Comments on New Mexico "Produced Water" Rule by Justin Nobel, Science Journalist & Author of Upcoming Book on Oilfield Waste & Radioactivity

Good Day, My name is Justin Nobel. I have a dual master's degree in earth and environmental science and journalism, write regularly on issues of science and the environment for US magazines and investigative sites, recently published a lengthy story for Rolling Stone magazine entitled, "America's Radioactive Secret" on the issue of the radioactivity brought to the surface in oil and gas production and the many different pathways of contamination posed to the industry's workers, the public and communities, and the environment, and I am presently writing a book on this topic to be published with Simon & Schuster. Ladies and gentleman, it is pathetic that a journalist for a music magazine has been forced to break news that the America's oil and gas industry has known full-well for four decades.

I quote, "Almost all materials of interest and use to the petroleum industry contain measurable quantities of radionuclides that reside finally in process equipment, product streams, or waste. In addition, groundwater used for waterflood and brine solutions from operating wells contain biologically significant quantities of Radium 226 and Radon 222." These lines do not come from a research scientist at some eastern university far removed from the oil patch, they do not come the newsletter of some environmental action group which may have a vested interest in halting oil and gas production. These lines, in fact, come from a 1982 report of the Department of Medicine and Biology, of the American Petroleum Institute. Apparently, the New Mexico Energy, Minerals and Natural Resources Department and the Oil Conservation Commission are unaware of this vital research by the nation's foremost oil and gas industry experts. The American Petroleum Industry report goes on to describe the radioactivity risks of the industry's waste, quote, "Radium 226 is a potent source of radiation exposure, both internal and external…Radon 222 and its daughters cause the most severe impact to the public health."

The 1982 American Petroleum Institute report also invalidates the Department's plan, as laid out in this proposed rule, to, quote, "encourage the recycling or re-use of produced water." Again, I quote from the American Petroleum Institute report, "Any control methodology proposed for radioactive materials must recognize the fact that radioactivity can not be modified or made inert by chemical means. It also must recognize that radioactivity dissipates at fixed rates through fixed sequences or series. Decay to daughter products cannot be guaranteed to reduce the hazard..." And just a few lines later the American Petroleum Institute report points out that any attempt to remove radioactivity is merely transforming, quote, "a very dilute source of radioactive materials into a very concentrated source of radioactivity." So your proposed rule, encouraging the treatment of this complex radioactive waste stream, is nothing more than a free pass for industry to contaminate uninformed and inappropriately protected oil and gas workers, ie, human beings, ie, men and women, mothers and fathers.

And members of the Department and Commission, this one damning 1982 American Petroleum Institute paper is not alone. I read you the first two lines of a 1993 article published by the Journal of Petroleum Technology, which is produced by the oil and gas industry's flagship professional society, the Society of Petroleum Engineers, quote, "Contamination of oil and gas facilities with naturally occurring radioactive materials (NORM) is widespread. Some contamination may be sufficiently severe that maintenance and other personnel may be exposed to hazardous concentrations." Later in this report it states, quote, "Much of the material wastes from a facility contaminated with NORM must be handled as low-level radioactive waste and disposed of accordingly."

So, the idea that this issue is not a big problem, or only a problem in the Marcellus shale play or back East, is not just absurd, this ignorance puts the lives and safety of the workers and communities of this great state in peril. And just to prove the point, from the opening lines of a 63-page report produced in 1991 by the esteemed petroleum geologist John B. Comer, of the Bureau of Economic Geology at the University of Texas at Austin, quote, "The Upper Devonian Woodford Formation is an organic-rich petroleum source rock that extends throughout West Texas and southeastern New Mexico and...is very radioactive."

Your rule makes no mention of this highly dangerous radioactivity, and it makes no mention of how you will protect the workers and residents of New Mexico from this contamination. While the present New Mexico regulatory agencies and commissions have unfortunately taken scant interest in assessing and monitoring radioactive elements inevitable in the oil and gas industry's waste streams, such as radium, a bone-seeking human carcinogen known to have pronounced effects in children with swiftly growing bones, that does not mean your workers and residents cannot be affected by radium, or any of the other well-known carcinogenic radioactive elements common to oil and gas waste such as produced water.

Quote, "There is no threshold of exposure below which low levels of ionizing radiation can be demonstrated to be harmless...The health risks – particularly the development of solid cancers in organs – rise proportionally with exposure." This from Harvard epidemiologist and committee chair of the National Academy of Sciences 2006 Biologic Effects of Ionizing Radiation report, known among radiation experts as the BEIR VII report.

Just because you do not believe the science or know the science or care to read a few research papers to understand the science does not mean the science doesn't exist, and does not mean the science won't eventually lead to lethal cancers in the residents you are charged with protecting. I sincerely hope the Department and Commission reconsiders this ridiculous science-starved rule and makes a complete about-face on the topic of oil and gas waste.

But either way, your paltry regulations have already enabled an easily traceable trail of contamination to be spilled across the great state of New Mexico, and quite literally, deposited in the bones and bodies of its people. Radium, again, as anyone in the medical community well-knows, is a "bone seeker," mistaken for calcium, and incorporated into our skeleton. And as cases during the 1980s and 1990s from the Mississippi and Louisiana oil patches have shown, these exposures may not just lead to cancer and disease in oil and gas workers, workers bring contamination home on their clothes and bodies and their family members can and will be contaminated as well. There is no reason to think that the science of exposure will operate any differently in New Mexico workers and residents in 2020 than it did in Louisiana and Mississippi workers and residents 30 and 40 years ago.

As Dr. Harrison Martland, one of the great founders of the field of occupational radiation safety, lays out in his seminal 1931 paper on the "Radium Girls" in the American Journal of Cancer, the bombardment of radioactivity given off by these women—who unknowingly digested radium in their use of radioactive paints in the painting of watch and clock dials—, quote, "will last, for an indefinite period. For instance in the year 3491 A.D., the skeleton will still be giving off 185,000

alpha particles per second." End quote. So the contamination you enable to be spread, spilled, and sloppily treated across this awesome Land of Enchantment is not going anywhere. Your carelessness will be recorded indefinitely on the land and in the bodies of its people, and myself and my colleagues and the scientific experts—and the many, many, attorneys of the future—will find your victims, and we will expose the catastrophe you have unleashed.

Please find all sources cited and linked or attached in full. Thank you.

Justin Nobel

SOURCES

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NORM Contamination in the Petroleum Industry

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Summary. Contamination of oil and gas facilities with naturally occurring radioactive materials (NORM) is widespread. Some contamination may be sufficiently severe that maintenance and other personnel may be exposed to hazardous concentrations. Contamination with radium is common in oil-production facilities, whereas contamination with radon and radon decay products is more prevalent in natural-gas production and processing facilities. Although largely unregulated until recently, U.S. states, notably Louisiana and Texas, have or are enacting legislation to control NORM contamination in the petroleum industry.

Introduction

NORM contamination can be expected at nearly every petroleum facility. Some of it can be sufficiently severe that maintenance and other personnel may be exposed to hazardous concentrations. In addition, the industry must comply with new regulations. Mississippi and Louisiana have enacted legislation to control NORM; Texas will have regulations early in 1993; and other states, as well as Canada, can be expected to have similar regulations shortly.

Two general types of common NORM contamination will be controlled by these regulations.

1. Radium contamination of petroleum production facilities—specifically of pipe scale and sludge and scale in surface vessels. In addition, produced water may be radioactive from radium dissolved in underground water.

2. Radon contamination of natural-gas production facilities. This includes contamination with the long-lived decay products of radon. Facilities that remove ethane and propane from natural-gas facilities are especially susceptible to NORM contamination.

Naturally occurring radionuclides are widespread in the environment. In many geologic formations, radium, radon, and other radioactive elements are associated with oil and gas. When oil and gas are produced, traces of these radioactive elements also are produced. When the formation water contains traces of radium (radium-226, a decay product of uranium, and radium-228 from thorium), scale in the production pipe can become radioactive, sometimes containing several thousand picocuries of radium per gram of scale.[1,2] The radioactivity results when radium coprecipitates with barium and strontium sulfates in the scale formation.

Radium also can contaminate scale and sludges in surface equipment by similar mechanisms, including carbonate precipitates and sulfate deposits. Produced water may contain dissolved radium. This can lead to contaminated sludges in waste pits and radioactive water.

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Contamination of gas wells, pipelines, and gas processing facilities results primarily from radon produced with natural gas.[3-6]

NORM Contamination

NORM contamination in the oil and gas industry commonly occurs as radioactive scale, films, and sludges.

Radium-Contaminated Scale and Sludge. Radioactive scale can contain uranium, thorium, radium, and associated decay products from the production of oil and associated brines contaminated with NORM. The radioactivity in the scale in production pipe originates mainly from radium, which coprecipitates with barium and strontium sulfate. Other isotopes in the uranium-238 and thorium-232 decay series also may be present. Contaminated scale may contain up to several hundred thousand picocuries of radium per gram of scale.

Radioactive scale may be found in surface processing and transport equipment and in downhole tubing. For example, piping, sludge pits, filters, brine disposal/injection wells, and associated equipment may be contaminated with radium NORM. Also, soils and equipment contaminated from well tubing workovers conducted to remove scale—both at the wellsite and at remote pipe cleaning yards—may be contaminated with NORM.

Films. Radioactive films, coatings, or plating can form from natural-gas production or processing. Often invisible to the naked eye, these films contain radon and its decay products, normally with no radon precursors (e.g., radium) associated with them. Because of radon contamination in natural gas, these radioactive films can be found at gas wellheads; in transport piping, headers, treater units, and pumps; and within natural-gas processing plants or other light-hydrocarbon facilities.

Sludge Contaminated With Decay Products of Radon. Radioactive sludges in pipelines, processing plants, natural-gas liquid (NGL) storage tanks and delivery facilities, pigging operations, and gas lines and other filter assemblies can be contaminated with

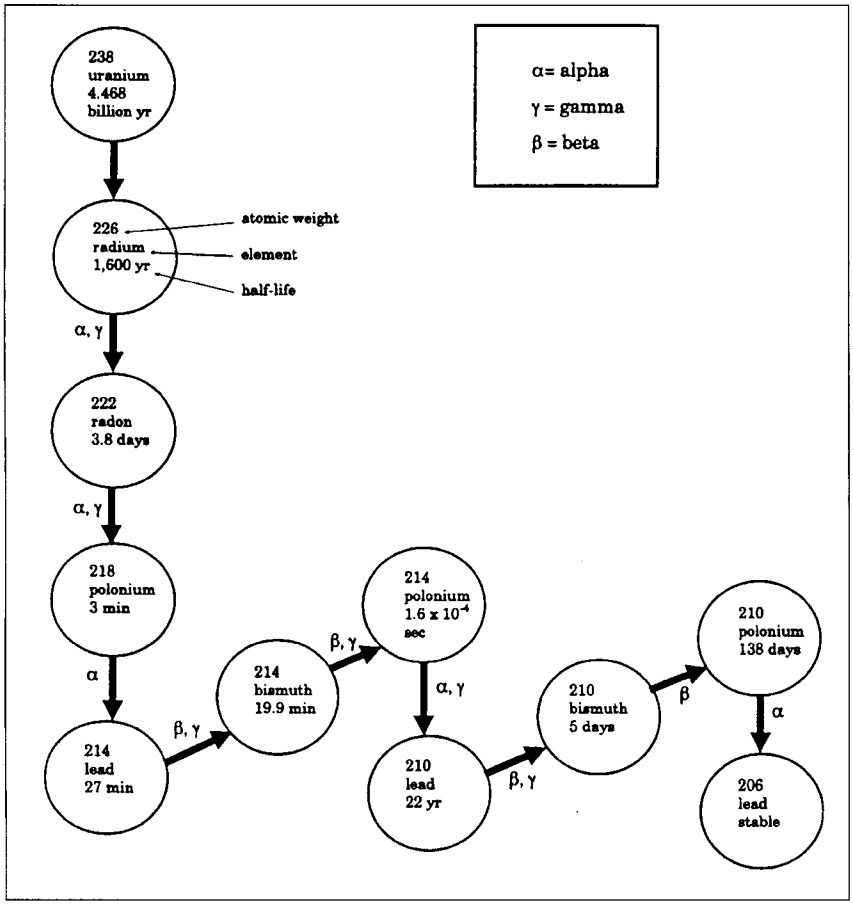

Fig. 1—Radioactive decay of uranium-238.

TABLE 1—RADON CONCENTRATIONS IN NATURAL GAS AT THE WELLHEAD*

Location of Well	Radon Concentration (pCi/L)
Borneo	1 to 3
Canada	
Alberta	10 to 205
British Columbia	390 to 540
Ontario	4 to 800
Germany	1 to 10
The Netherlands	1 to 45
Nigeria	1 to 3
North Sea	2 to 4
U.S.	
Colorado, New Mexico	1 to 160
Texas, Kansas, Oklahoma	1 to 1,450
Texas Panhandle	10 to 520
Colorado	11 to 45
California	1 to 100

*From *Radon Concentrations in Natural Gas at the Well*, U.N. Scientific Committee on the Effects of Atomic Radiation; Sources and Effects of Ionizing Radiation, United Nations, New York City (1977).

TABLE 2—BOILING POINTS AT 760-mm MERCURY

	°F
Methane	−258.0
Ethane	−124.0
Radon	−79.2
Propylene	−53.9
Propane	−44.4
Butane	+31.1

radon in the natural gas. Sludges also may be contaminated with several thousand picocuries per gram of the long-lived radon decay products (i.e., lead-210, bismuth-210, and polonium-210). These heavy-metal decay products may attach to dust particles and aerosols to become part of the sludge.

