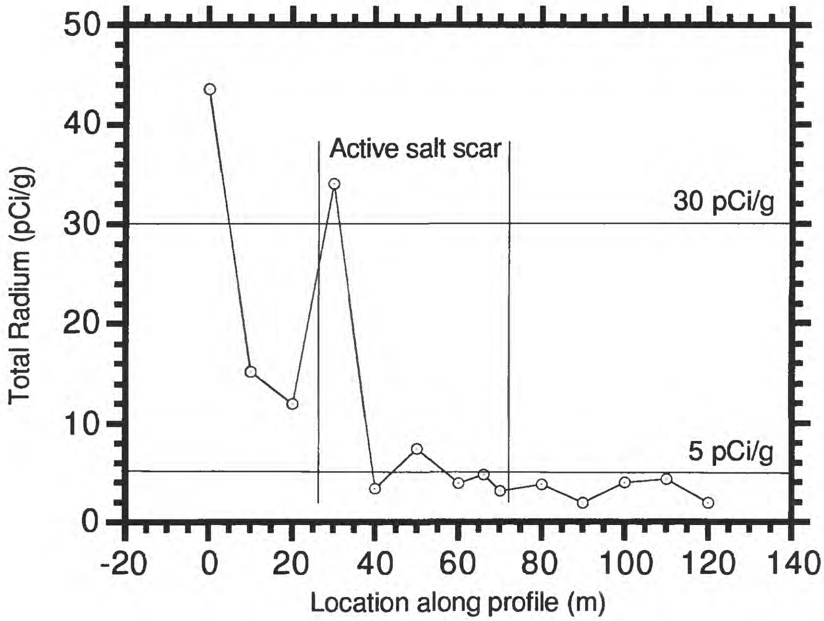


Figure 3- Profile at site OS95-3 showing total radium concentrations at gamma-spectrometer stations. See Fig. 2 for location of the profile. The 5 and 30 pCi/g lines are shown for reference to proposed national and Oklahoma standards for radium in soils.

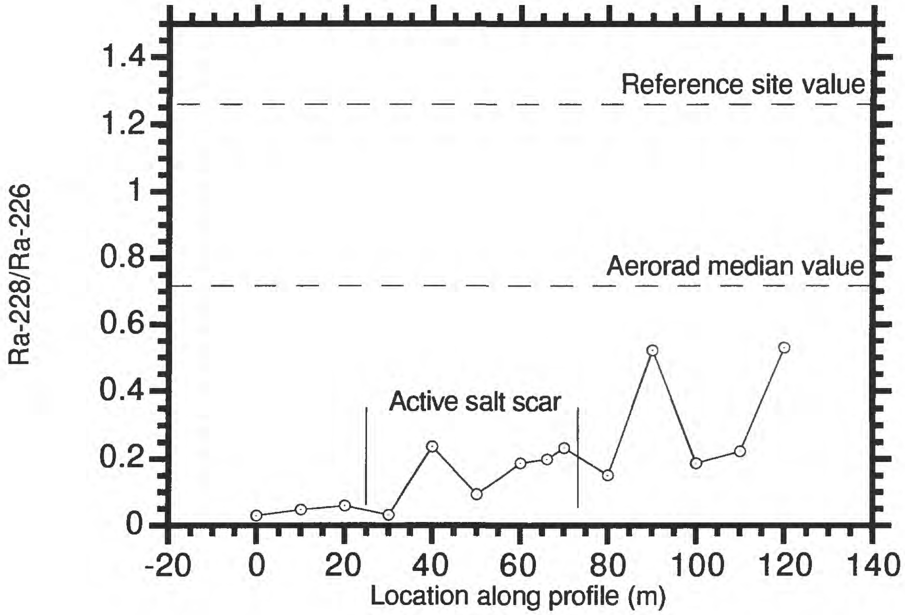


Figure 4- Profile at site OS95-3 showing radium-228/radium-226 values at gamma-spectrometer stations. See Fig. 2 for location of the profile. Reference values are shown.

seems likely that both radium isotopes have been added to the soil and that much of the radium-228, with a relatively short half-life of 5.8 years, has decayed away since its addition to the soil.

Elevated radium values in the grassy area and low radium-228/radium-226 values in all samples suggest that both the grassy areas and the active salt scar areas have been impacted by radium-bearing brine. It seems likely that soil along the entire profile was salt scarred at one time.

Laboratory radiochemical analysis of the surface soil sample from station 1H yielded 17±1 pCi/g radium-226 and less-than-detectable radium-228 (T. Kraemer, written commun., 1995). These values are less than the 42.37 pCi/g radium-226 and 1.24 pCi/g radium-228 measured in a larger volume of soil by the field gamma-spectrometer. Radium may be concentrated in deeper layers at this station.

Scale in the pipe from the creek (Sample OS95-1C, Table 3) contains 14.2 percent iron (probably from fragments of the corroded pipe included in the sample), and detectable copper, lead, zinc, bromine, and iodine. Strontium and barium are > 2 weight percent, suggesting the presence of barite and celestite, common scale minerals in oilfield tubular goods. The soil samples contain significantly less iron, copper, lead, strontium, and barium, but greater zinc and zirconium. Cadmium is only detected in the sample at the east end of the profile (OS95-1H, Table 3). Bromine was not detected in soil samples OS95-1H and 1G in the grassy areas at the east end of the profile, but was detected in sample OS95-1F near the salt scar and samples OS95-1E and 1D in the salt scar. Iodine concentrations were highest at the east end of the profile and apparently decrease to the west.

Water from the creek (OS95-3W, Table 4) was slightly alkaline (field pH=8), moderately briny (field conductivity=2700 μS/cm), and contained radium (radium-226=1.3±0.3 pCi/L). Water from the pond (OS95-3AW, Table 4) was slightly more alkaline (field pH=8.3), less conductive (field conductivity=515 μS/cm), and contained somewhat more radium (radium-226=1.8±0.2 pCi/L) than the water in the creek. Sodium and chloride are the major dissolved ions in the creek water sample and the pond water sample. The next most abundant ions are of Ca^{+2}, SO_4^{-2} and HCO_3^-. Bromine and traces of fluorine are present. The pond water is more dilute and it may be more representative of surface runoff from the heavy rains that preceded our June 1995 visit. The high chloride and sodium content of these water samples relative to their calcium and bicarbonate content strongly suggests that oilfield brine is a significant component of the water (Bingham and Bergman, 1980).

Site OS95-4

This site (Fig. 1B, Fig. 5, Fig. 6) lies near the crest of an open, broad, grassy, north-trending ridge (west edge of NE/4, SW/4, section 34, T22N, R10E). A poorly maintained dirt road passes along the east edge of the site. No abandoned oilfield equipment remains on site, but active power lines and an oil pipeline cross it. On the west side of the ridge are two salt scars which have been deeply eroded, exposing underlying shale and

Table 3- Trace element data for soil and pipe scale samples from various sites in the Wildhorse field.
ND- not detected.

				Site OS95-3							
Sample	Location	Fe (%)	Cu (ppm)	Pb (ppm)	Zn (ppm)	Cd (ppm)	Zr (ppm)	Sr (ppm)	Ba (ppm)	Br (ppm)	I (ppm)
OS95-1H	0 m	1.2	35	<40	85	1	505	140	1050	ND	10,20
OS95-1G	10 m	1.5	70	<40	210	<1	500	305	3250	ND	5,10
OS95-1F	20 m	0.8	<20	<40	50	<1	340	150	1200	5,20	5,10
OS95-1E	30 m	1.7	35	50	60	<1	405	275	1500	40,50	5,10
OS95-1D	40 m	0.4	<20	<40	<40	<1	425	50	115	10,20	ND
OS95-1C	Creek	14.2	230	100	40	<1	<10	22500	>30000	10,50	10,20
				Site OS95-4							
Sample	Fe (%)	Cu (ppm)	Pb (ppm)	Zn (ppm)	Cd (ppm)	Zr (ppm)	Sr (ppm)	Ba (ppm)	Br (ppm)	I (ppm)	
OS95-2	0.8	50	<40	<20	<1	185	185	610	ND	ND	
				Site OS95-14							
Sample	Fe (%)	Cu (ppm)	Pb (ppm)	Zn (ppm)	Cd (ppm)	Zr (ppm)	Sr (ppm)	Ba (ppm)	Br (ppm)	I (ppm)	
OS95-4B	1	30	40	65	<1	560	220	2790	ND	ND	
OS95-4C	3.9	120	190	265	<1	335	520	7050	ND	ND	
OS95-4D	1.2	40	40	45	<1	540	145	1940	ND	ND	
OS95-4E	0.8	<20	<40	<40	<1	495	80	730	ND	ND	

Table 4- Chemical data for three water samples from two sites in the Wildhorse field.

Sample number	Location	Field pH	Field conductivity µS/cm	Ca (ppm)	K (ppm)	Mg (ppm)	Na (ppm)	Sr (ppm)
OS95-3W	Creek	8	2700	80	5.1	21	430	3.6
OS95-3AW	Pond	8.3	515	30	0.5	16	80	1.1
OS95-14	Creek	6.5	6900	120	7.2	27	1200	5.4
				Continued				
Sample number	Location	Cl (ppm)	SO4 (ppm)	HCO3 (ppm)	Br (ppm)	F (ppm)	TDS (ppm)	Ra-226 (pCi/L)
OS95-3W	Creek	650	20	130	1.4	tr	1341.1	1.3±0.02
OS95-3AW	Pond	100	1.7	70	0.8	tr	300.1	1.8±0.02
OS95-14	Creek	1800	12	30	13	0.5	3215.1	1.6±0.01

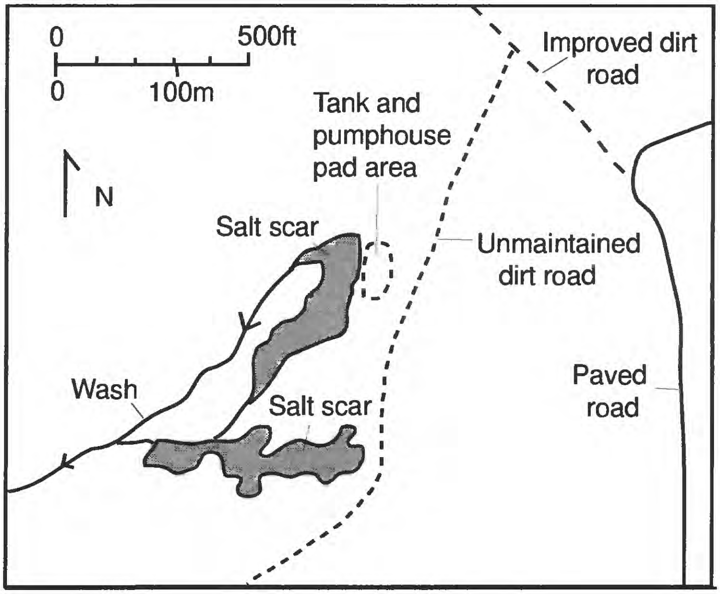


Figure 5- Sketch of features at and surrounding site OS95-4. Sketch is created from 1991 aerial photos of site provided by Raymond Lasley, Branch of Minerals, Bureau of Indian Affairs, Osage Indian Agency, Pawhuska, Oklahoma. The unmaintained dirt road follows the crest of the ridge. Shaded areas- salt scars. See Fig. 1B for location.