Filter assemblies in gas lines remove the radon decay products from the gas with other particulate matter and can become very radioactive.

History of NORM Contamination

Radium has been known as a trace contaminant of underground water for a long time but wasn't reported to be a contaminant of scale until the early 1980's, when the problem was first reported in the North Sea. Radon contamination of natural gas has been known for nearly 100 years.[7] However, it was only in 1971 that radon was found to concentrate in the lighter natural-gas liquids during processing and could present a serious health hazard to industry personnel, particularly maintenance employees.

Some radon was undoubtedly removed with the NGL's before 1971. However, deep extraction techniques developed to remove more ethane from the gas also extracted significantly greater concentrations of radon. The problem was discovered when the radon contamination in propylene became sufficiently high to interfere with liquid level sensors detecting slurry levels in a polypropylene plant.

The radioactive scale problem in the oil and gas industry has been reported in the literature.[1,2] With the notable exception of a 1975 report by Gesell[8] and a paper by Gray[9] in 1990, NORM contamination of gas facilities by radon and its decay products has not been as extensively reported.

Radium and Radon

Radium-226 is the fifth decay product of uranium-238, and radium-228 is the fourth decay product of thorium-232. Uranium and thorium are present in most soils and rocks in widely varied concentrations in the Earth's crust throughout the world. Some radium salts (e.g., radium chloride) are soluble in water, and underground water can dissolve the radium in the uranium and thorium formations. The radium may stay dissolved in the water as long as contact with sulfate and carbonate formations is limited. The radium-contaminated water may be produced with oil and gas.

Radon is a naturally occurring, highly mobile, chemically inert radioactive gas in the uranium-238 decay series. Radon-222 is produced by the radioactive decay of radium-226. Because radium is widely distributed in the Earth's crust, radon also is widely distributed. Recent reports of radon-contaminated buildings throughout the world attest to the wide distribution of radon in the environment. Radon is a noble gas, similar to helium and argon, and it is extremely unreactive chemically. Once formed by the radioactive decay of radium-226, radon is free to migrate as a gas or dissolve in water without being trapped or removed by chemical reaction. Migrating through rocks and soil, radon is produced with natural gas at the wellhead. **Table 1** shows that radon contamination of natural gas is a worldwide problem, and particularly high concentrations of radon are reported in the U.S. and Canada.

When radon-contaminated produced gas is processed to remove the NGL's, much of the radon is removed also. Radon's boiling (or condensing) point is intermediate between the boiling points of ethane and propane. Upon subsequent processing, radon tends to accumulate further in the propylene distillation stream. **Table 2** shows the boiling points of radon, the lighter NGL's, and propylene. As expected, radon usually is recovered more completely in plants with high ethane recovery. The radon is concentrated in the lighter NGL's and is detected relatively easily with radiation survey meters.

As long as it is contained and controlled within vessels, equipment, and piping, radon generally is not a health hazard to employees and the public. Even if radon-contaminated propane were released, the threat of fire or asphyxiation would far outweigh the hazard of a short-lived radiation exposure.

Although other radon isotopes exist [e.g., radon-220 (thoron)] from the decay of thorium-232, the only radon isotope of concern

TABLE 3—PRIORITY AREAS OF CONCERN FOR HIGH RADON AND RADON DECAY PRODUCT CONTAMINATION
NGL facilities
De-ethanizers
Stills
Fractionators
Product condensers
Flash tanks
Pumps in liquid service
Piping in liquid service
NGL storage tanks
Truck terminals
Filter separators
Dessicants
Waste pits
Pipelines
Filters
Pig receivers
Machine shops
In-house
Contract

is the 3.8-day half-life radon-222. Radon-220 and other radon isotopes have very short half-lives and will have decayed before the gas is produced at the wellhead. Because the half-life of radon-222 is 3.8 days, 99% of the radon will decay to its long-lived lead-210 decay product in 25 days.

Radon Decay Products

Radon itself is not a particularly hazardous material. Because it is chemically unreactive, it does not accumulate in the body. The health hazards associated with radon exposure are from its decay products. These long-lived radioactive materials present a growing problem to the industry, especially to personnel who may be exposed to contaminated surfaces, sludges, and other waste materials. **Fig. 1** shows each atom of radon-222 eventually decays to an atom of lead-210 and subsequently to bismuth-210 and polonium-210 before decaying to stable lead-206. The half-life of lead-210 (a solid metal material) is 22 years. Therefore, the concentrations of radioactive lead, bismuth, and polonium will continue to increase in pipelines, gasoline plants, tank cars, and trucks for more than 100 years.

Contaminated facilities and waste-material problems must be recognized and addressed. The presence of the radioactive metals from radon decay cannot be detected on the outside of contaminated equipment and vessels. Unlike radon, the radiations that the decay products emit are easily absorbed by the walls of the equipment. If present in sufficiently high concentrations, radon can be detected externally to storage vessels, pumps, etc. Radon has moderately energetic gamma radiation in its decay that can be detected with gamma survey meters.

If an alpha/beta probe is held close to contaminated internal surfaces and concentrations are sufficiently high, survey meters may detect the presence of the radon decay products. However, laboratory analyses are usually required to determine concentrations of lead, bismuth, and polonium accurately.

These radioactive materials are not a health hazard unless they are ingested or inhaled into the body—e.g., during repair and maintenance on the facility. If inhaled, the dust and aerosols containing NORM can attach to the lung surfaces, where they emit alpha radiation into the tissue of the lung lining. Studies of uranium miners indicate that extended exposure to these radon decay products pose an increased risk of lung cancer.[10,11]

NORM in NGL Facilities

Although entire natural-gas and NGL systems may be contaminated with NORM, some facilities will be contaminated to the extent that they present significant decontamination and disposal problems. Gasoline plants and other NGL facilities will be among the most highly contaminated areas in a system.

During processing in a gasoline plant, the levels of external radiation from radon in propane 1 ft from a liquids pump may be as high as 25 milliroentgens (mR)/hr. Radiation levels up to 6 mR/hr have been detected at outer surfaces of storage tanks containing fresh propane. Sludges in gasoline plants are often contaminated with several thousand picocuries of lead-210 per gram.

Table 3 shows vessels and equipment in NGL service that may be significantly contaminated with NORM. Although NORM contamination will be general throughout an NGL facility, the contamination usually will be greatest in areas of high turbulence, such as in pumps and valves.

When employees open equipment and vessels, precautions must be taken to prevent exposure to radioactive contamination.[12] Maintenance procedures should include the use of respirators and good hygiene to prevent inhalation of radioactive dust. Grinding, if necessary, should be done wet to minimize dust.

Occasionally, a plant or other facility that has been processing light hydrocarbons, particularly ethane and propane, is taken out of service and the facility sold or dismantled. Any equipment with internal surface deposits of NORM must receive special consideration when scrapped, sold, transferred, or otherwise disposed of, particularly when the facility is being released for unrestricted use. Analyses for lead-210 usually will be required to verify the extent of contamination and to determine if special handling is needed. Particular care must be used to prevent employee exposure to NORM contamination.

There are potential liabilities involved if contaminated equipment, vessels, and other parts of the facility are released or sold for unrestricted use without first being cleaned and tested to be essentially free of NORM contamination according to state and federal regulations.

Much of the material wastes from a facility contaminated with NORM must be handled as low-level radioactive waste and disposed of accordingly. Contaminated wastes should be consolidated and separated from noncontaminated waste to keep radioactive waste volumes as low as possible. Consolidated contaminated wastes should be stored in a controlled-access area. The area should be surveyed with a radiation survey meter and, if required, should be posted according to state and federal regulations.

Other NORM Contamination

Besides vessels and equipment in NGL service, other facilities susceptible to significant contamination include pigging operations, machine shops, and filter assemblies.

Pipeline sludges can obtain small radium-226 concentrations together with a few hundred to several thousand picocuries of radon decay products per gram. These sludges require the same handling as low-level radioactive wastes. The pig itself may be contaminated. This may require handling the pig with gloves and storing it in an area with restricted personnel access.

Machine shops present a special NORM situation. For example, pumps in NGL service may be among the most highly contaminated equipment in a plant. Occasionally, these pumps may need to be checked for leaking seals or impeller balance. NORM contamination inside a pump is often chemically bonded to the pump structural metal and cannot be easily removed without scraping and grinding. Because rebalancing is usually done by grinding until balance is established, the grinding may generate significant quantities of radioactive dust that can contaminate personnel as well as the shop facility. This can pose a very serious problem if contract machine shops are used.

Although pipelines and equipment in dry-gas service may be only marginally contaminated, filter assemblies in dry-gas service may be contaminated with very high concentrations of NORM and require special handling to prevent inhalation of the radioactive dust and contamination of the environment during changing of the filters and other required maintenance.

Radiation Surveys

NORM contamination is detected by radiation surveys with Geiger-Mueller or scintillation probes on a suitable survey meter. The gamma radiation emitted by radium and radon are sufficiently energetic that they are detected relatively easily if present in high concentrations. The radiations emitted by the decay products of radon are not easily detected. The raditions from lead-210 (low-energy gammas), bismuth-210 (betas), and polonium-210 (alphas) will not penetrate vessel and equipment walls and are detected only with low efficiency when a suitable probe (e.g., an alpha pancake probe) is used directly on the contaminated surface. Because these radon decay products are detected, at best, with low efficiency, any reading on the survey meter above background indicates significant contamination.

Samples should be taken and submitted to a laboratory for analysis. The exempt concentration levels for these radionuclides are very low, and contamination above the exempt concentrations is common. Because the radiations are easily absorbed, areal surveys of the ground and soil around petroleum facilities for radon-decay-product contamination are generally not meaningful and samples must be taken for laboratory analyses.

Radium and radon emit sufficiently energetic radiation to make their detection somewhat easier. The gamma rays will commonly penetrate structure walls, making external radiation surveys with Geiger-Mueller or scintillation detectors meaningful. The exempt concentrations in the Louisiana and Mississippi regulations and in pending regulations in other states are so low, however, that concentrations of radium and radon near the exempt levels are very difficult to measure accurately. A well-trained technician is required to make such surveys with confidence. Again laboratory analyses may be needed to determine accurately the amount of contamination. Such analyses are probably required when the facility or property is being sold, abandoned, or otherwise released. Accurate records of contamination will be required to prevent future litigation.

Disposal of NORM Wastes

The disposal of NORM-contaminated wastes is a major problem with no completely satisfactory solution. The disposal of NORM wastes is regulated by Louisiana and Mississippi and will be regulated in all other states as their regulations become effective. Options are limited. For example, the NORM wastes must be separated from non-NORM wastes and cannot be disposed of by "ordinary" methods of waste disposal, such as landfills. Disposal of contaminated wastes with uncontaminated material in a landfill or by other methods of disposal is not allowed unless the contamination level is below exempt concentrations in state and federal regulations. The few facilities licensed to accept NORM wastes are expensive to use and require a complete paper trail.

Although individual states or groups of states are obligated to have low-level radioactive waste repositories by 1993, these facilities may not accept NORM wastes from the petroleum industry. This is the case in Texas, for example, where the Texas Low Level Radioactive Waste Repository is designed to accept radioactive wastes from medical facilities, educational institutions, and industrial non-NORM wastes. The cost of disposal will be expensive—Texas estimates that the cost of storing radioactive wastes in its low-level repository will be about $\$175/ft^3$.

Currently, the most economical and practical method may be to store the NORM wastes on the facility property in an area with controlled access. The revised Louisiana regulations address the disposal problem and require a proposed disposal plan be submitted to the state within 90 days of the NORM generation.

It sometimes may be possible to dilute the wastes sufficiently with noncontaminated material so that the NORM concentrations are below exempt levels. For example, moderately contaminated soil may be diluted with noncontaminated soil or radium-contaminated water may be diluted with "clean" water. If sufficiently diluted, the resulting wastes may possibly be disposed of by ordinary methods.

Reinjection of radium-contaminated water is a possible solution to the disposal of such water. Injection of other NORM wastes (e.g., contaminated scale) in a Type II injection well may be the best possible disposal method for these wastes when allowed by the regulations.

The high cost of disposing of NORM wastes is opening new opportunities for R&D in methods and techniques for reducing waste volumes. For example, production waste may be contaminated above exempt levels with radium-226 and radium-228. If the radium could be removed from the water economically, the costs of disposing of the contaminated water would be reduced significantly. There are R&D efforts in progress to do this, such as using resins and membranes to absorb or separate the radium from water and other corrosive liquids. Similar efforts are being applied to concentrate radium and lead-210 and its radioactive daughters from organic and inorganic sludges. If successful and economical, this may be a solution to the disposal of large volumes of NORM-contaminated wastes.

"The high cost of disposing of NORM wastes is opening new opportunities for R&D in methods and techniques for reducing waste volumes."

Decontamination of facilities by sandblasting can generate large volumes of NORM wastes. Novel methods of "sandblasting" with materials that will minimize the solid wastes are being explored. Reaming out scale from production pipe can generate large quantities of NORM wastes. Because only a fraction of the scale, possibly as low as 5% to 10%, may be contaminated above exempt concentrations, preliminary gamma surveys of the pipe to locate NORM sites can be used to guide reaming operations and to reduce NORM-contaminated scale wastes. Contaminated scale may be spotty (i.e., not uniform within the pipe), so the total joint should be surveyed on all sides. External scale on the pipe also can be contaminated with radium, necessitating careful handling to prevent ingestion or inhalation of NORM dust and contamination of the environment.

As an alternative to reworking or cleaning of contaminated production pipe, the pipe can be left in place in the ground. It is not required to pull the pipe and remove the contaminated scale.