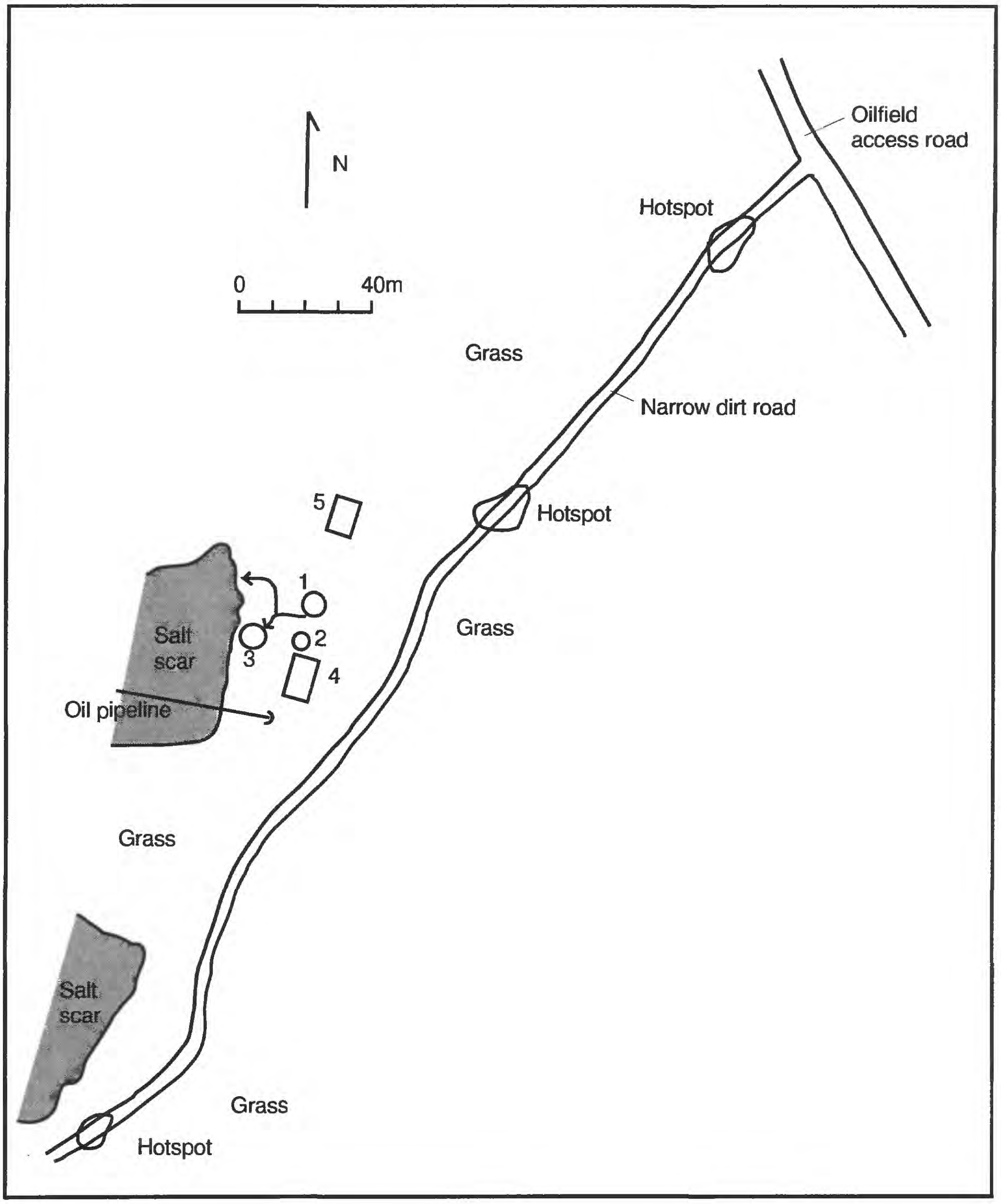


Figure 6- Detailed map of features adjacent to the road and salt scars with emphasis on radioactive localities. Shaded areas- salt scars. 1,2,3- Circular gravel tank pads; 4- concrete pumphouse pad mostly covered by a layer of greenish gray gravel; 5- concrete pumphouse pad.

sandstone. These salt scars are in the advanced stage of erosion. Washes in both salt scars drain west and southwest. Two rectangular concrete pads and 3 circular tank pads occur along the eastern edge of the northern salt scar (Fig. 6). One of the concrete pads (4, Fig. 6) and its adjacent area have been covered with a thin layer of gray gravel that has an oily, sandy matrix. The concrete pads probably supported pumping houses. Pieces of pump rod lay on the site locally. Piles of sandstone blocks have been dumped at the heads of two washes in the east half of the southern salt scar, apparently to arrest headward erosion. A few wet, seepy areas with salt crusts occur in the southern salt scar.

Three oval areas of radioactive soil occur along the road ("hotspot", Fig. 6). The two more northerly hotspots are about 15-20 m long and 8-12 m wide. The southerly hotspot is about 10 m long and 5-6 m wide. Maximum surface readings at all three sites are 1,500 μR/hr. The three hotspots contain a surface layer of gray gravelly material. A hole dug at the hottest surface point in the middle "hotspot" (the southwest corner) showed 8 cm of loose greenish gray gravel with a sandy matrix, 5 cm of cemented greenish gray gravel, and 3 cm of orange-weathered sandstone. The maximum radioactivity reading in the hole was 3,100 μR/hr at 7 cm.

The circular tank pad at site 1 (Fig. 6) is about 4.6 m in diameter. A pile of scaly material 1m by 2m lies at the south edge of the pad and shows maximum radioactivity of 2200 cps (360 μR/hr). A long, perforated pipe 3 m long with abundant scale in it reads 4350 cps (620 μR/hr). The surface of the tank pad at site 2 is about 4.3 m in diameter and it ranges from 100-750 cps (20-130 μR/hr). Tank pad 3 is about 6.1 m in diameter and it ranges from 1500-6700 cps (250-600 μR/hr). Values greater than 1000 cps (175 μR/hr) extend 1-3 m away from the edge of the pad on its south and southwest edges.

The rectangular pad at site 4 is a partly covered, concrete pad 16 m x 9 m. Most of the pad is thinly covered with the gray gravelly material described above. Radioactivity across the entire pad is elevated, with the gravel-covered part of the pad everywhere exceeding 1,000 cps (175 μR/hr). The most radioactive portion, just north of a juniper tree at the eastern edge of the pad, reads >10,000 cps (1400 μR/hr).

Laboratory radiometric analysis of a sample of the gray gravelly material with some oily, sandy matrix from this 1400 μR/hr spot (OS95-2) yielded 95±1 pCi/g radium-226 and undetectable radium-228 (Thomas Kraemer, U.S. Geological Survey, written commun., 1995). This same sample contained modest concentrations of iron (0.8%), copper (50 ppm), zirconium (185 ppm), strontium (185 ppm), and barium (610 ppm) and undetectable lead, zinc, and cadmium (Table 3). The relatively low radium activity for the whole sample suggests that the gray gravel itself is not very radioactive, but that the sandy oily matrix is.

A replicated gamma-spectrometer reading at the north edge of the site 4 pad yielded average values of 262 pCi/g radium-226 and 9.5 pCi/g radium-228 ("Pad site" and "Rep", Table 5). Gamma-spectrometer readings were not possible at the location with the highest scintillometer readings.

Table 5- Gamma-spectrometer data for selected stations at Site OS95-4, Wildhorse field.
1 ppm eU= 0.33 pCi/g eRa-226. 1 ppm eTh= 0.11 pCi/g eRa-228.
The boulder site and the seep site are in the southern salt scar (Fig. 5A).

Location	eU (ppm)	eTh (ppm)	eRa-226 (pCi/g)	eRa-228 (pCi/g)	Ra-228/Ra-226	Total radium (pCi/g)
Pad site	789.3	82.3	263.10	9.14	0.0348	272.24
Replicate	781.5	87.9	260.50	9.77	0.0375	270.27
Boulder site	151	15.7	50.33	1.74	0.0347	52.08
Seep site	190.9	18.9	63.63	2.10	0.0330	65.73

The second rectangular concrete pad (5, Fig. 6) showed no radioactivity above background.

Gamma-spectrometer measurements were made at two localities near the eastern end of the southern salt scar: one near the head of the wash, and the other at a salt-encrusted seep. The first locality yielded 50 pCi/g radium-226 and 1.7 pCi/g radium-228; the second, 64 pCi/g radium-226 and 2.1 pCi/g radium-228 (Table 5). The radium-228/radium-226 values at all three sites are consistent and very low (about 0.034) suggesting a common age of radium addition and subsequent decay of radium-228.

Site OS95-5

This site (Fig. 1B, Fig. 7) is located on the west side of Wildhorse Creek adjacent to a dirt road that skirts the edge of the sandstone bluff that overlooks the creek (SE/4, sec 32, T22N, R10E). Located at this site is a single brine injection well, a valve, valve assembly, brine pipelines, and oil pipelines. An active salt scar extends downslope from the injection well, the valve at the north end of the site, and the valve assembly at the south end of the site (Fig. 7). This site is in the advanced stage of erosion. A grassy area lies between and surrounds the salt scarred areas. An area of grass with dead oak stumps lies east of the valve at the north end of the site. An oak forest surrounds the entire site. At the time of our 1995 visit, produced water was actively leaking from the injection wellhead and some of the valves. The site was visited again in 1996.

Background at the site was 14 cps (2 μR/hr). Radioactivity in damp, clayey sediment in the salt scar adjacent to the injection well was 100-150 cps (20-30 μR/hr) in 1995 and 100-300 cps in 1996 (20-55 μR/hr). An adjacent oil pipe leaked between our 1995 and 1996 visits and a small oil spill developed across the salt scar adjacent to the injection well and down the wash east of the injection well. A patch of hot soil 30 cm by 50 cm within this oily area read 4000 cps (525 μR/hr). One active produced-water pipe read 1700 cps (280 μR/hr), with a salt-encrusted leaky joint along the pipe reading 2500 cps (380 μR/hr). Another pipe read 2200 cps (350 μR/hr). Older, used pipe on the site read as much as 3600 cps (about 500 μR/hr). Exposed scale at the end of this pipe read 4000 cps (525 μR/hr). The valve assembly read 30-65 cps (8-14 μR/hr).

Site OS95-6

This site (Fig. 1B) consists of a large tank battery surrounded by a soil berm. It is located just south of a well-maintained dirt road (NE/4, NW/4, NW/4 of sec 4, T21N, R10E). Salt-scarred soil extends downslope south and east of the bermed area. The site is underlain by shale. This site is in the intermediate stage of erosion. Local background on apparently uncontaminated soil upslope from the site is about 16 cps (5 μR/hr). Clayey sediment in the salt scar reads 30 cps (8 μR/hr). Radioactivity at the base of the separator tank ranges from 70-180 cps (15-35 μR/hr). The base of the water storage tank reads 50-60

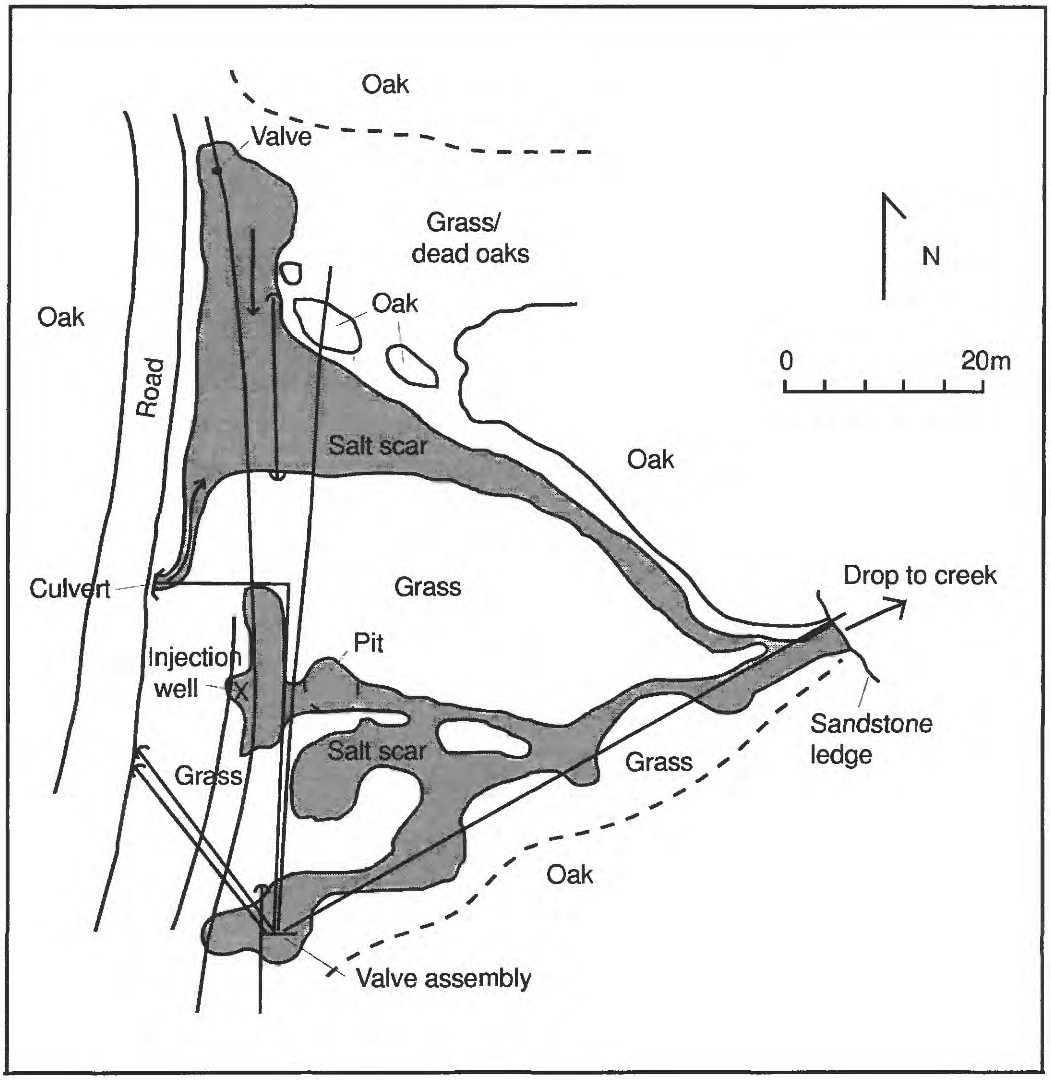


Figure 7- Map of features at site OS95-5. The salt-scarred area is shaded. During the 1996 visit an area of spilled oil (not mapped) occurred near the injection well. See Fig. 1B for location.

cps (11-13 μR/hr). The oil storage tank reads 10 cps (4 μR/hr). Soil near one of the tanks which is contaminated with oily and scaly material (possibly discarded tank sludge) reads as much as 230 cps (45 μR/hr). Sediment in the berm of an old overflow pit to the east of the tank battery reads about 30 cps (8 μR/hr).

Site OS95-7

This site (Fig. 1B) is an operating tank battery comprised of 4 oil tanks, 1 separator, and 1 water storage tank located (NW/4, SE/4, NE/4, section 35, T22N, R10E). A large salt scar extends east from the tank battery. This site is in the advanced stage of erosion. Clayey beds exposed in the salt-scarred soils underlie the site and give scintillometer readings about 50 percent above values at the reference site. The base of the brine storage tank reads 120-180 cps (24-35 μR/hr) whereas the separator tank reads 80-100 cps (17-21 μR/hr). Oil-stained soil occurs in the salt scar about 50 m downslope from the tank battery.

Site OS95-8

This site (Fig. 1B) includes a wellhead with an adjacent retaining pond (SE/4, NE/4, NE/4, section 35, T22N, R10E). *Typha* are growing in the pond bottom. No radioactivity above reference background was observed on the wellhead, on old pipe on the site, or in sediment in the pond bottom. A salt scar extends downslope from the site to the stream below. This site is in the advanced stage of erosion.

Site OS95-9

This site (Fig. 1B) consists of an active wellhead, an injection well, a storage tank, and a retaining pond (SW/4, NW/4, NW/4, section 36, T22N, R10E). An oil film covers the surface of the pond water. Salt crystals occur on damp soil adjacent to the wellhead. The wellhead and the tank read about 30 cps maximum (about 8 μR/hr). This site is in the intermediate stage of erosion.

Site OS95-10

An active tank battery at this site (Fig. 1B) is composed of 2 oil tanks and 1 separator tank on a graded hillslope (NE/4, NW/4, SW/4, sec 36, T22N, R10E). An older rusted-out tank is also present. No counts above the reference site background were observed on any of this equipment or on the nearby soils. No salt scar is present.

Site OS95-11

This site consists of a section of radioactive road surface (Fig. 1B). The radioactivity occurs along a section line road on the south edge of SE/4, SW/4 of section 26, T22N, R10E. The radioactive area covers several square meters with maximum radioactivity of 2100 cps (about 330 μR/hr). No features are present to distinguish the radioactive road surface from adjacent areas.

Site OS95-12

This site consists of another section of highly radioactive road surface (Fig. 1B). The radioactivity occurs along a section-line road on the south edge of SW/4, NW/4 of section 34, T22N, R10E. The radioactive area covers a few square meters with maximum radioactivity of 8500 cps (about 850 μR/hr). No features are present to distinguish the radioactive road surface from adjacent areas. The radioactivity at this site and the previous site suggest that radium-bearing brine solids were transported from oilfield production sites and that some spillage occurred.

Site OS95-13

This site (Fig. 1B) includes an area about 140 m by 70 m comprised of several linear salt scars on a gentle hillslope with extensive erosion along them and along a wash interconnected with them (SW/4, NW/4, SW/4, section 33, T22N, R10E). The site is at an advanced stage of erosion. Reconnaissance with the scintillometer showed no radioactivity greater than 10-20 percent above the reference site background.

Site OS95-14

This site (Fig. 1B, Fig. 8) is located on the west flank of the crest of a north-trending ridge (SE/4, NW/4, NE/4 section 33, T22N, R10E). The site is at the west edge of a graded area along the crest of the ridge that is covered by crushed rock. At the south end of the graded area lies a single active tank, however discarded equipment onsite suggests that tank batteries were sited along the ridge to the south and north of the present tank. Downslope to the west is a salt scar that trends west, then northwest away from the graded area (Fig. 9). At the low end of the salt scar, a small wash has formed which carries away sediment from the site during runoff events. Depth of erosion on the salt scar reaches a maximum of about 1 m. Sandstone bedrock is exposed across much of the scar, but a thin veneer of sand fills lower areas and remnants of oily sandy soil are present on the bedrock surface. A small creek lies to the west of the large scar (Fig. 8 and 9). This creek heads in some exposed sandstone bedrock ledges at the low end of a smaller salt-scarred area southwest of the main salt scar. Below the bedrock ledge this drainage has cut a channel in the valley floor. This drainage and the drainage from the larger salt scar merge downvalley to the northwest (Fig. 8). This site is at an advanced stage of erosion.