The trend in U.S. state regulations is toward more regulation and control of NORM wastes. NORM disposal will undoubtedly become very expensive.

Regulations

Radium and radon in oil and gas operations produce radioactive waste materials that contaminate facilities and equipment, exposing employees to hazardous materials and creating waste disposal problems. Such wastes and facilities should be treated as much as possible like other facilities and equipment covered by the U.S. Atomic Energy Act (e.g., soil contamination limits, criteria for facilities and equipment released for unrestricted use, and rules for proper handling and disposal of contaminated materials).

Several state and federal agencies have potential jurisdiction over NORM, but their application to NORM is unclear. NORM does not fall under the definition of source, special nuclear, or by-product material as currently defined in the Atomic Energy Act. Therefore, NORM is not subject to the Nuclear Regulatory Commission regulations. States have laws and regulations governing the use, possession, handling, and disposal of radioactive materials, but their application to NORM is still unclear. Except for Louisiana and Mississippi, no specific state regulations for the control of NORM contamination exist. Texas and several other states are expected to have NORM regulations in 1993. Louisiana specifically exempts the wholesale and retail distribution, possession, use, and transportation of oil and natural gas and NGL's from the regulations. The exemption, however, does not apply to contaminated facilities, such as pipelines, gasoline plants, and other physical facilities.

The Louisiana and Mississippi and other proposed state regulations are very specific regarding disposal of contaminated wastes and sale, abandonment, or release of facilities that may be contaminated. Companies doing production pipe cleaning and workovers must be specifically licensed, as do contractors supplying decontamination services. Louisiana has required radiation surveys of every petroleum facility in the state. As proposed, the Texas regulations will not require such extensive surveys. Texas will require surveys only of specific licensed facilities.

To ensure compliance, companies must be familiar with the regulations as they evolve. Although only Louisiana and Mississippi have regulations in effect, Texas, other states, and Canada are expected to have regulations soon for the control of NORM in the petroleum industry. The U.S. Environmental Protection Agency (EPA) is also

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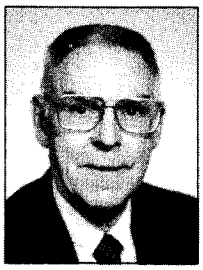

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considering enacting NORM regulations on the federal level.

Regulatory developments must be monitored as current knowledge of the NORM issues evolves. Where possible, industry input should be directed to minimize an overregulation of NORM contamination in the industry.

Suggested Program for the Control of NORM

The following are suggestions for use in establishing a program for the control of NORM contamination.

1. Determine whether there is a NORM contamination problem.
2. Determine areas of potential NORM exposure and contamination.
   A. Make gamma radiation surveys of facilities and equipment.
   B. Make wipe tests on accessible interior surfaces of selected equipment and vessels, especially any in NGL service.
   C. Obtain samples of sludges and scale and analyze for radium and lead-210.
   D. Obtain samples of other waste materials, such as dessicants and filters.
   E. Analyze produced water and waste pond water for radium.
3. Establish programs to ensure personnel safety, product quality, customer satisfaction, and protection of the environment.
   A. Establish policy on periodic surveys, inspection and maintenance procedures, product controls, and record keeping.
   B. Provide safety-manual material that informs employees and details required procedures, particularly for maintenance personnel.
   C. Recommend a management and audit system.
   D. Develop plans and procedures for the disposal of contaminated waste materials, equipment, and facilities.
   E. Prepare a public relations release to use if questioned by employees, customers, the public, and the media.
4. Inform facility personnel of the possibility of NORM contamination.
5. Review governmental regulations to ensure regulatory compliance.

Conclusions

1. NORM contamination can be expected at nearly every petroleum facility.
2. The presence of NORM in oil and gas production facilities, gas processing plants, pipelines, and other petroleum equipment and facilities is not, in general, a serious technical problem.
3. The concentrations of NORM contamination and the energies of the radiation are relatively low and do not usually present a health hazard to the public or to most personnel in the industry. Some facilities may be more highly contaminated, however, and may be hazardous to maintenance personnel in particular.
4. Radium contamination of pipe scale can be a serious problem requiring special procedures for the removal and disposal of contaminated scale to prevent contamination of personnel and the environment.
5. Produced water may be contaminated with radium, requiring special procedures for the protection of the environment.
6. Surface equipment and facilities at production sites also may be contaminated with NORM, requiring special repair and maintenance procedures and the disposal of NORM-contaminated wastes.
7. The buildup of long-lived radon decay products (specifically lead-210) in gas pipelines, gasoline plants, and refineries requires that specific procedures be implemented for inspection and maintenance personnel to ensure their safety when working on the internal parts of equipment and facilities where radon may have been present.
8. A serious problem that must be addressed is the disposal of radioactive materials and equipment. Options available for the disposal of NORM and NORM-contaminated wastes are limited.
9. Although only Louisiana and Mississippi have enacted regulations for the control of NORM, Texas will have regulations early in 1993, and other states and Canada can be expected to enact similar legislation. The U.S. EPA is considering enacting NORM regulations on the federal level.
10. The industry must comply with the regulations.

Although potentially hazardous to personnel and the environment, NORM contamination is controllable.

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SI Metric Conversion Factors

curie	× 3.7*	E+10	= Bq
°F	(°F−32)/1.8		= °C
ft	× 3.048*	E−01	= m
ft³	× 2.831 685	E−02	= m³
R	× 2.58	E−04	= C/kg

*Conversion factor is exact.

Provenance

Original SPE manuscript, **NORM Contamination in the Petroleum Industry,** received for review Oct. 6, 1991. Revised manuscript received Oct. 29, 1992. Paper accepted for publication Jan. 15, 1992. Paper (SPE 22880) first presented at the 1991 SPE Annual Technical Conference and Exhibition held in Dallas, Oct. 6–9.

JPT

OCC Hearing Exhibit 44b

163535

An Analysis of the Impact of the Regulation of "Radionuclides" as a Hazardous Air Pollutant on the Petroleum Industry

Prepared for the Committee for Environmental Biology and Community Health, Department of Medicine and Biology, American Petroleum Institute

October 19, 1982

EMLEI 0069428

Executive Summary

The impact of regulating "Radionuclides" as a hazardous air pollutant under Section 112 of the Clean Air Act is examined and is found to depend upon what is defined as an "acceptable level" of risk, and whether the regulation will be based upon committed dose equivalent to the general public, source characteristics, or individual radioisotopes.

Almost all materials of interest and use to the petroleum industry contain measurable quantities of radionuclides that reside finally in process equipment, product streams, or waste. In addition, groundwater used for waterflood and brine solutions from operating wells contain biologically significant quantities of Radium 226 and Radon 222. The mining, cleaning, and combustion of coal also add measurably to the burden of radioactive pollutants in ambient air.

Listing radionuclides as a hazardous air pollutant also brought radionuclides under the umbrella of CERCLA. Again, the impact of defining a "reportable quantity" depends upon the definition of "acceptable risk" and whether the standard is based upon a committed dose equivalent to a member of the general public or is established isotope by isotope.

Table 10 in the main body of the report summarizes the quantities of radionuclides found in products and raw materials of most concern to API member companies. Table 13 summarizes the EPA's estimate of risk associated with certain industry operations to a maximum exposed individual inhaling and ingesting radionuclides from products of combustions. Table 17 shows how the impact upon the industry expands as the level of acceptable risk is reduced, and Table 18 summarizes the combined potential impact of regulations under both the Clean Air Act and CERCLA.

It is concluded that the regulation of radionuclides could impose a severe burden on API member companies, and it would be prudent to monitor closely both regulatory actions.

EMLEI 0069429

What Radionuclides Should Be of Concern?

When the EPA listed "RADIONUCLIDES" as a hazardous air pollutant, they meant all radioactive materials without exemption for material concentration (specific activity), quantity, or material with which it is associated. There were no exemptions for the non-nuclear industries.

The general classification "Radionuclides" includes:

- By-Product Material - the material made radioactive through the use of special nuclear material or bombardment by radiations resulting from the use of special nuclear material (CFR, 1982).
- Special Nuclear Material - the fuel for reactors.
- Source Material - essentially the concentrated elements from which special nuclear material is separated.
- Naturally Occurring or Accelerator-Produced Radioactive Materials - those radioactive materials found in nature or made radioactive in a laboratory by an energetic ion beam. These are the materials that are present in our products in minute amounts.

While many petroleum companies use radioactive materials as tracers and in process control, these are carefully regulated by the U.S. Nuclear Regulatory Commission present little, if any, environmental hazard, and are of small concern. The API should be more concerned with the potential for naturally occurring radionuclides being in our raw materials. Naturally occurring radioactive material is either produced in the earth's atmosphere as a result of cosmic-ray bombardment, i.e. Carbon-14, or exists as primordial radionuclides, i.e. radionuclides present from the event of creation in the earth's crust, such as Potassium 40 and Uranium. The families of radionuclides or series of radionuclides that are of most significance are in this primordial grouping. These are the decay series of Uranium 238, Uranium 235, Thorium 232. Uranium 235 is the nuclear fuel. About 0.7% of natural uranium is Uranium 235. Uranium 238 and Thorium 232 are uniformly distributed in the earth's crust.

The Uranium 238 (Figure 1) series can be divided into some four subseries, all possessing significant exposure potential to man. These subseries are the decay of Uranium 238 and Uranium 234 to Thorium 230, the decay of Thorium 230 to Radium 226, the decay of the inert gas Radon 222 and its short-lived daughters to the long-lived daughter, product Lead 210, and finally the decay of Lead 210 to stable lead (NCRP, 1975). The elements in the Subseries Uranium 238 to Thorium 230 represent significant sources of internal exposure, primarily in the occupational environment. Radium 226 is a potent source of radiation exposure, both internal and external. Radon 222 and its short-lived progeny deliver significant population and occupational exposures to the upper tracheobronchial tree, while Lead 210 and its decay product contaminate much process equipment and can represent significant exposure to the bone in some occupational subgroups. Radon 222 and its daughters cause the most severe impact to the public health.

EMLEI 0069430

The Thorium series (see Figure 2) is characterized by the long-lived Thorium 232 at the head of the series and decay products that are relatively short lived. If no migration of the series members takes place, radio-equilibrium is established in about 60 years. In minerals and rocks of low permeability, the thorium series radionuclides are expected to be in equilibrium. In soils, natural waters, natural gas, crude oil and the atmosphere, the disparate chemical and physical properties of the series tend to cause disequilibrium. Certain parts of the world, Kerala in India and monazite mining districts in Brazil, are famous because of their high background levels of external radiation from the thorium series.

The Presence of Radionuclides in Crude Oil, Natural Gas (NG), Liquefied Petroleum Gas (LPG), Coal, Phosphate Rock, and Groundwater

It is well known that some naturally occurring elements, uranium for example, have an affinity for crude oil. The uranium that accumulates in crude oil, oil shale, coal, and phosphate rock is the residue remaining after the marine deposits have been consolidated. Petroleum is often assumed to have migrated to a position of minimum hydraulic potential in a "reservoir rock", which may or may not be derived from the same source deposits as the petroleum. Associated with the petroleum in widely ranging proportions are brine and natural gas. The radionuclides, particularly those of the uranium series (see Figure 1), distribute themselves among the three fluid phases and the crusty, solid lining of the intergranular spaces according to chemical affinity, sorption phenomena and the vagaries of radioactive recoil. The gaseous radon isotopes follow the temperature-pressure dependent Henry's Law in their portioning among the gas and liquid phases. The sites of major uranium-series nuclides in the Texas Panhandle gas field and adjacent areas have been studied extensively (Pierce, 1964). In the gas reservoir, uranium is resident mainly in the crude oil and in pellets of solid hydrocarbon, radium is found in the brine and in the solid crust, and radon distributes itself among the oil, gas and brine in that order. The series equilibrium is evidently disrupted continually by movement of decay products from one phase to another that is chemically or physically more compatible.

Crude Oil

Very little has appeared in the literature concerning the levels of radioactivity in crude oil, but it would be safe to assume that the actual levels of contamination would be between that found in coal and that found in sedimentary rock similar to that of the reservoir rock or where the petroleum was formed. Uranium in the earth's crust averages 4 parts per million (CRC, 1969). The NCRP (NCRP, 1975) reported the data shown in Table 1 for the various rock types.

EMLEI 0069431

TABLE 1 —*Summary of concentrations of major radionuclides in major rock types and soil*[a]

Rock Type	Potassium-40		Rubidium-87		Thorium-232		Uranium-238	
	percent total Potassium	pCi/g	ppm total Rubidium	pCi/g	ppm	pCi/g[b]	ppm	pCi/g[c]
Igneous Rocks								
Basalt (Crustal average)	0.8	7	40	0.9	3–4	0.3–0.4	0.5–1	0.2–0.3
Mafic[d]	0.3–1.1	2–9	10–50	0.3–1	1.6, 2.7	0.2, 0.3	0.5, 0.9	0.2, 0.3
Salic[d]	4–5	30–40	170–200	4–5	16, 20	1.7, 2.3	3.9, 4.7	1.3, 1.6
Granite (Crustal average)	>4	>30	170–200	4–5	17	1.9	3	1
Sedimentary Rocks								
Shale	2.7	22	120[e]	3	12	1.3	3.7	1
Sandstones:								
clean quartz	<1	<8	<90[e]	<1	<2	<0.3	<1	<0.3
dirty quartz	2?	16?	90?	2?	3–6?	0.3–0.7?	2–3?	1?
arkose	3–3	18–24	80–120[e]	3	3?	0.3?	1–2?	0.3–0.7?
Beach sands (unconsolidated)	<1	<8?	<90?	<1?	6	0.7	2	1
Carbonate Rocks	0.3	2	10[e]	0.3	2	0.3	2	0.7
Soils[f]	1.5	12	85[e]	1.4	9	1	1.5	0.6

[a] References cited in text unless otherwise noted; single values are averages; values estimated in absence of reference are followed by question mark.