Most of the salt-scarred area immediately west of the graveled tank battery site was mapped in detail, surveyed, and sampled (Fig. 9,10). In the salt-scarred area, oily soil has been bulldozed into a single large pile that lies within the salt scar and into three other piles that lie at the west edge of the salt scar. This oily soil appears to be the remnants of spilled oil and tank sludge at the site. This oil spill can be seen intact in 1991 aerial photos (in possession of Ray Lasley, June 1995, Branch of Minerals, Bureau of Indian Affairs, Pawhuska, Oklahoma). Pooled oil occurs in three places on these piles and in the smaller salt scar to the southwest (Fig. 9). A thin intact layer

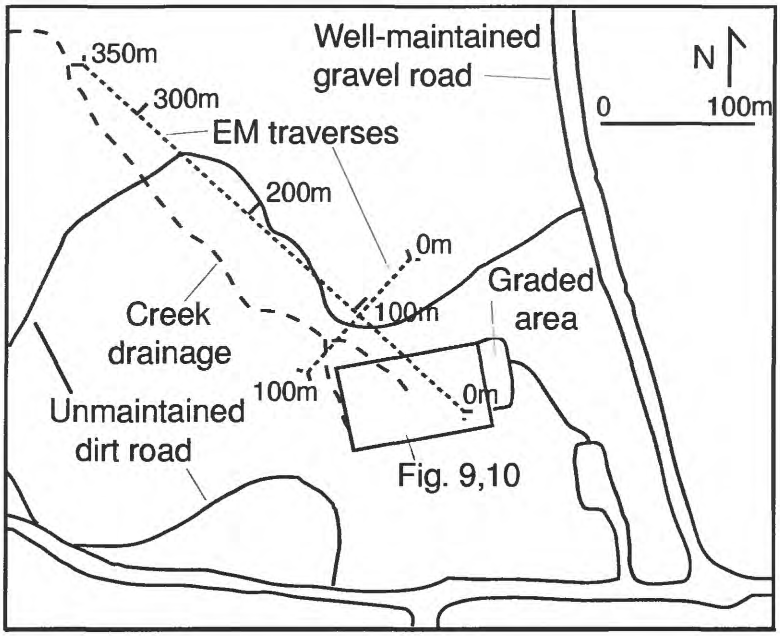


Figure 8- Sketch showing overview of location at Site OS95-14 and location of EM-31 traverses (short-dashed lines). Graded area is approximately located. Sketch is created from 1991 aerial photos of site provided by Raymond Lasley, Branch of Minerals, Bureau of Indian Affairs, Osage Indian Agency, Pawhuska, Oklahoma. See Fig. 1B for location.

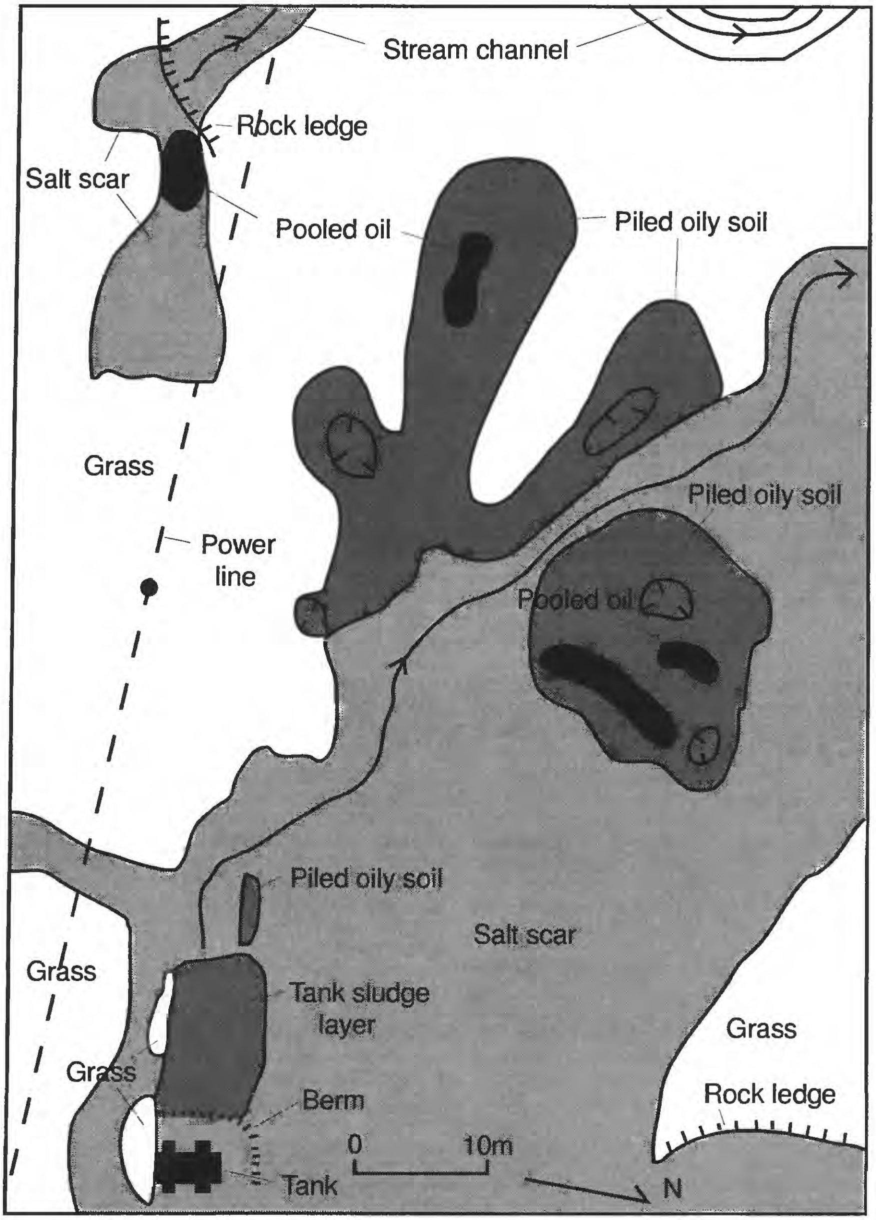


Figure 9- Detailed map showing natural and cultural features at Site OS95-14 in June of 1995. Arrowed line shows the general trend of well-defined surface drainage on the salt scar. Light shading- salt scarred area; medium shading- areas of oily soil including a layer of tank sludge; black- pooled oil.

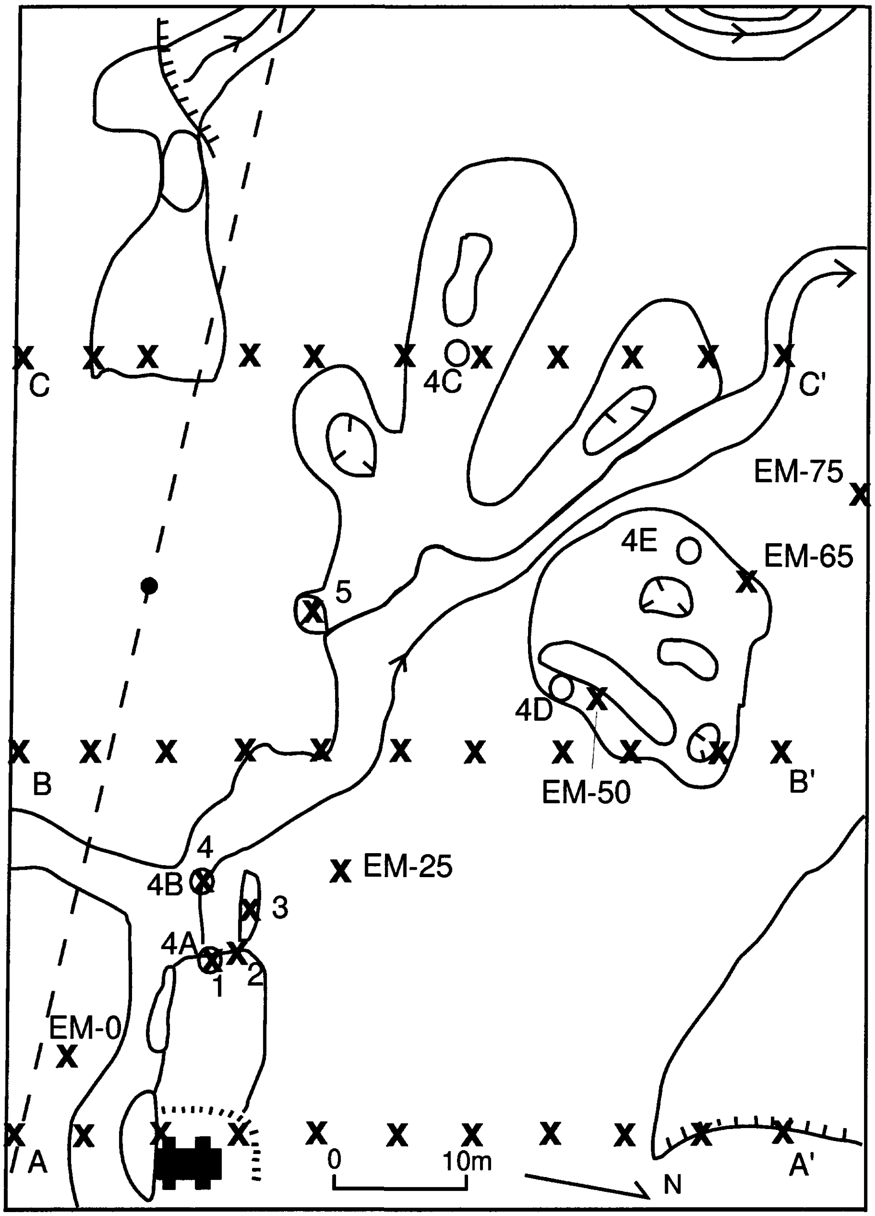


Figure 10- Detailed map showing survey and sample locations at Site OS95-14. x- Gamma-spectrometer stations. o- soil sample stations (4A-4E). The stations labeled EM are also locations for a soil conductivity survey. Refer to Fig. 9 for description of associated natural and cultural features.

of weathered oily soil with abundant flakes of scale or sludge in it extends from the west side of the berm of the active tank battery downslope about 10 m to the west. At its western edge, this layer is about 6 cm thick.

Gamma-spectrometer measurements were made at selected sites within the salt scar and along three north-south profiles (A-A',B-B',C-C', Table 6, Fig. 10, Fig. 11, and Fig. 12) across the salt scar. They were also made at five soil conductivity stations (EM-0-EM-75) that cross the area of Fig. 10 along a diagonal (Table 6, Fig. 10, and Fig. 13). Water was sampled from a pool in the creek just below the bedrock ledge (Fig. 9). Field pH was circumneutral (pH=6.5), field conductivity equaled 6900 µS/cm, and radium-226 activity equaled 1.6±0.1 pCi/L. This water (OS95-14, Table 4) is moderately saline (TDS=3215 ppm) with major Na-Cl and lesser Ca^{+2}, SO_4^{-2}, and HCO_3^-. Br and F are present. These data suggest that oilfield brine is a major component of the water sampled.

Five soil samples (OS95-4A-E, Fig. 10) were taken from the site. One sample (OS95-4A) was measured for radium and the others were submitted for analysis of iron and trace elements (Table 3). Sample OS95-4A was taken at the lower edge of the thin layer of weathered oily soil mentioned above. Laboratory radiochemistry shows that it contains 1497±61 pCi/g radium-226 and 115±1 pCi/g radium-228 (Thomas Kraemer, USGS, written commun., 1995).

Profiles for total radium (gamma-spectrometer traverses A-A', B-B', and C-C') are shown in Fig. 11. Profile A-A' shows the highest total radium concentrations in two stations near the south edge of the salt scar at the foot of the present tank (480 and 40 pCi/g). The rest of the values are in the 3-15 pCi/g range, with the exception of the northernmost station which registered 1.14 pCi/g. This station was located on a sandstone bedrock ledge at the boundary of the graveled area to the east and grassy hillslope to the west. This latter radium value probably approximates the local background for this site.

Profile B-B' also shows highest total radium values at the south edge of the salt scar (53 and 19 pCi/g) and elevated values near the south edge of the waste pile. The 53 and 19 pCi/g sites receive detritus that is eroding from the weathered oily soil layer upslope. The station at the north end of this profile has the least total radium although the station is still within the salt scar. Along profile C-C' elevated total radium values occur in the waste piles or at their margins. The station at the north end of this profile contains 4.38 pCi/g total radium. Detritus washed down from the weathered oily soil layer upslope is visible at this station.

The radium-228/radium-226 data for these same profiles are shown in Fig. 12. In profile A-A', radium-228/radium-226 values are below 0.4 except for the northernmost station (60/00m) which approaches the ratio at the reference site. This latter value (1.02) may approximate the local background ratio. This value is above the median ratio (0.72) for the Barnsdall Formation in the NURE dataset (Texas Instruments, Inc., 1978). In profile B-B' the ratio is again below 0.4 for the samples across the heart of the salt scar (12/30-54/30m), but is above 0.4 in the grassy areas

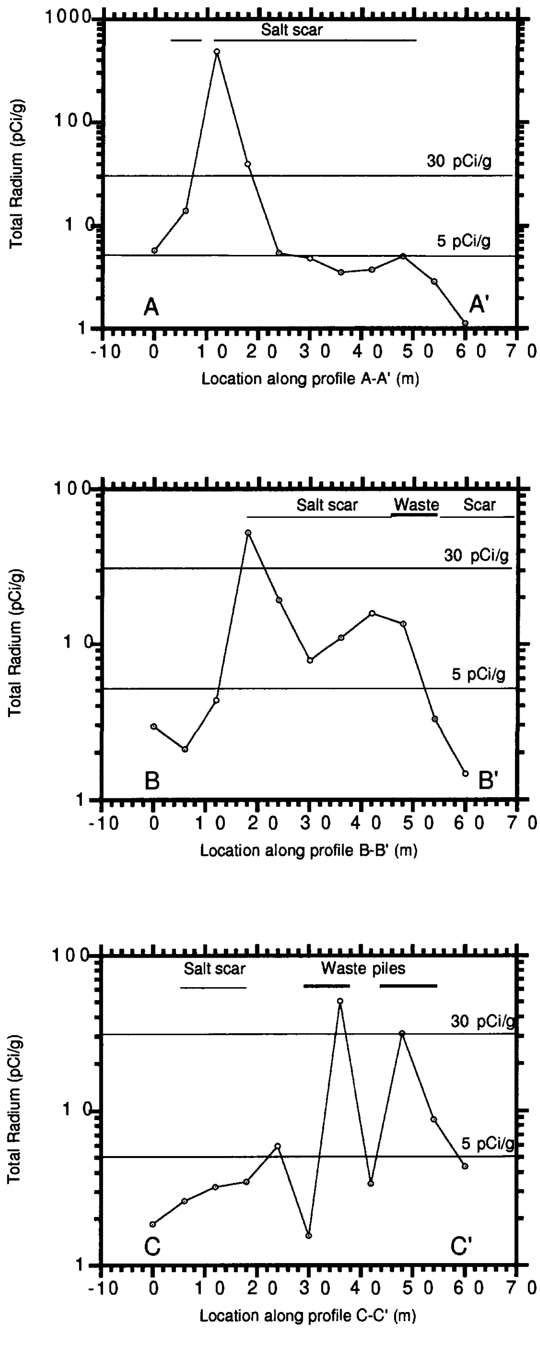


Figure 11- Profiles of total radium along gamma-spectrometer traverse lines (A-A', B-B', and C-C') at Site OS95-14. See Fig. 10 for location of survey sites. The 5 and 30 pCi/g lines are shown for reference to proposed national and Oklahoma standards for radium in soils.

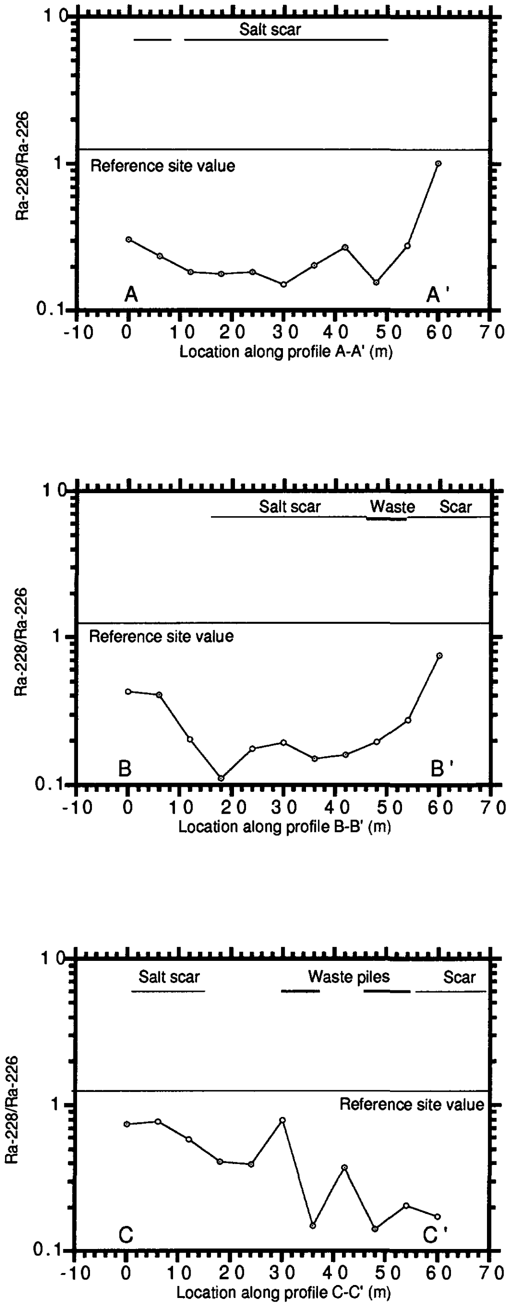


Figure 12- Profiles of radium-228/radium-226 along gamma-spectrometer traverse lines (A-A', B-B', and C-C') at Site OS95-14. See Fig. 10 for location of survey sites.

Table 6- Gamma-spectrometer data for Site OS95-14, Wildhorse field.
1 ppm eU= 0.33 pCi/g eRa-226. 1 ppm eTh= 0.11 pCi/g eRa-228.
Locations are shown in Fig. 10.