[b] To obtain series equilibrium alpha, beta, or approximate gamma (excluding bremsstrahlung and α radiation) activity, multiply by 8, 4, or 3 respectively.

[c] To obtain series equilibrium alpha, beta, or approximate gamma (excluding bremsstrahlung and α radiation) activity, multiply by 8, 8, or 3, respectively.

[d] From Clark et al. (1966); for potassium and rubidium, the range of values for rocks within the class is given; for thorium and uranium, the median and mean value are given, respectively.

[e] Estimated by application of crustal abundance ratio with respect to potassium.

[f] In-situ gamma-spectral measurements at 200 locations by Lowder et al. (1964).

Table 2 (UNSCEAR, 1977) shows additional data.

TABLE 2. TYPICAL ACTIVITY CONCENTRATION OF ^{40}K, ^{238}U AND ^{232}Th IN COMMON ROCKS AND ESTIMATED ABSORBED DOSE RATE IN AIR 1 m ABOVE THE SURFACE

Type of rock	*Typical activity concentration (pCi g^{-1})*			*Absorbed dose rate in air (μrad h^{-1})*
	^{40}K	^{238}U	^{232}Th	
Igneous				
Acidic (e.g. granite)	27	1.6	2.2	12
Intermediate (e.g. diorite)	19	0.62	0.88	6.2
Mafic (e.g. basalt)	6.5	0.31	0.30	2.3
Ultrabasic (e.g. dunite)	4.0	0.01	0.66	2.3
Sedimentary				
Limestone	2.4	0.75	0.19	2.0
Carbonate	–	0.72	0.21	1.7
Sandstone	10	0.5	0.3	3.2
Shale	19	1.2	1.2	7.9

Sources: References 1, 353.

EMLEI 0069432

Gulf (Rhodes, 1972) has measured the amount of Lead 210 - a Uranium 238 daughter product - in light hydrocarbon streams. Their finding suggests concentrations as high as 1.2 ± 0.9 pCig^{-1} in such streams.

Natural Gas

The quantities of radon contained in the natural gas of the Panhandle Field and at all other gas fields sampled for radon is of significance to radiation exposure estimates for the U.S. general population. Natural gas of the Panhandle field was found to contain an average radon concentration of about 100 pico curies per liter (pCi/ℓ). Maximum concentration as much as 1450 pCi/ℓ were observed after expansion to atmospheric pressure (Pierce, 1964). In-transit decay, processing of gas for pipelines, and storage decrease the radon contamination, but increase daughter (decay) product, i.e. Lead-210 (see Figure 1), contamination of lines, processing equipment, and storage tanks. This contamination can produce significant occupational exposures. Radon concentrations found in natural gas are summarized in Tables 3 and 4 (UNSCEAR, 1977).

TABLE 3. RADON CONCENTRATION IN NATURAL GAS AT THE WELL

Location of well	Radon concentration (pCi l^{-1}) Average	Range	Reference
Borneo			
Ampa field	...	1.5-3.2	352
Canada			
Alberta	62	10-205	
British Columbia	473	390-540	302
Ontario	169	4-800	
Germany, Federal Rep. of	...	1.0-9.6	352
Netherlands			
Slochteren	...	1.1-2.8	
Other fields	...	3.7-44.7	352
Nigeria			
Niger delta	...	0.9-2.9	352
North Sea			
Leman field	...	2.0-3.8	
Indefatigable field	1.8	...	352
United States			
Colorado, New Mexico	25	0.2-160	
Texas, Kansas, Oklahoma	< 100	5-1 450	
Texas Panhandle	...	10-520	
Colorado	25.4	11-45	
Project Gasbuggy area	15.8	...	171
California	...	1-100	
Kansas	100	...	
Wyoming	10	...	
Gulf Coast (Louisiana, Texas)	5	...	
California, Louisiana, Oklahoma, Texas	...	1-120	98

TABLE 4. RADON CONCENTRATION IN NATURAL GAS IN THE DISTRIBUTION LINE

Area	Radon concentration (pCi l^{-1}) Average	Range
Poland (Warsaw)	8	4-14
United States		
Chicago	14.4	2.3-31.3
New York City	1.5	0.5-3.8
Denver	50.5	1.2-119
West coast	15	1-100
Colorado	25	6.5-43
Nevada	8	5.8-10.4
New Mexico	45	10-53
Houston	8	1.4-14.3

Sources: Poland, 359; United States, 171.

EMLEI 0069433

Table 5 summarizes data from the USEPA.

Table 5. Radon-222 concentrations in natural gas at production wells

Area	Radon-222 level, pCi/l Average	Range	Reference
Colorado New Mexico	25	0.2-160	1
Texas, Kansas, Oklahoma	<100	5-1450	2
Taxas Panhandle	---	10-520	3
Colorado	25.4	11-45	5-7
Project Gasbuggy Area	15.8-19.4	--------	7
Project Gasbuggy Area	29.4	12-59	8
California	---	1-100	10
Gulf Coast (Louisiana, Texas)	5	--------	11
Kansas	100	--------	11
Wyoming	10	--------	11
Overall average	37		

Liquefied Petroleum Gas

When natural gas is thermally fractionated to recover the heavier hydrocarbons, the radon tends to concentrate in the ethane and propane fractions (Gessell, 1975). These are sold in mixtures sometimes including butane, as liquefied petroleum gas (LPG) for use as a fuel. Typically, the concentration of Radon 222 in LPG is eight times the concentration in the natural gas before processing (Gessell, 1974). Subsequent storage allows the Radon 222 to decay, however, and there are indications that despite the higher initial Radon 222 concentration, LPG is no more important than natural gas as a pathway for population exposures to Radon 222.

EMLEI 0069434

An occupational external exposure situation can occur in gas processing plants where daughters of Radon 222 collect on the inside of processing equipment, especially pumps, and also create some disposal problems (Gessell, 1974).

Coal

Coal and its residues appear to be significantly contaminated with Radium 226. Table 6 (USCEAR, 1977) shows that U.S.-mined coal contains biologically significant quantities of Uranium 238, Radium 226, Bismuth 214, Thorium 228 and Thorium 232. Barber (Barber, 1977) also reported significant concentrations of Bismuth 214, Potassium 40 and Thallium 208. The U.S. Geological Survey Service (USCGS, 1959) has reported uranium concentrations in coal up to 0.2%.

TABLE 6. ACTIVITY CONCENTRATION OF RADIONUCLIDES IN COAL AND COAL RESIDUES

($pCi\,g^{-1}$)

Type of coal or coal residue and its origin	^{40}K	^{238}U	^{226}Ra	^{210}Pb	^{228}Ra	^{228}Th	^{232}Th	*Reference*
Coal								
Australia			0.8-1.3					23
Czechoslovakia (brown)			0.11, 0.35					165
Germany, Fed. Rep. of	< 2.5		< 0.7				< 0.6	307a
Hungary (bituminous)			0.04					165
Poland (bituminous)			0.048-0.94					165
Poland (brown)			0.90					165
United States								
Illinois	2.5		0.6[a]			0.04[b]		20
Montana	0.7		0.3[a]			0.07[b]		20
North Dakota	2.2		0.2[a]			0.02		20
United States		0.7					0.2	185
United States			0.914	0.28[c]				175
Coal ash (laboratory processing)								
Australia			4.7-8.3					23
Germany, Fed. Rep. of			6.2[c]			2.6		172
	19		5.8				3.4	307a
Japan								
Central			0.10	19.8	1.15	15.3		257
Southern			0.98	8.16	0.46	2.35		257
Northern			0.63	105.0	1.45	6.79		257
United States (semi-bituminous)			3.8		2.4	2.6		79
Slag								
Poland	17.3		4.3[a]			1.2[b]		272
United States	26		4.5[a]			0.5[b]		20
United States		4.9					1.5	185
United States			0.55	1.0				175
Fly ash								
Australia			14.0					23
Hungary			0.6-15					204
Poland			1.0					165
Poland	22.5		6.4[a]			1.1[b]		272
Poland (bituminous)		1.5, 2.8	0.61, 4.18	4.4, 6.7			0.18, 0.22	166
Poland (lignite)			0.91					166
United States		10					2.6	185
United States			0.4	17.3				175
United States	11		3.1[a]			0.4[b]		20

[a] Assumed equal to activity concentration of ^{214}Bi.
[b] Assumed equal to activity concentration of ^{208}Tl.
[c] Including activity concentration of ^{223}Ra.

EMLEI 0069435

Solvent Refined Coal

Hittman Associates (USDC, 1978) have analyzed solvent refined coal for radionuclides in 1970 and noted concentration of uranium in the SRC particulates. These data are summarized in Table 7.

TABLE 7. RADIONUCLIDE CONCENTRATIONS

(ppm by weight)

Source	Uranium	Thorium
Coal		
Sample #1	1.3	4.74
Sample #2	1.4	4.24
SRC		
Sample #1	0.8	4.99
Sample #2	1.3	3.73
Coal Particulates		
Sample #1	2.6	14.99
Sample #2	1.9	20.50
SRC Particulates		
Sample #1	39	11.46
Sample #2	28	9.48

EMLEI 0069436

Phosphate Rock

Many of the American Petroleum Institute's members are also engaged in the peripheral activity of mining phosphate rock and manufacturing fertilizer. Table 8 (UNSCEAR, 1977) summarizes the presence of radioactivity of the rock and its products.

TABLE 8. ACTIVITY CONCENTRATION OF ^{226}Ra, ^{238}U, AND ^{232}Th IN PHOSPHATE ROCK AND IN PRODUCTS DERIVED FROM IT

Marketable rock produced in Florida (United States)

Sample	Production in the United States in 1973[a] (10^4 t)		Activity concentration (pCi g^{-1})		
	Amount	P_2O_5 content	^{226}Ra	^{238}U	^{232}Th
Marketable rock	38	–	42	41	0.4
Wet process products					
Normal superphosphate	3.1	0.6	25	[b]	–
Triple superphosphate	3.4	1.6	21	57	0.4
Ammonium phosphate	5.3	2.4	5.7	63	0.4
Phosphoric acid	10.0	5.1	0.6	–	–
Gypsum	23.0	–	3.3	6.1	0.3
Electric furnace process products					
Slag	–	–	56[c]	–	–

Source: Reference 109.

[a] Florida accounts for 82 per cent of the marketable rock production of the United States.

[b] The activity concentration of ^{238}U in normal superphosphate is expected to be equal to that of ^{226}Ra.

[c] The ^{226}Ra activity concentration in the input feed ore was 60 pCi g^{-1}.

Groundwater

In groundwaters, such as those used for waterflood operations, Radon 222 is usually present in a concentration range of from several hundred to several thousand pico curies per liter. In North Carolina, where the geology is primarily sedimentary, Radon concentrations vary from 20 to 47,000 pCi/ℓ. Approximaately 33% of supplies tested had concentrations greater than 2000 pCi/ℓ (Sasser, 1978).

The groundwaters around Houston are probably typical of those associated with most petroleum operations. The radon concentrations shown in Table 9 (Prichard, 1981) are for water as it is delivered to Houston homeowners for consumption. In-ground levels are probably similar to the higher samples in North Carolina.

EMLEI 0069437

Table 9
Radon in Houston Homeowners' Water Supplies from Groundwater Sources (Prichard, 1981)

Tracts Included	Average Concentration of Radon (pCi/ℓ)
All	437
Tracts with Concentration greater than 500 pCi/ℓ	853
Tracts with Concentrations greater than 1000 pCi/ℓ	1722

Summary

Table 10 estimates the amounts of radioactivity contained in petroleum products in more familiar units. If we assume that a refinery processes one million barrels of crude per day, we find that we have handled some 1.46 curies per day or 533 curies per year of radioactivity, mostly in the form of naturally occurring Potassium 40.

If it is correct to assume that the uranium in the oil is at the same concentration as the host rock, then a one-million-per-day-capacity refinery could be throughputting some 480 lb of uranium per day (177,200 lb uranium per year).

EMLEI 0069438

TABLE 10

Quantities of Radionuclides in Normal Measurement Units Used by the Petroleum Industry

Item/Product	Units	Radioactive Contaminant						
		^{40}K	^{238}U	^{226}Ra	^{210}Pb	^{232}Th	^{222}Rn	Total
Crude Oil*	uCi/BBL	1.4	0.07		0.17	.04		1.46
Kuwait Oil	uCi/BBL				0.17			0.17
Natural Gas**	$uCi/10^6ft^3$						1400	1400
LPG	$uCi/10^6ft^3$						1400	1400
Coal-US	uCi/T	23.6	4.5	4.0	0.9	1.3	—	30.3
SRC-Product	uCi/T		0.6			100		100.6
Shale Oil	uCi/BBL	2.8	.17			.17		3.14
Shale Waste	uCi/T	17	1.0			1.0		.19
Phosphate Rock (Marketable)	uCi/T		38	38		.36		76.36
Ground Waters	uCi/1,000 gal.						1.6	1.6

* Assumes Uranium in Oil is equal to Uranium in host Rock

** Assumes Average Concentration of 50pCi/l

Note: The USNRC regulates microcurie amounts of radioactive materials that are not naturally occuring.

EMLEI 0069439

Potential Public Health Effects of the Use of Materials and Products Important to the API and Its Member Companies

There are probably as many estimates of impact of radionuclides in air as there are individuals capable and incapable of making such estimates. Whether or not a radioactive material contained in petroleum, natural gas, or coal, is taken into the body depends upon a number of factors, including:

- amount originally present
- amount made airborne
- atmospheric phenomena and transport
- plate out and rain out
- routes of entry
- amount retained
- clearance mechanisms
- dietary sources
- dose contribution of "infinite cloud" and "infinite plane"
- and others

The EPA method of analysis assumed certain source characteristics and target populations (EPA, 1979), used a Gausian computer model to disperse the radioactive materials (BAES, 1981) and a second computer program to model intake, dose, and dose response based upon the linear non-threshold model (Begovich, 1981), (Sullivan, 1981), (Dunning, 1981). The first analysis by EPA concerning the naturally occurring radioactive materials is shown in Table 11 (EPA, 1979). Table 12 is a later analysis, currently in draft form, that expanded the original list (Teknekron, 1981).

Analysis of the data in both reports suggests that API companies should be concerned with operations described in Table 13. Table 13 suggests that the radioactive material emissions having the greatest potential impact on API member companies are Radon-222, followed closely by Uranium-238 and Radium-226. The two EPA analyses demonstrate that any operation involving the combustion of fossil fuels or the preparation of such fuels for use could be subject to regulation under the Clean Air Act.

EMLEI 0069440

Table 11. Summary of radiological impact caused by atmospheric emissions of natural radioactive materials

Source category	Number of sources	Model facility: Principal radionuclide emissions (Ci/y)[a]		Exposure levels: Maximum individual (WL)	Exposure levels: Regional population (Person-WL)	Principal dose equivalent rates:	Maximum individual (mrem/y)[b]	Regional population (Person-rem/y)[c]	Lifetime risk to the maximum individual (x 10^{-9})	Expected fatal cancers per year of operation: Regional population	Expected fatal cancers per year of operation: U.S. (Fatal cancers)
Uranium Mines (4.1)											
Underground	251	Rn-222	6700	0.006	1.3		-	-	10,000	0.03	0.03
Open pit	36	Rn-222	2000	0.0008	0.4		-	-	1,000	0.008	0.02
Uranium Mills (4.2)	20	Rn-222	2700	0.005	0.5	Lung	350	3.4	10,000	0.01	0.03
		U-238+d	0.4			Bone	360	3.9			
Phosphate industry (4.3)											
Mining and beneficiation	35	Rn-222	1300	0.0002	4.9		-	-	300	0.1	
Drying and grinding facilities	20	Rn-222	20	0.00005	0.08	Lung	54	17	500	0.004	
		U-238+d	0.03			Bone	79	18			
Phosphoric acid plant	35	Rn-222	480	0.0007	2.0	Lung	85	46	2,000	0.05	
		U-238+d	0.1			Bone	110	45			
Elemental phosphorus plant	9	Rn-222	490	0.0004	2.0	Lung	740	770	6,000	0.1	
		U-238+d	0.15			Bone	570	440			
		Po-210	7.4			Kidney	1800	1400			
Coal-fired power stations[d] (4.4)											
New stations	145	Rn-222	1.9	<0.00001	<0.00001-0.024	Lung	0.8-2.1	0.5-2600	10-60	0.00008-0.2	
		U-238+d	0.3			Bone	1.6-16	1.5-1300			
		Th-232+d	0.07								
Existing stations	250	Rn-222	0.7	<0.00001	<0.00001-0.013	Lung	6.7-15	2.7-19,000	60-700	0.0004-1.5	
		U-238+d	0.8			Bone	8.3-62	7.1-11,000			
		Th-232+d	0.3								

See footnotes at end of table.

EMLEI 0069441

Table 11. Summary of radiological impact caused by atmospheric emissions of natural radioactive materials--continued

Source category	Number of sources	Model facility: Principal radionuclide emissions (Ci/y)[a]	Exposure levels: Maximum individual (WL)	Exposure levels: Regional Population (Person-WL)	Principal dose equivalent rates: Maximum Individual (mrem/y)[b]	Principal dose equivalent rates: Regional Population (Person-rem/y)[c]	Lifetime risk to the maximum individual (x 10^{-6})	Expected fatal cancers per year of operation: Population Regional	Expected fatal cancers per year of operation: Population U.S. (Fatal cancers)
Metal mining and milling[e] (4.5)	177	Rn-222	17 to 3000	<0.00001 to 0.001	0.005 to 0.8	-	-	20 to 2000	0.0001 to 0.02
Nonmetal mining and milling[f] (4.5)	4,200	Rn-222	0.2 to 18	<0.00001 to 0.00004	0.0007 to 0.06	-	-	0.7 to 50	0.00002 to 0.001
Geothermal power site (4.6A)	1	Rn-222	540	0.0004	1.5	-	-	700	0.03
Ground water treatment plants (4.6B)	40,000	Rn-222	3.4	<0.00001	0.06	-	-	10	0.001

[a]U-238+d emission rates are the sum of the individual release rates for uranium-238, and its daughter products uranium-234, thorium-230, radium-226, lead-210, and polonium-210. (For elemental phosphorus plants only, polonium-210 is not included in this sum.)
Th-232+d emission rates are the sum of the individual release rates for thorium-232 and its daughter products radium-228, thorium-228, and radium-224.

[b]The maximum dose equivalent rate an individual is likely to receive living near the facility.

[c]The maximum collective dose equivalent rate to the regional population. This is the maximum value expected to occur within 100 years following the start of facility operation.

[d]Ranges of impact values represent variations due to station siting.

[e]Includes iron, copper, zinc, and bauxite.

[f]Includes clay, limestone, fluorspar.

EMLEI 0069442

Table 12

SUMMARY OF RISKS FROM SOURCES OF AIRBORNE EMISSIONS OF RADIONUCLIDES

Source Category	Principal Radionuclide Emissions (Ci/yr)		Dose Equivalent Rates: Maximum Exposed Individual (mrem/yr)		Dose Equivalent Rates: Collective (person-rem/yr)	Radon Daughter Exposure: Maximum Individual (working level)	Radon Daughter Exposure: Regional Population (person working level)	Health Effects: Lifetime Risk to the Maximum Exposed Individual	Health Effects: Expected Fatal Cancers per Year of Operation to the Population at Risk
Ground Water Treatment Plant (3.1)									
Southeastern Site	Rn-222	8.1	Lung Bone	5.7E-3 1.9E-4	2.9E-2 9.3E-4	3.8E-6	1.9E-2	6E-6	5E-4
Southwestern Site	Rn-222	8.1	Lung Bone	9.6E-3 3.1E-4	0.15 4.9E-3	6.4E-6	0.10	1E-5	2E-3
Geothermal Power Plant (3.2)	Rn-222	5.5E+2	Lung	1.22	3.1	8.1E-4	2.1	1E-3	5E-2
Phosphate (3.3)									
Phosphate Mine: Stack	Rn-222 U-238	2.1E+1 1.8E-2	Lung Bone	3.5E+1 5.8E+1	8.8E+1 2.4E+2	9.7E-6	5.0E-2	1E-4	7E-3
Area Source	Rn-222 U-238	2.6E+3 4.0E-3	Lung Bone	1.7 5.5	9.2 0.3	5.9E-4	3.2	1E-3	2E-2
Phosphate Acid Plant: Stack	Rn-222 Ra-226 U-238	6.5E+1 1.8E-2 3.5E-2	Lung Bone	6.4E+1 1.0E+2	1.5E+2 3.5E+2	3.1E-5	0.16	2E-4	1E-2
Area Source	Rn-222	3.2E+2	Lung	0.22	1.1	1.4E-4	0.75	3E-4	2E-2
Elemental Phosphorus Plant: Stack	U-238 Ra-226 Pb-210 Po-210	2.2E-2 7.0E-3 3.3E-2 3.2E+0	Lung Liver Bone	2.1E+2 1.7E+1 7.0E+1	5.0E+2 2.6E+2 2.5E+2			7E-4	4E-2
Area Source	Rn-222	2.2E+2	Lung	0.15	0.78	1.0E-4	4.3E-2	2E-4	4E-2
Non-Uranium Metal Mining, Milling, Processing (3.4)									
Underground Mine, Area Source #1	Rn-222 U-Nat	2.1E+2 2.3E-5	Lung Bone	0.52 0.21	3.0E-2 7.2E-3	2.7E-4	1.8E-2	4E-4	4E-4
Area Source #2	Rn-222 U-Nat	2.3E+2 1.0E-2	Lung Bone	4.1E+1 6.7E+1	1.2 2.8	2.3E-4	2.0E-2	5E-4	5E-4
Open-Pit Mine	Rn-222 U-Nat	4.5E+3 5.0E-2	Lung Bone	3.6E+1 5.7E+1	2.6 6.2	7.2E-4	0.15	1E-3	4E-3
Copper Ore Mill	Rn-222 U-Nat	1.7E+3 2.0E-2	Lung Bone	7.3E+1 1.2E+2	6.5 1.6E+1	1.6E-3	0.38	3E-3	1E-2

EMLEI 0069443

Table 12 (Cont.)

SUMMARY OF RISKS FROM SOURCES OF AIRBORNE EMISSIONS OF RADIONUCLIDES

Source Category	Principal Radionuclide Emissions (Ci/yr)		Dose Equivalent Rates			Radon Daughter Exposure		Health Effects	
				Maximum Exposed Individual (mrem/yr)	Collective (person-rem/yr)	Maximum Individual (working level)	Regional Population (person working level)	Lifetime Risk to the Maximum Exposed Individual	Expected Fatal Cancers per Year of Operation to the Population at Risk
Non-Uranium Mining, Milling, Processing (Cont)									
Metal Smelter: Main Stack	Rn-222	8.0	Lung	5.3E+1	1.5E+1	Negligible		2E-4	2E-3
	Pb-210	1.0E+1	Liver	1.6E+1	2.4E+1				
	Po-210	1.0E+1	Bone	3.7E+1	4.0E+1				
	U-Nat	4.5E-2							
Area Source	Rn-222	1.7E+2	Lung	2.0E+2	6.3	1.5E-4	1.4E-2	9E-4	6E-4
	U-Nat	5.3E-2	Red Marrow	2.3E+1	1.1				
			Bone	3.2E+2	1.5E+1				
Non-Metal Mining (3.5) Kiln	Rn-222	4.3E-1	Lung	2.0E+1	1.1E+2	Negligible		7E-5	8E-3
	U-Nat	2.8E-4	Liver	1.8	8.3E+1				
			Bone	2.6	1.2E+2				
Area Source	Rn-222	4.3E-1	Lung	0.79	1.1	1.4E-6	6.3E-3	4E-6	2E-4
	U-Nat	5.1E-6	Bone	4.6E-2	1.2				
Coal Mining and Cleaning (3.6) Underground Mine	Rn-222	1.6E+1	Lung	2.6E-2	2.2	Negligible		9E-3	6E-4
	U-238	3.4E-6	Red Marrow	1.6E-2	2.2				
	Th-232	3.5E-6	Bone	3.1E-2	3.3				
Strip Mine	Rn-222	1.4E+0	Lung	1.1	2.3E+1	8.0E-7	3.1E-2	5E-6	2E-3
	U-238	3.6E-4	Bone	2.8	6.4E+1				
	Th-232	2.8E-4							
Coal Cleaning Plant	Rn-222	0.17	Lung	0.27	8.9	Negligible		1E-6	1E-3
	U-238	2.2E-4	Bone	0.69	3.0E+1				
	Th-232	2.2E-4							
Natural Gas Combustion Units (3.7) Natural Gas Boiler	Rn-222	2.4	Lung	2.9E-1	4.5E-2	1.9E-7	3.0E-2	3E-6	6E-4
Natural Gas Turbine	Rn-222	6.7E-2	Lung	5.2E-3	1.3E-2	3.5E-6	8.8E-2	4E-6	2E-4

EMLEI 0069444

Table 12 (Cont.)