Location	eU (ppm)	eTh (ppm)	eRa-226 (pCi/g)	eRa-228 (pCi/g)	Ra-228/Ra-226	Total radium (pCi/g)
A 00/00m	13.30	12.20	4.43	1.36	0.3058	5.79
06/00m	34.40	24.40	11.47	2.71	0.2364	14.18
12/00m	1217.00	666.00	405.67	74.00	0.1824	479.67
18/00m	101.00	53.90	33.67	5.99	0.1779	39.66
24/00m	13.80	7.60	4.60	0.84	0.1836	5.44
30/00m	12.60	5.70	4.20	0.63	0.1508	4.83
36/00m	8.80	5.40	2.93	0.60	0.2045	3.53
42/00m	8.90	7.20	2.97	0.80	0.2697	3.77
48/00m	13.10	6.10	4.37	0.68	0.1552	5.04
54/00m	6.80	5.70	2.27	0.63	0.2794	2.90
A' 60/00m	1.70	5.20	0.57	0.58	1.0196	1.14
B 00/30m	6.20	7.90	2.07	0.88	0.4247	2.94
06/30m	4.50	5.50	1.50	0.61	0.4074	2.11
12/30m	10.80	6.60	3.60	0.73	0.2037	4.33
18/30m	142.50	47.40	47.50	5.27	0.1109	52.77
24/30m	49.40	26.10	16.47	2.90	0.1761	19.37
30/30m	19.70	11.40	6.57	1.27	0.1929	7.83
36/30m	28.70	13.00	9.57	1.44	0.1510	11.01
42/30m	41.00	19.70	13.67	2.19	0.1602	15.86
48/30m	34.10	20.00	11.37	2.22	0.1955	13.59
54/30m	7.70	6.40	2.57	0.71	0.2771	3.28
B' 60/30m	2.50	5.60	0.83	0.62	0.7467	1.46
C 00/60m	3.20	7.10	1.07	0.79	0.7396	1.86
06/60m	4.40	10.30	1.47	1.14	0.7803	2.61
12/60m	6.10	10.60	2.03	1.18	0.5792	3.21
18/60m	7.40	9.10	2.47	1.01	0.4099	3.48
24/60m	12.80	15.00	4.27	1.67	0.3906	5.93
30/60m	2.60	6.20	0.87	0.69	0.7949	1.56
36/60m	132.50	59.20	44.17	6.58	0.1489	50.74
42/60m	7.40	8.30	2.47	0.92	0.3739	3.39
48/60m	82.20	34.70	27.40	3.86	0.1407	31.26
54/60m	21.90	13.60	7.30	1.51	0.2070	8.81
C' 60/60m	11.20	5.80	3.73	0.64	0.1726	4.38
EM-00m	47.90	19.90	15.97	2.21	0.1385	18.18
EM-25m	72.20	16.00	24.07	1.78	0.0739	25.84
EM-50m	36.20	19.60	12.07	2.18	0.1805	14.24
EM-65m	3.00	4.90	1.00	0.54	0.5444	1.54
EM-75m	3.40	4.50	1.13	0.50	0.4412	1.63
EM-100m	4.40	4.80	1.47	0.53	0.3636	2.00
EM-125m	2.00	3.50	0.67	0.39	0.5833	1.06
Spot-1	2002.00	922.00	667.33	102.44	0.1535	769.78
2	1039.00	467.00	346.33	51.89	0.1498	398.22
3	224.60	103.20	74.87	11.47	0.1532	86.33
4	40.10	15.50	13.37	1.72	0.1288	15.09
5	52.80	24.20	17.60	2.69	0.1528	20.29

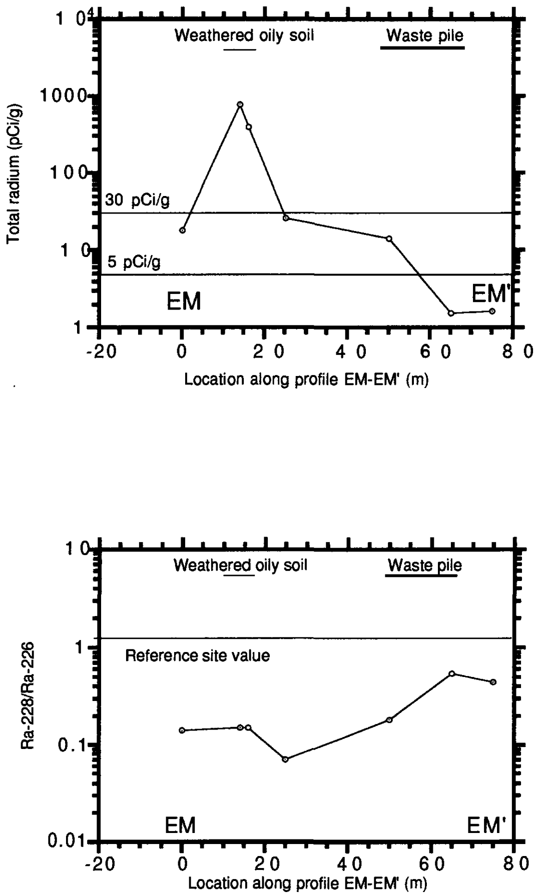


Figure 13- Profiles of total radium and radium-228/radium-226 along a gamma-spectrometer traverse (EM0-EM75, Fig. 10). This line parallels the southeast part of the EM-31 traverse line.

to the south and is above 0.72 for the salt scar site at the north end. In profile C-C', the only values below 0.4 are observed at the stations on the waste piles, between them, or in the salt scar to the north. Stations on the grassy areas and the upper part of the smaller salt scar range from 0.4-0.8.

Total radium data for the diagonal profile through the soil conductivity stations (EM-0 to EM-75) are portrayed in Fig. 13 (Table 6). Data from two spot localities (1,2, Table 6) on the weathered oily soil between EM-0 and EM-25 are included in this profile. The highest radium is observed on the weathered oily layer soil downslope from the tank (Spot 1). Lowest radium occurs at the station on the northwest side of the large waste pile (EM-65) and on the exposed bedrock in the adjacent salt scar (EM-75). Readings for radium-228/radium-226 are below 0.4 for most of the profile except for EM-65,75 where values range from 0.4-0.6.

Areas exceeding 5 pCi/g and 30 pCi/g in the gamma-spectrometer data are shown in Fig. 14. Highest levels of radium (>30 pCi/g) are associated with 1) the thin layer of weathered, oily soil that occurs immediately west of the tank, 2) the areas downslope from this layer which have received weathered fragments transported by slopewash, and 3) the two waste piles west of the main salt scar. Areas presently vegetated with grasses along the southeast edge of Fig. 14 have elevated levels of radium (5-30 pCi/g) and this area of elevated radium extends off the area of Figure 14 to the south and east.

Fig. 14 illustrates the different-sized areas that would have to be remediated at the proposed thresholds of 5 and 30 pCi/g using gamma spectrometry as the assessment method. The areas could differ if core sampling and laboratory analyses were performed as required in Louisiana state regulations. The areas may also differ if the two thresholds were set as "above background" thresholds. The surface area within Fig. 14 underlain by material containing 5 pCi/g total radium or more is an estimated 2150 m^2 whereas the area underlain by material containing 30 pCi/g or more is an estimated 420 m^2.

Samples OS95-4B-E show varying amounts of iron, copper, lead, and zinc (Table 3). Sample OS95-4C, taken from a pile of oily soil on the west side of the salt scar, shows the highest levels of heavy metals. The lead concentration in this sample is about 50% of the remedial action level suggested by EPA for CERCLA and RCRA sites (400 ppm). This sample also contains relatively elevated barium and strontium concentrations suggesting that barite may be present in the soil. In contrast to Site OS95-3, Br and I were not detected in the soil samples.

A 350 m soil conductivity survey included a traverse of the study site and a continuation northwest down the axis of the drainage. An shorter perpendicular traverse intersected this longer traverse at the 100 m station (locations of the lines are shown in Fig. 8).

Soil conductivity measurements range from 9 mS/m at the northeast end of the crossing traverse to 158 mS/m at station 75m in the salt scar near the southeast end of the longer traverse (Tables 7 and 8, Figs. 15 and 16). Values for the shallower-

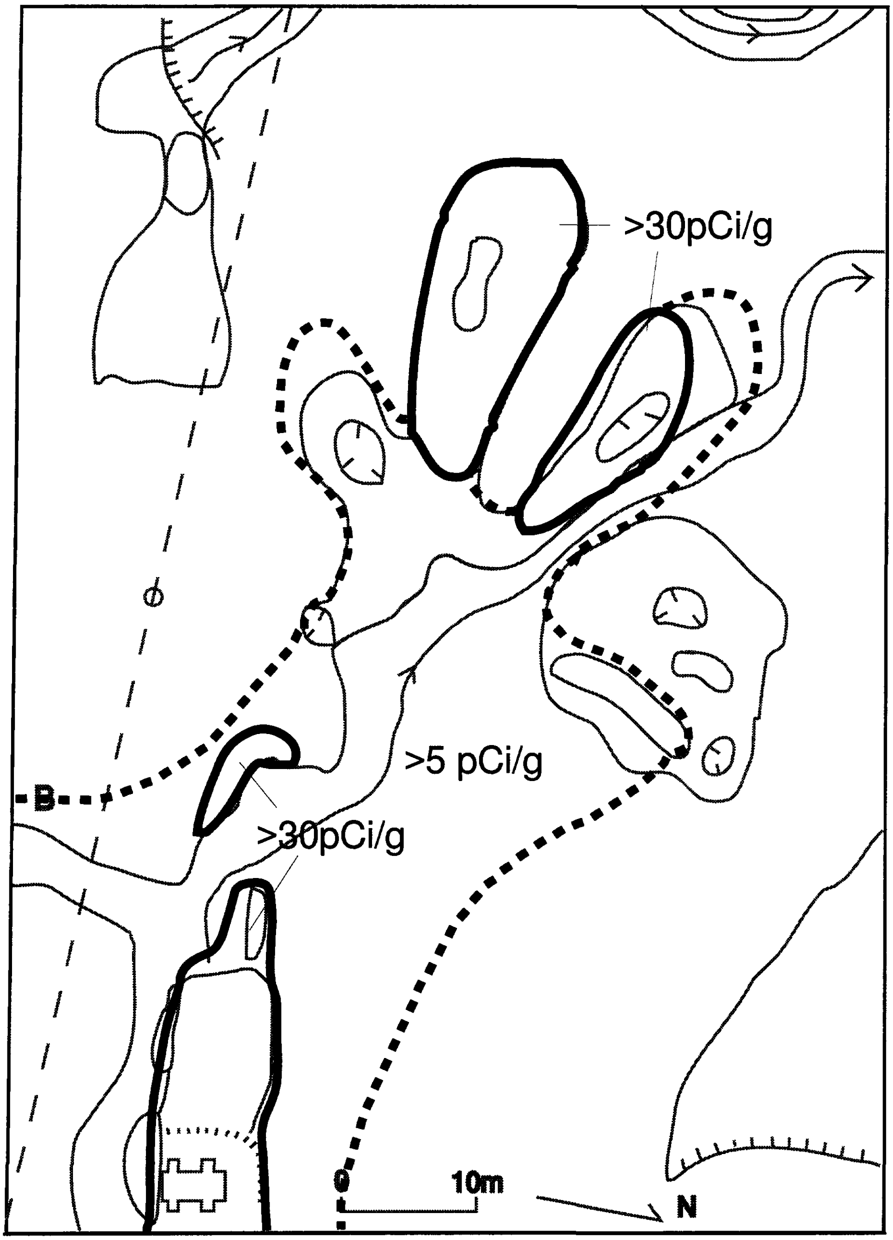


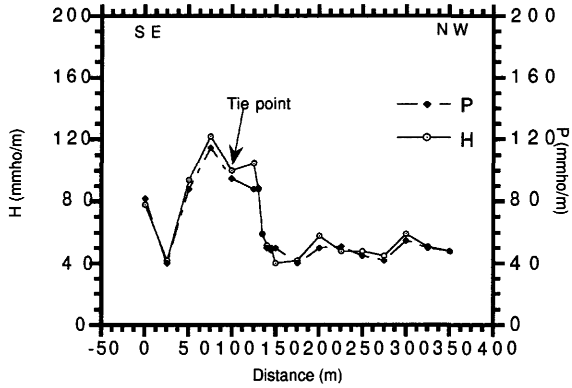
Figure 14- Detailed map showing areas where surface materials exceed 5 pCi/g (heavy dashed line) and 30 pCi/g (heavy solid line) at Site OS95-14. See Fig. 10 for location of data points used to contour the map.

Table 7- Conductivity measurements along a 350 m SE-NW traverse at Site OS95-14, Wildhorse field. See Fig. 8 for location.

Distance (m)	Conductivity values (mmho/m)				
along profile	Vertical dipole	Perpendicular	Horizontal dipole	Perpendicular	Notes
0	100	110	78	82	About 10 m west of tank.
25	62	60	42	40	Pipe parallel to traverse line at 5 m.
50	130	120	94	88	Small pit with water and oily sludge.
75	158	153	122	115	
100 (tie point)	150	148	100	95	
125	120	112	105	88	
130	98	95	88	89	
135	90	86	59	59	
140	71	72	52	50	
145	71	75	50	49	
150	65	70	40	50	11 m west of pumper, overhead power line.
175	74	72	42	40	
200	77	70	58	50	
225	68	67	48	51	
250	63	67	48	45	
275	70	68	45	42	
300	80	80	59	55	6 m from pumping unit, edge of stream.
325	70	69	51	50	Creek bottom on sandstone.
350	68	69	48	48	Creek bottom on bedrock.

Table 8- Conductivity measurements along a 100 m SW-NE traverse at Site OS95-14, Wildhorse field. See Fig. 8 for location.

Distance (m)		Conductivity values (mmho/m)			
along profile	Vertical dipole	Perpendicular	Horizontal dipole	Perpendicular	Notes
50 E	22	21	9	9	
25 E	58	58	30	39	
12.5 E	100	95	54	50	
0 (tie point)	145	150	95	100	
25W	90	90	70	69	
50W	70	62	29	29	Pipes 1-3 m away.



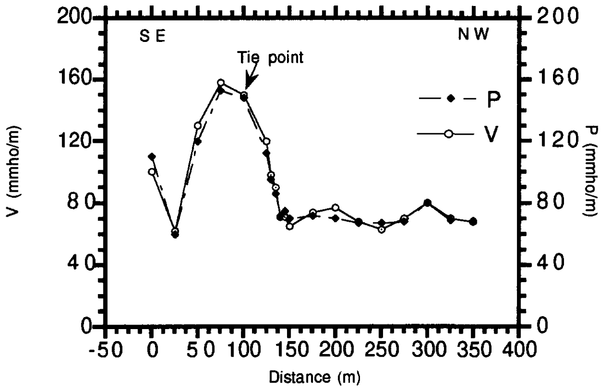


Figure 15- Profile showing EM-31 conductivity measurements along a 350 m SE-NW profile at site OS95-14, Wildhorse field, Osage County, Oklahoma. For location of the profile see Fig. 8. Data are in Table 6. Profile A- Measurements of conductivity for the horizontal dipole instrument orientation. H- horizontal measurement ; P- measurement at right angles to line of traverse. Effective depth of observation is 3m. Profile B- Measurements of conductivity for the vertical dipole instrument position. V- vertical measurement; P- measurement at right angles to line of traverse. Effective depth of observation is 6m.

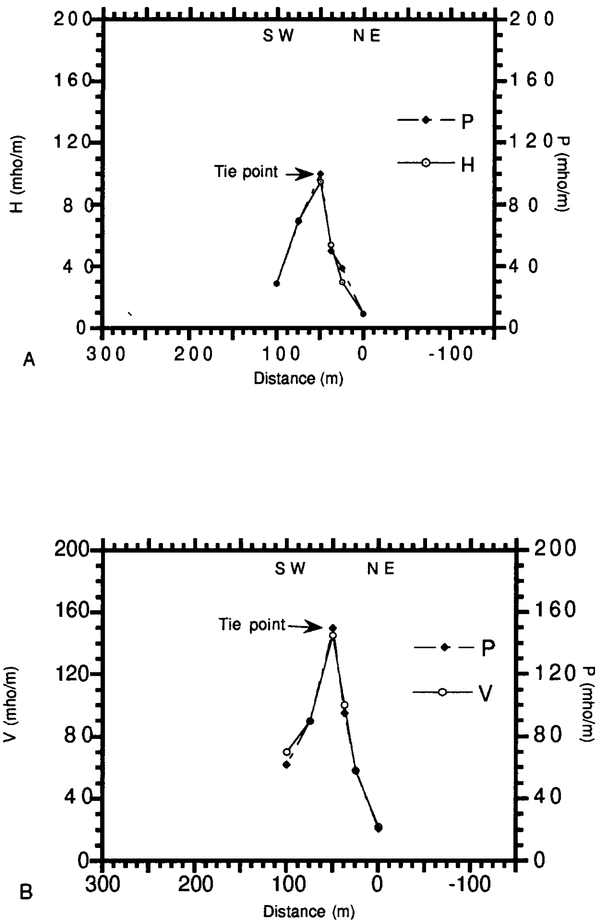


Figure 16- Profile showing EM-31 conductivity measurements along a 100 m profile perpendicular to the profile in Fig. 15. For location of the profile see Fig. 8. Data are in Table 7. Profile A- Measurements of conductivity for the horizontal dipole instrument orientation. H- horizontal measurement ; P- measurement at right angles to line of traverse. Effective depth of observation is 3m. Profile B- Measurements of conductivity for the vertical dipole instrument position. V- vertical measurement; P- measurement at right angles to line of traverse. Effective depth of observation is 6m.

looking horizontal-dipole mode (0-3 m) were consistently lower than the vertical dipole (0-6 m). This may indicate lower salt content of the near-surface soil possibly because of flushing of the salt with infiltrating precipitation. A sharp drop in both conductivity values occurs between stations at 100 m and 150 m in the longer profile. This is interpreted as marking the leading edge of brine-affected soil.

The crossing traverse shows highest conductivity values at the point of intersection with the longer traverse (0 m station, Table 8). This suggests that the zone of brine-affected soil and bedrock is relatively narrow at the 100m station, perhaps 20-30m wide. Lowest conductivity values occur at the northeast end of the crossing traverse. This station was on relatively well-drained sandy soils on the valley wall slope that showed no evidence of past brine movement.

BURBANK FIELD

The Burbank field lies mostly in the western part of Osage County (Fig. 1A) and extends from T27N, R5E in the eastern part of adjacent Kay County to the middle of T25N, R6E in Osage County. The field was initially developed from 1921 to 1923 with drilling on 10-acre centers. Production is from the Burbank sand at an average depth of 2900 feet. The average thickness of the sand is 47 feet. Gas injection in the field started in 1926 and continued into the early 1950s. Waterflooding started in late 1949 and was expanded to cover the whole field in the early 1950s. Throughout the surveyed area, it is apparent from the remains of old drilling roads and site access roads that oilfield equipment was formerly present at many sites that have been reclaimed by the operator.

Results

A brief examination of nine sites in the Burbank field (Fig. 17) was conducted by the senior author and Marvin Abbott (U.S. Geological Survey, Oklahoma City, Oklahoma) in September of 1995. All sites visited were in the central and southern part of the field. Active salt scars were fewer, typically much smaller, and less deeply eroded than at sites in the Wildhorse field.

Radiometric examination of equipment at an oil-production site (1, Fig. 17) showed that 2 separator tanks had radioactivity near their bases that ranged from 12-15 times background (N/2, SE/4, sec 8, T25N, R6E). An older, abandoned heater/treater tank lying on its side yielded maximum readings about 16 times local background. Adjacent to the heater/treater tank was a small salt scar. At the south edge of the scar, a few very small areas (<<1m^2) of slightly oily soil with flakes of scale or sludge read as much as 40 times local background (about 600-800 cps or 180-230 μR/hr). This site was in the intermediate stage of erosion.

A large produced-water storage tank (2, Fig. 17) showed no anomalous radioactivity (N/2, NE/4 of sec 9, T25N, R6E). An old separator tank at an oil production site (3, Fig. 17) read about 12 times background around its base (N/2, SW/4, sec 10, T25N,

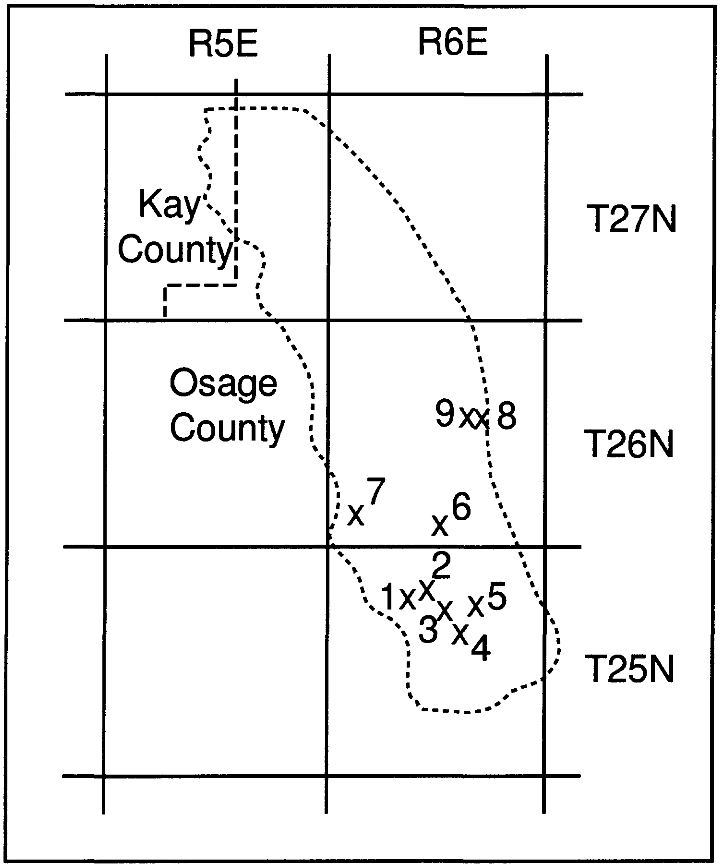


Figure 17- Map of the Burbank oilfield (dashed line) showing sites surveyed for radioactivity in the central and southern part of the field. See Figure 1A for location of the Burbank field in Osage County.