SUMMARY OF RISKS FROM SOURCES OF AIRBORNE EMISSIONS OF RADIONUCLIDES

Source Category	Principal Radionuclide Emissions (Ci/yr)		Dose Equivalent Rates: Maximum Exposed Individual (mrem/yr)		Dose Equivalent Rates: Collective (person-rem/yr)	Radon Daughter Exposure: Maximum Individual (working level)	Radon Daughter Exposure: Regional Population (person working level)	Health Effects: Lifetime Risk to the Maximum Exposed Individual	Health Effects: Expected Fatal Cancers per Year of Operation to the Population at Risk
Coke Production (3.8)									
Northeastern Site	Rn-222	1.9E+0	Lung	1.8E+1	5.7E+2	Negligible		6E-5	3E-2
	Th-232	1.1E-3	Bone	4.3	1.9E+2				
	Po-210	6.2E-1							
	U-238	1.1E-3							
Midwestern Site	Rn-222	1.9E+0	Lung	1.9E+1	3.6E+1	Negligible		1E-6	3E-3
	Th-232	1.1E-3	Liver	7.1	2.8E+1				
	Po-210	6.2E-1	Bone	5.9	1.7E+1				
	U-238	1.1E-3							
Coal-fired Steam Electric Generating Stations (3.9)									
New CFSEGS: Midwestern Site	U-238	2.0E-2	Bone	4.2	2.9E+2			5E-5	3E-3
	U-235	1.2E-3							
	Th-232	7.3E-3							
Southeastern Site	U-238	2.0E-2	Bone	1.3E+1	2.2E+1			5E-5	2E-4
	U-235	1.2E-3							
	Th-232	7.3E-3							
Existing CFSEGS: Midwestern Site	U-238	2.9E-2	Bone	1.2+1	7.4E+2			9E-5	1E-2
	U-235	1.6E-3							
	Th-232	2.1E-2							
Southeastern Site	U-238	2.9E-2	Bone	3.1E+1	4.9E+1			5E-5	5E-4
	U-235	2.1E-2							
	Th-232	2.1E-2							
Coal-fired Industrial Boilers (3.10)									
Eastern Site	U-238	4.5E-3	Lung	7.4	2.3E+2			3E-5	2E-2
	U-235	2.6E-4	Bone	1.0E+1	6.2E+2				
	Th-232	3.3E-3							
Midwestern Site	U-238	4.5E-3	Lung	8.0	1.5E+1			3E-5	1E-3
	U-235	2.6E-4	Bone	2.2E+1	5.2E+1				
	Th-232	3.3E-3							

EMLEI 0069445

TABLE 13

Summary of Operations Whose Regulation Will Impact On API Member Companies

Operation	Isotype of Interest	Lifetime Risk to the Maximum Exposed Individual
Ground Water Treatment		
Southeastern Site	^{222}Rn	6×10^{-6}
Southwestern Site	^{222}Rn	1×10^{-5}
Geothermal Power	^{222}Rn	1×10^{-3}
Coke Production		
Northeast	^{222}Rn ^{232}Th ^{210}Pu ^{238}U	6×10^{-5}
Southeastern	ditto	1×10^{-6}
Coal Fired Steam		
New Midwestern	^{238}U ^{235}U ^{232}Th	5×10^{-5}
Southeastern	ditto	5×10^{-5}
Existing Coal Fire Industrial Boilers		
Eastern	ditto	3×10^{-5}
Midwestern	ditto	3×10^{-5}
Coal Mining and Cleaning		
Underground Mining	^{222}Rn ^{238}U ^{232}Th	9×10^{-3}
Strip Mining	ditto	5×10^{-6}
Coal Cleaning	ditto	1×10^{-4}
Natural Gas Combustion	^{222}Rn	3×10^{-6}
Natural Gas Turbine	^{222}Rn	4×10^{-6}

EMLEI 0069446

Regulatory Options and Their Implications

As far as industry is concerned, the regulatory issues should be:

1. What is an "acceptable level of risk"?
2. Which approach will be followed in setting the standard, a generic "committed" dose equivalent approach or regulation isotope by isotope?

The EPA risk assessment in part evaluated the risk to a "maximum exposed individual". The risk to this person from sources of interest to the API ranged from 9×10^{-3} (underground coal mining) to 1×10^{-6} (coal cleaning) Risks for this individual resulting from the combustion of fossil fuels ranged in the 5×10^{-5} area (Teknekron, 1981). Table 14 (Wilson, 1981) gives an indication of how those risks compare with others "accepted" by United States residents.

The federal bureaucracy also has been pondering over the concept of acceptable and de minimis risk. Dr. Roy Albert has been supporting 1×10^{-5} excess lifetime risk of fatal cancer in the drinking water area. The FDA has accepted 1×10^{-6} excess risk as acceptable for acrylonitrile migration in food containers. The USNRC is considering in staff discussions 1×10^{-4} excess lifetime risk of death from occupational exposure and 1×10^{-6} excess lifetime risk of death or lower as de minimis. The EPA assessment lists the combustion of fossil fuels as lying between 10^{-4} and 10^{-5}.

In addition to the definition of acceptable risk, the method of setting the limits could have considerable impact. There are two methods available to the EPA: regulate population-committed dose equivalent to air pollutants, the generic approach; or limit the emission of specific radionuclides.

The generic approach specifies that the emissions of radionuclides will be controlled to a level such that the total committed dose equivalent received by an individual does not produce a risk of fatal cancer exceeding that of a preselected whole-body dose commitment (ICRP, 1977; ICRP, 1980).

Mathematically, this can be expressed as

$$\frac{H_d}{D} + \sum_j \frac{I_{i,j}}{(ALI)_{i,j}} + \sum_J \frac{I_{o,J}}{(ALI)_{o,J}} \leq 1$$

where H_d is the deep dose commitment or (whole body dose)

$I_{i,j}$ is the annual intake of radionuclide j by inhalation

$I_{o,j}$ is the annual intake of radionuclide j by the oral route

$ALI_{i,j}$ is the annual intake by inhalation which will provide a risk equal to a deep dose commitment D

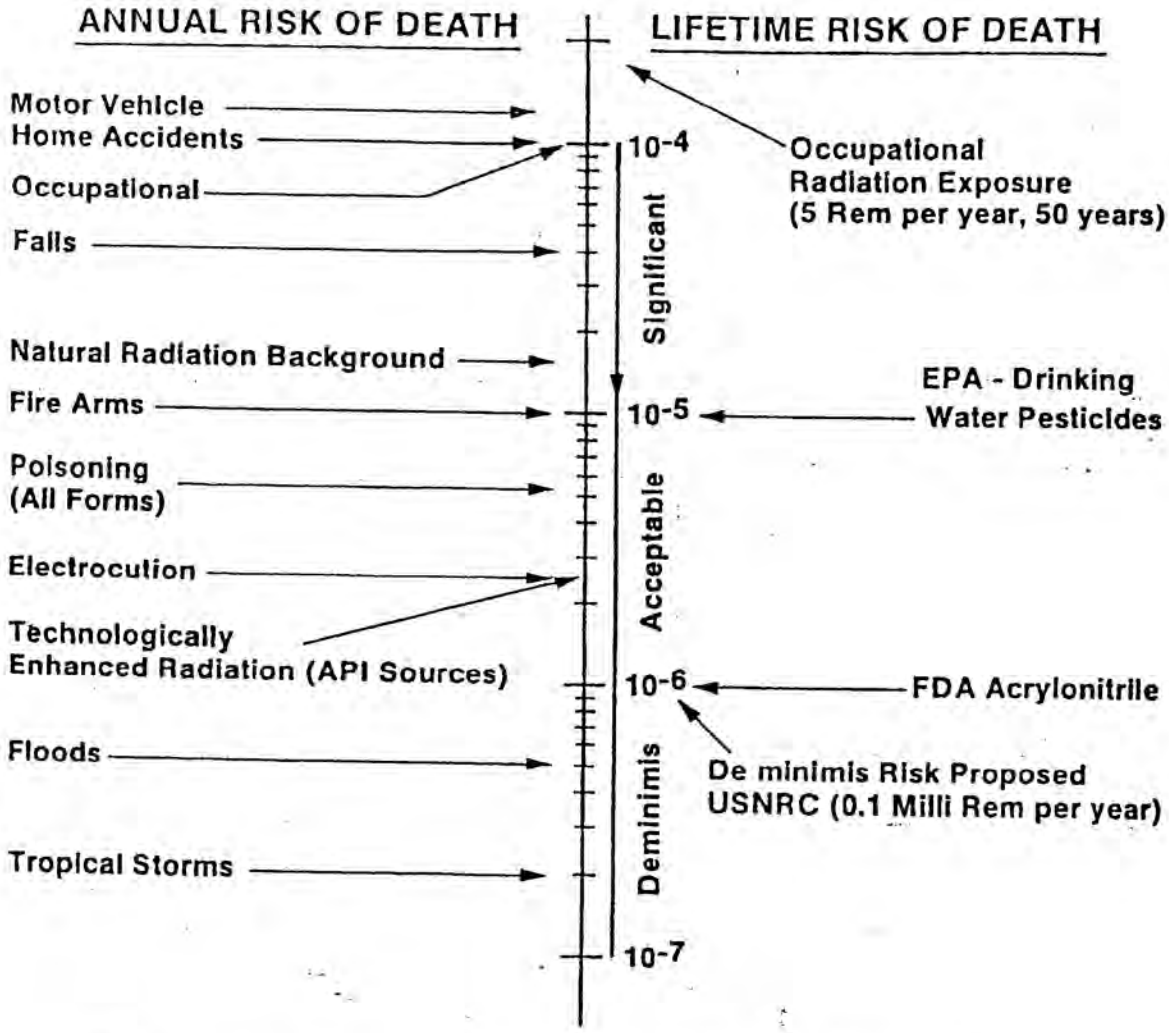
$ALI_{o,j}$ is the annual intake by the oral route that will produce a risk equal to a deep dose commitment D, and

D is the deep dose commitment resulting in an acceptable level of risk

EMLEI 0069447

TABLE 14

DEFINED LEVELS OF RISK



*Being considered in revision of 10CFR 20 Standards for Radiation Protection. This is not an agency position.

EMLEI 0069448

The risk factor for whole body radiation is about 1.65×10^{-4} fatal cancers per Rem (ICRP, 1977). If we calculate the committed whole body dose equivalent to produce an excess lifetime risk of 1×10^{-5}, we find

$$10^{-5}\left(\frac{\text{cancer death}}{\text{lifetime}}\right) = D\left(\frac{\text{rem}}{\text{yr}}\right) \times 1.6 \times 10^{-4} \frac{\text{cancer deaths}}{\text{rem}}$$

and that D, the whole body committed dose equivalent whole body, is 62.5 millirem for a single exposure. If we further average that exposure over a lifetime, as would be realistic for an air pollutant, the dose committed is 0.9 millirem/year. It could then be concluded that exposure to radioactive materials in combustion products of interest to the API plus all other sources should be less than 0.9 millirem per year.

The second approach, one based on a variant of derived air concentrations (DAC), is less complicated and perhaps more reasonable. It encompasses a bubble concept in that only that material leaving the plant confines is of interest. If the concentration of radionuclides, Uranium, Thorium, Radon, etc., is less than an established limit based on the Annual Limit of Intake (ICRP, 1980), the plant would be in compliance. It must be recognized that the current occupational DACs would have to be adjusted for 24-hour exposures and for the most susceptible exposed population. Compliance could be judged on an isotope-by-isotope limit or added in the manner of the TLV as below:

$$\frac{\text{Conc U}}{\text{DAC-U}} + \frac{\text{Conc Th}}{\text{DAC Th}} \cdots\cdots\cdots\cdots \frac{\text{Conc}^{210}\text{Pb}}{\text{DAC}^{210}\text{Pb}} \leq 1$$

where Conc is the concentration of the element of interest and DAC is the derived air concentrations for that environmental exposure.

The advantage of this system would be that each location could measure its own compliance without regard for air modeling, transport and dose response modeling. The disadvantage would be that the measurement is both difficult and expensive to make.

Table 15 compares the two methods and gives estimates of some limits. For either approach, 10^{-5} excess risk permits very small increases over the natural background.

Similar approaches as those suggested to regulate air pollutants are being applied to the development of the Reportable Quantity under CERCLA. Table 16 estimates the amount of raw material or product that will contain one reportable quantity of selected radionuclide for a weight, activity, or dose-equivalent approach. Depending on the mode of definition, very small quantities of petroleum products could easily contain reportable quantities of radionuclides.

EMLEI 0069449

Table 15
Estimate of Radioactive Material Concentrations to Produce
10^{-5} Lifetime Excess Risk of Fatal Cancer to a Maximum-Exposed Individual

Radioisotope	Solubility Class	Concentrations to Produce 10^{-5} Excess Risk in Target Population (curies per cubic meter)		
		At Stack	At Fenceline	
		Generic*	DAC**	MPC**
Uranium 238	D	2.6×10^{-8}	8×10^{-14}	6×10^{-15} (S)
	W		4×10^{-14}	1×10^{-14} (I)
	Y		2.6×10^{-14}	
Thorium 232	W	6.5×10^{-11}	6.5×10^{-17}	2×10^{-15} (S)
	Y		1.3×10^{-16}	2×10^{-15} (I)
Radium 226		3.9×10^{-8}	3.9×10^{-14}	(S) 6×10^{-15}
				(I) 4×10^{-15}
Radon 222		5.2×10^{-6}	5.2×10^{-12}	6×10^{-12}
Lead 210		1.3×10^{-8}	1.3×10^{-14}	8×10^{-15}
				1.6×10^{-14}

* Assumes 10^{-6} dilution factor, and the children (10-year old) as the target population, 15 m^3 air inhaled per day (ICRP, 1975).

** Assumes children (10-year) as target population.

EMLEI 0069450

TABLE 16

Amount of Product Needed to Assemble One Reportable Quantity of Uranium or Radon

Item/Product	Possible Form of Reportable Quantity			
	One Pound	One Milli Curie	One Micro Curie	5 Rem Committed Dose Equivalent
Crude Oil	2,162 Bbl	14,200 Bbl	14.2 Bbl	0.5 Bbl
Natural Gas	4.9×10^{16} MCF	714 MCF	714,000 CF	.017 MCF
LPG	4.9×10^{16} MCF	714 MCF	714,000 CF	.071 MCF
US Coal	33.6 T	222 T	0.2 T	.88 T
SRC Product	252 T	1,600 T	1.6T	.067 T
Shale Oil	890 Bbl	5,882 Bbl	5.8 Bbl	0.24 Bbl
Shale Waste	151 T	1,000 T	1 T	.04 T
Phosphate Rock	3.98 T	26.3 T	.026 T	.001 T
Ground Water	4.4×10^{16} Gals.	6.04×10^{9} Gals.	6.04×10^{5} Gals.	2.5×10^{4} Gals.

EMLEI 0069451

Control Options

Any control methodology proposed for radioactive materials must recognize the fact that radioactivity can not be modified or made inert by chemical means. It also must recognize that radioactivity dissipates at fixed rates through fixed sequences or series. Decay to daughter products cannot be guaranteed to reduce the hazard.

The control of emissions of naturally occurring radioactive materials can be accomplished by removing the radioactivity from the raw material or product, or by removing the radioactive materials after combustion. This removal can be accomplished by taking advantage of radioactive decay; by physically removing the radioactive material by washing, filtering, or by absorption; by chemically scrubbing the material from the product or combustion gas stream; or by combination thereof.