R6E). An operating separator tank at a site (4, Fig. 17) read 3-4 times background (N/2, NE/4, sec 15, T25N, R6E). A small separator tank with an associated minor salt scar (5, Fig. 17) was 2 times background at its base (SW/4, NW/4, sec 11, T25N, R6E).

Farther to the north, tanks in a tank battery (6, Fig. 17) yielded maximum readings about 5 times background (SW/4, NW/4, sec 34, T26N, R6E). All the tanks in a tank battery (7, Fig. 17) were at background (NW/4, NW/4, NW/4 of sec 32, T26N, R6E). A large tank battery (8, Fig. 17) showed tanks slightly above background (NE/4, NE/4, SW/4, sec 14, T26N, R6E). One tank was about 4 times background, the other three were 1-1.8 times background. A salt scar extends southeast away from the bermed area. Soil within this salt scar was 1-1.8 times background. An injection well site (9, Fig. 17) did not read above local background (SE/4, SE/4, NE/4 of sec 15, T26N, R6E), but local background was higher than at the reference site.

DISCUSSION AND CONCLUSIONS

In this study we compared radiometric readings at various sites to readings at a reference site. The natural radiochemical background for soils in Osage County is not known, yet if regulatory standards include reference to background or if cleanup at sites is designed to return the site to background levels, then establishment of background becomes very important because it may affect the volume of material to be removed and thus the costs of cleanup. Further work needs to be done to determine how field and laboratory gamma-spectrometry may be used to establish background radium concentrations in soils.

A field gamma spectrometer was used to measure radium-226 and radium-228 at several sites in this study. The results suggest that field gamma spectrometry can be used to screen sites for the presence of added radium-226 and radium-228 in soils. The inability to determine the radium content of discrete 15-cm-thick intervals limits the present usefulness of the technique in states that have or may adopt regulations that require core sampling and laboratory radiochemical analysis of such layers. However, this technique can be used to screen and prioritize sites to determine those in most need of immediate attention. At many sites study of the distribution of radium-bearing material in the soil profile may show that it is confined to layers whose thickness can be measured. If so, the radium content for that layer could be estimated from the thickness data and the gamma-spectrometer radium readings at the site.

The soil-conductivity readings can be used to determine the extent of saline soils at a site and the depth and the apparent direction of movement of the salts.

Salt scarring has caused erosion of the thin soils at eleven sites in the Wildhorse field. Erosion at most of these sites is in the advanced stages. Salt scarring probably extended beyond the limits of present-day scars at many older sites but some natural remediation has occurred. The aerial extent of past salt scars now revegetated could be determined by examining older aerial photos of these sites or by using gamma-spectrometer data in those areas where radium-bearing brines were involved. These areas may be indicated by anomalous radium-228/radium-226 values and elevated total radium.

Salt-scarred areas have contributed sediment to local washes and streams and probably have shortened the life of downstream stock tanks and reservoirs. These sediments may also have carried NORM and trace elements into these sediment traps. Where the geochemical environment of the stock pond or reservoir differs from soil conditions, radium and trace elements may be remobilized and present further hazards. Such effects are little studied and need further evaluation.

In the Wildhorse oilfield and, to a lesser degree, in the Burbank oilfield, radioactivity in some oilfield equipment and radium in soils exceed regulatory limits imposed in other states and limits proposed by the CRCPD (>5 pCi/g radium in surface layers, >25 μR/hr radioactivity) and, in some cases, exceed proposed limits for the state of Oklahoma (>30 pCi/g radium in surface layers, >50 μR/hr radioactivity). Among 14 sites studied in the Wildhorse field, oilfield equipment radioactivity or radioactivity in soils or on road surfaces exceeded 50 μR/hr at 10 of them. NORM levels in the Burbank field sites were generally lower.

Material interpreted as tank bottom sludges discarded on soils at production sites consistently contains the highest radium activities. As this material ages and weathers it can be transported downslope by slope wash processes. Equipment radioactivity is highest on old pipe with thick scale. Radioactive material of uncertain origin spilled on road surfaces at three sites may yield dust that can be inhaled by passersby.

TDS concentrations in small streams draining two sites in the Wildhorse oilfield (OS95-3 and OS95-14) exceed drinking water limits of 500 ppm. The water at these two sites is clearly affected by oilfield brine. Concentrations of radium-226 in three water samples from the two sites range from 1.3-1.8 pCi/L. Current USEPA radionuclide standards for radium-226 and radium-228 combined is 5 pCi/L. Radium-228 was not measured, but it seems likely that these waters do not exceed current radium standards as doubling the radium-226 values to allow for radium-228 still would not exceed the existing limits. New, proposed maximum contaminant levels for radium-226 and radium-228 in public water supplies are 20 pCi/L each.

The presence of radium and trace elements may influence the choice of remedial methods used to remove salts from brine-contaminated soils and ground waters. Amendments should be selected carefully to avoid mobilization of radium and to enhance fixation of iodine or other soluble trace elements that inhibit plant growth in soluble forms. Where soil radium levels are high, workers should avoid inhalation of dust

REFERENCES

Bingham, R.H., and Bergman, D.L., 1980, Reconnaissance of the water resources of the Enid quadrangle, north-central Oklahoma: Oklahoma Geological Survey Hydrologic Atlas Map HA-7, 4 plates, scale 1:250,000.

Bourlier, B.G., Nichols, J.D., Ringwald, W.J., Workman, P.J., and Clemmons, Stanley, 1979, Soil survey of Osage County, Oklahoma: United States Department of Agriculture, Soil Conservation Service and United States Department of the Interior, Bureau of Indian Affairs, 164 p.

Broecker, W.S., 1965, An application of natural radon to problems in ocean circulation, *in* Ichiye, T., ed., Symposium on Diffusion in Oceans and Fresh Waters: Lamont Geological Observatory, Palisades, NY., pp. 116-145.

Collins, A.G., 1975, Geochemistry of oilfield waters: New York, Elsevier, Developments in Petroleum Science, vol. 1, 475 p.

Fishman, M.J. and Pyen, G. (1979), Determination of selected anions in water by ion chromatography: U.S. Geological Survey Water Resources Investigations Report 79-101.

Fitterman, D.V., 1985, Mapping of brine contamination in Osage County, Oklahoma, using transient electromagnetic soundings: U.S. Geological Survey Open-File Report 85-210, 57 p.

Greater Egypt Regional Planning and Development Commission, 1982, An overview of oil field brine problems in three Illinois Counties: Carbondale, Illinois, Greater Egypt Regional Planning and Development Commission Publication No. GERPDC-82-626, 149 p.

Johnson, K.H., and Castagno, J.L., 1961, Developments in waterflooding and pressure maintenance in Osage County, Okla. oilfields, 1961: U.S. Bureau of Mines Information Circular 8038, 38 p.

McNeill, J.D., 1980a, Electromagnetic terrain conductivity measurement at low induction numbers: Mississauga, Canada, Geonics Limited Technical Note TN-6, 15 p.

McNeill, J.D., 1980b, Electrical conductivity of soils and rocks: Mississauga, Canada, Geonics Limited Technical Note TN-5, 22 p.

Michel, J., Moore, W.S., and King, P.T., 1981, Gamma ray spectrometry for determination of radium-228 and radium-226 in natural waters, Anal. Chem., v. 53, pp. 1885-1889.

Otto. G.H., 1989, A national survey on naturally occurring radioactive materials (NORM) in petroleum producing and gas processing facilities: Dallas, Texas, American Petroleum Institute, 265 p.

Raab, P.V., and Frischknecht, F.C., 1985, Investigation of brine contamination using time-domain electromagnetic soundings: U.S. Geological Survey Open-File Report 85-528, 54 p.

Rogers, V.C., and Nielson, K.K., 1995, Surveying for oil and gas NORM: what can be learned from gamma radiation measurements? *in* Environmental issues and solutions in petroleum exploration, production and refining, Proceedings of the Second International Petroleum Environmental Conference, September 25-27, 1995, New Orleans, LA, p.799-809.

Smith, G.E., Fitzgibbon, Timothy, and Karp, Steven, 1995, Economic impact of potential NORM regulations, *in* Proceedings of the SPE/EPA Exploration and Production Environmental Conference, 27-29 March 1995, Houston, Texas: Society of Petroleum Engineers, Richardson, Texas, SPE 29708, p. 181-194.

Texas Instruments, Inc., 1978, Aerial radiometric and magnetic reconnaissance survey of portions of the Great Plains and Central Lowlands, Enid Quadrangle: Department of Energy Report GJBX-100 (78), 127 p.

USEPA, 1993, Diffuse NORM wastes-Waste characterization and preliminary risk assessment: United States Environmental Protection Agency, Office of Radiation and Indoor Air, Washington, D.C.

USEPA, 1994, Revised interim soil lead guidance for CERCLA sites and RCRA corrective action facilities: Office of Solid Waste and Emergency Action, U.S. Environmental Protection Agency, Washington, D.C., OSWER Directive #9355.4-12.

Wright, Jack, Pearson, Cynthia, Kurt, E.T., and Watkins, J.W., 1957, Analyses of brines from oil-productive formations in Oklahoma: U.S. Bureau of Mines Report of Investigations 5326, 71p.