The removal of Radon 222 from natural gas could be accomplished by either decay or by absorption on a molecular sieve such as activated charcoal. Radon has a 3.83 day half-life. Storing natural gas for 5 half-lives approximately 20 days would change some 99.5% of the Radon in the influent stream to 21-year Lead 210, much of which will plate out in the storage tanks, pipeline, and process equipment. When one compares the derived air concentration for each, however, it appears that the relative health hazard may have been increased. The DAC for Radon plus daughters, target organ the lung, is 3×10^{-8} Ci per cubic meter, while that for Lead 210, target organ bone, is 1×10^{-10} (ICRP, 1980). Capturing the Radon on a molecular sieve and the Radon daughters on a high-efficiency (HEPA) filter cleans the product stream but changes a very dilute source of radioactive materials into a very concentrated source of radioactivity, presenting both an internal and external radiation hazard.

The removal of Radon from groundwaters can be accomplished by aeration (which releases the radioactive material to the ambient air) or through decay. The decay again introduces Lead 210 into the water which, again, is not totally free of hazard. The Lead 210 can be removed using bacterial filters; i.e., diatomaceous earth, with the resultant hazards associated with concentrating radioactive materials.

Uranium in crude oil presents a somewhat different dilemma. We estimated earlier in this paper that significant quantities of uranium potentially enter our refineries via crude oil. Little is known of its fate, however. Since the law of conversation of matter must apply, it can only end up in the product, the process waste, remain in the process equipment, or escape into the environment. The chemical properties of uranium suggest something concerning its ultimate fate. Uranium can be isolated by reducing uranium halides with alkali or alkaline earth metals or by reducing uranium oxides by calcium, aluminum or carbon at high temperatures. Strong acids can dissolve the metal, but it is relatively unaffected by alkali (CRC, 1981). It would seem likely to find most of the uranium plated out in the process equipment or concentrated in process wastes. Better understanding of the presence and fate of uranium in fuel oils is needed before a control scheme can be proposed.

EMLEI 0069452

The main contaminants in coal are members of the Uranium 238 decay series, primarily Radium, Radon, and Uranium. Cleaning the coal will remove much of the radioactive materials on the surface of the coal but will concentrate the material in the waste water. Pulverizing the coal will release much trapped radon to the atmosphere. Combustion will cause most of the radioactivity to be concentrated in the fly ash. High-efficiency scrubbers or filters may be required to reduce the health risks of such exposures to acceptable levels.

Impact of Regulation on API Members

The impact that the regulation of "radionuclides" under the Clean Air Act (CAA) will depend largely upon what the EPA decides is an "acceptable risk". The EPA has been forced to make this decision, and we will know the answer in 180 days.

What the EPA decides depends largely upon what society, as represented by its most vocal members, wants. Table 14 gives some indication of what we might expect, and it is likely that lifetime excess risks greater than one one-hundredth of that imposed by the natural background (1.5×10^{-5}) will be considered unacceptable. It is also equally likely that excess risks less than 10^{-7} will be considered de minimis. Table 17 summarizes candidates for regulation for different levels of acceptable risk.

Table 17
Operations Subject to Regulation as a
Function of Defined Acceptable Risk

Acceptable Risk Level
(Lifetime Excess Risk of Contracting Fatal Cancer)

1.5×10^{-5}	5×10^{-6}	1×10^{-6}
Geothermal Power	Groundwater Use (all locations) Geothermal Power	Groundwater Use (all locations) Geothermal Power
Coke Production (all locations)	Coke Production (Northeast only)	Coke Production (all locations)
Coal-Fired Steam	Coal-Fired Steam	Coal-Fired Steam
Coal-Fired Industrial Boilers	Coal-Fired Industrial Boilers	Coal-Fired Industrial Boilers
Underground Coal Mining	Underground Coal Mining Strip Mining (coal)	Underground Coal Mining Strip Mining (coal) Coal Cleaning Natural Gas Combustion Natural Gas Turbines

EMLEI 0069453

The impact of CERCLA on API members depends on the definition of reportable quantity. The data collected in this report appear to suggest that the CERCLA will place reporting requirements on many operating locations.

The impact of both regulatory actions is summarized on Table 18. It appears that regulation of radionuclides could impose a severe burden on API member companies and that both regulatory actions should be closely followed.

EMLEI 0069454

TABLE 18

Potential Impact of Regulation on API

Operation	Radio-Isotopes	Form	Potential For Regulation CAA	Potential For Regulation CERCLA	Potential Impact
Production					
LPG/NG	$^{222}Rn+d$	Gas	X		Removal of Radon (20 day storage)
Gas Liquids	$^{222}Rn+d$	Liquid	X	X	Removal of Radon (20 day storage)
Crude Oil	$^{238}U+d$	Liquid		X	Reporting and Control
Water Flood	$^{222}Rn+d$	Gas	X		Control Release of Radon
Brine Disposal	$^{226}Ra+d$	Solid	X	X	Control Release of Radon
					Reporting and Control, Disposal Site
Disposal of	$^{238}U+d$	Solid		X	Reporting and Control
Scrap Equip.,	^{226}Ra	Solid		X	of Disposal Site
Pipe etc.	$^{222}Rn+d$	Gas	X	X	Control of Release of
	^{210}Pb	Solid		X	Radon
Manufacturing					
Process Heat	$^{222}Rn+d$	Gas	X	X	Control of Release of Radon
Power Generation					
Gas Turbine	$^{222}Rn+d$	Gas	X		Control of Release of Radon
Gas Furnace	$^{222}Rn+d$	Gas	X		Control of Release of Radon
Coal	$^{238}U+d$	Solid	X	X	Control of Release of Radioactive
	$^{226}Ra+d$	Solid	X	X	materials. Control of Release of Radon
		and Gas	X		Radon from Flyash Disposal Site.
Geothermal	$^{222}Rn+d$	Gas	X		Control of Release of Radon
Disposal of	$^{238}U+d$	Solid		X	Reporting and Control of Disposal
Process Equip.					Control of Release of Radon
Bottoms/Sludge	$^{238}U+d$	Liquid	X	X	Reporting and Control of Disposal
					Control of Release of Radon
Coal Mining					
Underground	^{238}U	Solid	X		Control of Release of Radioactive
	$^{226}Ra+d$	Solid & Gas	X		Materials and Radon
Strip Mining	ditto	ditto	X		ditto
Cleaning	ditto	ditto	X	X	Reporting and Control of Waste
					Disposal Site

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OCCUPATIONAL EXPOSURES TO RADIOACTIVE SCALE AND SLUDGE

Coleman *et al* v. H.C. Price Co. *et al*

December 2013

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Table of Contents

1.0 Introduction

Radioactive Waste Management Associates has been retained by the Smith Stag law firm to evaluate the radiation and toxic exposures of the 33 plaintiffs involved in the case Coleman et al v. H.C. Price Co. et al.

The aforementioned plaintiffs worked in pipe yards and on onshore and offshore oil production rigs for various companies in Louisiana[1]. During these times, the workers were regularly exposed, without their knowledge, to naturally occurring radioactive material (NORM) in the course of oil field pipe cleaning and refurbishing operations at the pipe yards and oil production rigs. Workers were exposed to radiation through inhalation of the radioactive scale dust, incidental ingestion of radioactive scale dust and radioactive sludge, and to external radiation from the scale and sludge in the oil production pipes, radiographic inspections and from the scale and sludge deposited on their clothing and the ground of their work areas.

The plaintiffs were diagnosed with cancer, which we determined to be a consequence of their occupational exposures to radiation. Two of the thirty-three plaintiffs were diagnosed with diseases that often precede a cancer diagnosis. The remaining thirty-one plaintiffs involved in the case Coleman et al v. H.C. Price Co. et al. have been diagnosed with cancer, which we determined to be a consequence of their occupational exposures to radiation.

There were no radiation protection programs at the pipe yards and on the oil production rigs on which the workers worked and therefore no radiation measurements were made at the time the work was performed. Thus, the true radiation doses received by these workers will never be exactly known. In this report, a range of likely radiation doses is employed based on the technical literature. It is very likely that workers received doses well in excess of applicable limits to nuclear industry workers. This conclusion is evident even when modest values for exposure factors are used (scale and sludge activities, breathing rates, dust loadings, and so on). The radiation doses received by the workers greatly increased the workers' risk of developing cancer.

To prepare this report we reviewed court petitions, exhibits, deposition transcripts, previous work in similar cases, and the plaintiffs' medical and social security records. Interviews with the plaintiffs or the plaintiffs' family members were also conducted as well as several articles and reference documents which are listed at the end of this report. We performed spreadsheet calculations using standard dosimetry methodology for exposure to radiological contaminants, which are summarized in the tables at the end of the text. As additional information becomes available, we reserve the right to supplement this report.

2.0 Naturally Occurring Radioactive Materials (NORM)

As discussed earlier, the workers were exposed to naturally occurring radioactive materials (NORM) in scale and sludge though a variety of different pathways, including inhalation of scale dust, incidental ingestion of scale dust and sludge, and external direct gamma radiation emanating from radiographic inspections and scale and sludge deposited on the workers' clothing, work equipment, and on the floor of their work areas. Radiation exposure is assumed to have occurred from radium-226 (Ra-226) and

[1] See Section 5 for detailed descriptions of the plaintiffs' work histories.

radium-228 (Ra-228) and their radioactive decay products (all of which are assumed to be in secular equilibrium).

The following sections describe the presence of Ra-226 and Ra-228 in oil production piping. A more detailed discussion of the activities of scale and sludge used in this report can be found in Appendix A.

2.1 Radioactivity in Scale

Louisiana contains elevated naturally occurring radioactive materials (NORM) concentrations in its oil and natural gas production equipment[2]. When oil and natural gas are pumped from an underground formation, water contained within the formation is also extracted with the oil and gas. This water, known as produced water, contains dissolved mineral salts, which are radioactive. Uranium and thorium compounds are fairly insoluble and remain in the formation, but Ra-226 and Ra-228, progeny of uranium and thorium, are more soluble in water and become mobilized in the reservoir liquid.

As the natural pressure and temperature within the bearing formation falls, the dissolved solids in produced water precipitate out of solution and deposit as scale within the oil production piping. Scale, a hard residue, consists of salts that are composed of mainly barium, calcium, and strontium compounds. Because radium (Ra-226 and Ra-228 combined) shares similar chemical properties with these three elements, it also precipitates to form complex sulfate and carbonate salts in scale. Higher salinity in produced water results in higher radium concentrations, although the presence of high salinity does not necessarily mean that the water contains radium.

Scale is typically found in piping and tubing (oil flow and water lines), injection and production well tubing, manifold piping, and small diameter valves, meters, screens, and filters. According to the American Petroleum Institute (API), radium concentrations in scale tend to be highest in wellhead piping and in production piping near the wellhead, with concentrations as high as tens of thousands pCi/g. The largest volumes of scale have been found in water lines associated with separators, heater treaters, and gas dehydrators.

Scale in an oil production well increases over time, i.e. the scale buildup will be thickest in pipes that have been in the ground the longest. The thickness of scale build up in production piping and equipment may vary from a few millimeters to more than an inch. At times the scale may build up in production equipment to completely block the flow in 4-inch diameter pipes.

It is not clear that the contaminated piping with which the plaintiffs worked was screened for radioactivity before being handled by the plaintiffs. Because direct measurements are not available, we estimate the radioactivity in scale using reported measurements by the U.S. Environmental Protection Agency (US EPA)[3], Chevron[4] and Reed et al.[5].

[2] US EPA, 1993b
[3] US EPA, 1987
[4] NORM Study Team, 1990
[5] Reed, G, B Holland, and A McArthur, 1991

A study performed by the Chevron NORM Study Team reported an average Ra-226 content of 5,500 pCi/g for pipe scale[6]. The maximum readings observed in this study were much higher than this value. In addition, an earlier analysis by Chevron found a similar average of 5,960 pCi/g Ra-226 in pipe scale[7]. The report by Reed, *et al*. lists Ra-226 concentrations in pipe scale up to 6,027 pCi/g. Based on these studies, in this report we assume an average Ra-226 concentration of 6,000 pCi/g in pipe scale.

The ratio of Ra-226 to Ra-228 activity concentrations in fresh pipe scale is reported to be approximately 3:1[8,9]. Based on these findings, in this report we use a concentration of 6,000 pCi/g for Ra-226 and 2,000 pCi/g for Ra-228 in pipe scale. We assume secular equilibrium between Ra-226 and Ra-228 and their respective progeny, i.e. we apply the same activity in scale (in pCi/g) for the daughter nuclides as their parents.

Used, offshore oilfield production pipes contaminated with radioactive scale were handled onsite by many of the workers who worked on onshore and offshore production rigs and were also sent off-site to various pipe yards where workers cleaned and refurbished the contaminated pipes. Most often, used, contaminated pipes were cleaned by reaming out the scale using a rattler or sandblaster. In addition, pipes were also often cut and refurbished using acetylene torches. The scale removed from the cleaned pipes was generally left on the ground of the pipe yards after cleaning activities.

2.2 Radioactivity in Sludge

Like scale, sludge also deposits within oil production equipment. Sludges tend to accumulate on the oil and water side of the separation process, especially in areas where there are changes in pressure and temperature. The concentrations of radionuclides in sludge depend on the chemistry of the geologic formation and characteristics of the production process. Like scale, the quantity and concentration of sludge changes over time as the quantities of gas, oil, and water in the geologic formation change, with sludge increasing as the well ages and gas and oil are depleted.

Sludge deposits usually contain silica and are oily and loose, while dried sludge is more granular and has a consistency similar to that of soil. Some sludge remains oily even when dried.

Sludge deposited in oil production equipment during the extraction process is further removed from extraction fluids in the separator, a piece of oilfield production equipment that divides oil, gas and water into separate fluid streams based on their different densities. Thus, the extracted sludge tends to accumulate in the separator. The American Petroleum Institute (API) has determined that the greatest volumes of sludge settle and remain in the oil stock and water storage tanks. Like in scale, it appears that the activity of Ra-226 in sludge is approximately three times greater than that of Ra-228[10].

Since we do not have measurements of sludge concentrations present in production pipes of the oil rigs on which the plaintiffs worked, we use a range of sludge concentrations provided by the International

[6] NORM Study Team, 1990
[7] Scott, LM, 1986
[8] US EPA, 1993a
[9] Wilson, AJ, and LM Scott, 1992
[10] US EPA, 1993a

Atomic Energy Agency (IAEA)[11]. These concentrations were measured in various locations within the United States and we believe them to be a representative range of the concentrations to which the plaintiffs were most likely exposed. Table 3 lists the range of activities of Ra-226 and Ra-228 and some of their progeny in oil production sludge. For the sludge calculations, we assume secular equilibrium between Ra-226 and Ra-228 and their respective progeny, i.e. we apply the same activity in sludge (pCi/g) for the daughter nuclides as their parent.

2.3 Regulation of NORM in Louisiana Pipe Yards

NORM regulations on contaminated oil production equipment in pipe yards were not enforced in Louisiana until 1989. Long before regulations specific to NORM were promulgated, the oil and gas industry was aware that radioactivity was present in oil production tubulars. Radioactivity in oil and brine was reported as early as the 1930's[12], the USGS reported radioactivity in Kansas oil fields[13] in the 1950's, and the American Petroleum Institute (API) issued a report in 1982 that analyzed the potential impact of the inclusion of radionuclides into the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)[14] process of the petroleum industry. The report described in detail where specific radionuclides were prevalent: Uranium in crude oil, radium in brine, and radon in both oil and brine[15]. The report concluded, "*the regulation of radionuclides could impose a severe burden on API member companies*".

The first rules in Louisiana that specifically addressed NORM in relation to oil field equipment and pipe yards were promulgated by a "Declaration of Emergency" in February 1989. In September 1989, the Division of Radiation Control issued the State's current regulations regarding radioactive materials associated with oil and gas producing operations through the Department of Environmental Quality (DEQ) under Title 33 Part XV, Radiation Protection. The regulations state that individual pieces of incoming pipe yard shipments cannot exceed a dose rate limit of 50 µR/hr. Workers who are to handle equipment that exceeds the 50 µR/hr-limit require an appropriate license. Workers without an appropriate license could not work. These regulations are discussed in greater detail in section 7.0 of this report.

It is unclear to us when, or if at all, the pipe yards in which the plaintiffs worked began scanning their incoming shipments of used, contaminated oil production piping. In this report, we assume that all companies for which the plaintiffs worked abided by all regulations beginning in 1990, even though the regulations were repealed and repromulgated in 1992. In our calculations, we assume no pipes entering the pipe yard facilities after 1990 exceeded the limit of 50 µR/hr. If the pipe yards did not actually begin to scan their shipments in 1990, the actual radiation dose received by the plaintiffs will be greater than the doses calculated in this report.

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[11] IAEA, 2003
[12] Komlev, LV, 1933
[13] Armbrust, BF, and PK Kuroda, 1956
[14] Also commonly known as the Superfund Act. This law created a tax on the chemical and petroleum industries and provided broad Federal authority to respond directly to releases or threatened releases of hazardous substances that may endanger public health or the environment.
[15] API, 1982

In order to determine the concentrations of Ra-226 and Ra-228 that correspond to a dose rate of 50 µR/hr, we employed the program MicroShield Version 8.02[16], by Grove Software, Incorporated. MicroShield is a program used to estimate dose rates due to a specific external radiation source.

A linear relationship exists between radiation concentrations and their corresponding external dose rates. Therefore, we first used MicroShield to obtain the dose rate that corresponds to the total radium (Ra-226 + Ra-228) concentration in scale used in this report. We then extrapolated these results to determine the radium concentration that corresponds with a dose rate of 50 µR/hr.

As inputs to MicroShield, we assume an outer pipe diameter of 2 7/8 inches (7.3025 cm), a scale thickness of 0.2 cm, and a pipe wall thickness of 0.551 cm, as suggested by the US EPA[17]. We assume that each contaminated pipe is 30 feet long, and that radiation measurements would have been taken at the center of the pipe, on contact with the outer pipe wall. From MicroShield, we obtain a Ra-226 concentration in scale of 1,313.5 pCi/g, and a Ra-228 concentration in scale of 437.8 pCi/g that correspond with a dose rate of 50 µR/h.

Since Louisiana's NORM regulations apply only to oil production equipment entering pipe yards, we do not adjust the radioactivity of the scale and sludge the plaintiffs were exposed to on onshore and offshore oil production rigs after the year 1990.

A more detailed discussion on the activities of scale used in this report can be found in Appendix A. The following section describes the health effects caused by exposure to radioactive materials.

3.0 Radiation Exposure Pathways

Workers were occupationally exposed to radiation while working at various pipe cleaning yards and onshore and offshore oil production rigs. For the time workers spent working in these locations, they were primarily exposed to radiation via inhalation of radioactive scale dust, incidental ingestion of radioactive scale dust and sludge, and direct gamma radiation.

We calculate the radiation dose rate due to inhalation and ingestion of radioactive scale and sludge by first calculating the amount of radioactivity that a person inhaled or ingested per unit time, and then by employing standard dose conversion factors (DCFs) recommended by the International Commission on Radiological Protection (ICRP). These DCFs convert an amount of a specific inhaled or ingested radionuclide into the resulting inhalation or ingestion dose. Age-dependent DCFs from ICRP 68[18] (specific for workers) were also used to calculate doses from the inhalation and ingestion of radioactive materials. These age-dependent DCFs have been compiled into a database and put on the CD-ROM, ICRPDOSE2[19]. For this report, the appropriate DCFs were extracted from the database and used in our dose calculations.

[16] Grove Software Incorporated, 2008
[17] US EPA, 1993b
[18] ICRP, 1995
[19] ICRP, 2001

In addition to being age-dependent, ICRP 68 DCFs are specific to effected organ and/or tissue types (i.e., if a worker was diagnosed with bladder cancer, ICRP 68 DCFs specific to the bladder were used). In our calculations, we use the appropriate target organ recommended for each of the plaintiffs' cancer types by the National Institute of Occupational Safety and Health (NIOSH)[20].

The ICRP 68 DCFs were scaled in one-year increments of the commitment period to which each of the pipe yard workers were exposed to radiation. A commitment period is the time period between when a person is diagnosed with cancer and the time he was first exposed to radioactive materials. For example, if a pipe yard worker began working in 1973 and he was diagnosed with cancer in 1987, in 1973 he had a commitment period of 15 years, in 1974 a commitment period of 14 years, in 1975 a commitment period of 13 years, and so on and so forth.

For direct gamma radiation exposure, we employ the program MicroShield, version 8.02[21], developed by Grove Software, Incorporated. MicroShield 8.02 is a program used to estimate external dose rates due to specific radiation source geometries. The program allows its user to choose from sixteen different source geometries (such as a cylinder, sphere, disk, or rectangle) and up to ten different radiation shields. The program does not allow the use of multiple source geometries at a single time.

MicroShield users may also choose custom source and shield materials from the MicroShield database, or design their own source and shield materials with the option of over thirty different constituents. When designing a source or shield material, MicroShield calculates the attenuation and build up factors of all constituents.

MicroShield simultaneously calculates un-collided and build up results for 19 different organs by employing ICRP 74 dose conversion factors. ICRP 74[22] dose conversion factors link the operational quantities defined by International Commission of Radiation Units (ICRU) with the dosimetric and protection quantities defined by the International Commission on Radiological Protection (ICRP). We use MicroShield to calculate external radiation doses to the appropriate target organ for each of the plaintiffs' specific cancer type, as recommended by NIOSH[23].

3.1 Dose Due to Inhalation of Radioactive Particulates

We calculate the radiation dose rate due to inhalation of radioactive particulates by first calculating the amount of radioactivity that a worker inhaled per unit time, and then employing standard dose conversion factors (DCF) recommended by the International Commission on Radiological Protection (ICRP)[24]. These DCFs convert an amount of a specific inhaled radionuclide into the resulting inhalation dose. The inhalation dose rate can therefore be calculated using the following equation:

$DR_{inh} = C * A * V * DCF_{inh}$

[20] NIOSH, 2006a & 2006b
[21] Grove Software Incorporated, 2008
[22] ICRP, 1997
[23] NIOSH, 2006a & 2006b
[24] ICRP, 2001

Where:

DR_{inh}	Inhalation dose rate (mrem/time)
C	Air particulate concentration (mg/m^3)
A	Activity of Ra-226 and Ra-228 in scale (pCi/g)
V	Ventilation, or breathing rate (m^3/time)
DCF_{inh}	Dose conversion factor for inhalation for Ra-226 and Ra-228 decay chains (mrem/pCi)

The concentration of radioactive particulates in the air of the plaintiffs' work environment depended on the type of equipment used to clean and refurbish the used, NORM contaminated oil production pipe the plaintiffs handled. Pipes were cleaned using a rattler or a sandblasting machine, and particulate matter would also enter the air due to the cutting of used pipe with an acetylene torch.

A rattler, or reamer, is a rotating metal device attached to an air gun that spins at high speeds inside of the contaminated pipe. During this process, the rattler grinds and pulverizes the scale attached to the pipe wall and large amounts of particles and dust are blown out of the pipe with the air that powers the rattler. At the same time, scale is brushed off the outside of the pipe. The outside scale is sucked into a dust collector where the larger particles fall into a compartment known as a catcher and the smaller particles are blown directly into the air. Depending on the degree of contamination within each pipe, the cleaning process removes about 0.5 to 2 pounds of scale from the inside of 30-foot pipe joints[25].

At some pipe yards, sandblasters were also employed to clean the inner and walls of used, NORM contaminated pipe. Each sandblasting machine contains a large pot that carries sand or other abrasive blasting materials. A hose connected to the pot is inserted inside of a contaminated pipe and the tip of the nozzle sprays sand radially against the walls of the pipe, removing scale deposited on the pipe walls[26]. Many of the workers who operated the sandblasting machines recall that this process produced a great deal of dust in the air and on the ground of the pipe yards.

In addition to cleaning the inner and outer walls of pipes, workers often utilized an acetylene torch to cut used pipe. Acetylene torches were used to cut damaged pipe into smaller 3- to 4-foot segments so that it could be more easily disposed of, and workers also used the torches to cut the ends off of old oil production pipe before beveling new pipe threads at the ends of the pipes. The workers who used an acetylene torch to cut pipes wore a standard welding face shield. Many of the workers who used an acetylene torch recall that dust, sometimes as thick as cigarette smoke, was generated while they cut pipes.

As stated previously, there are no exact measurements of air particulate concentrations at the pipe yards and oil production rigs at which the plaintiffs worked. However, isolated measurements of particulate air concentration have been made at various Louisiana pipe yards, such as the Intracoastal Tubular Services (ITCO) pipe yard, and we employ these measurements in our calculations. Particulate

[25] Testimony of Mike Bulot in Grefer Case, p. 26.
[26] Garverick, L, 1994

air concentrations were measured as 11 mg/m^3 in the ITCO yard[27] and 53 mg/m^3 at another Louisiana pipe yard[28]. Both measurements were taken while pipe was being cleaned, but presumably at different distances from the cleaning machine. We assume these air concentrations resulted from the use of a rattler, since pipe cleaning was carried out using rattlers at the ITCO pipe yard.

Respirable particulate air concentrations resulting from sandblasting and other abrasive blasting activities have been measured and well documented. In one study[29], the abrasive blasting of a ship hull was found to generate respirable dust concentrations in air of 55 mg/m^3. A study by Samimi, et al,[30] measured dust concentrations due to abrasive blasting activities in a steel fabrication yard to be 37 mg/m^3. Additionally, the air concentrations of respirable dust in other abrasive blasting workplaces have been found to be greater than 100 mg/m^3.[31]

According to a 1987 report by GJ Newton[32] the measured concentration of aerosols in air from using an oxygen acetylene torch was 15 ± 11 mg/m^3, meaning that the concentration could be as high as 26 mg/m^3. The worker breathing zone is about 1.5 to 2 feet from the flame or saw. In a 1994 report by J.T. Karlsen et al[33], exposure to workers from aerosols was greater, but Karlsen only measures particulates that are 0.8 microns or larger. The Newton paper, on the other hand, measured particulates, ranging in size from a gas to 10 microns, with an average size of 0.3 microns in the breathing zone.
Due to a lack of specific measurements, we employ an air particulate concentration range, as opposed to a single value in our calculations. We expect that this range includes the "true" average air particulate concentration to which the plaintiffs were exposed while cleaning and cutting pipe. In the vicinity of the pipe cleaning and cutting processes, we use a respirable dust concentration of C = 10 mg/m^3 as a lower bound and a concentration of C = 30 mg/m^3 as an upper bound. This range includes the air particulate concentration measured at the ITCO pipe yard and from using an oxygen acetylene torch, but it is below the measurement obtained at the additional pipe yard and for the sandblasting processes.

Several of the plaintiffs wore protective hoods and respirators when operating the sandblasters in order to help protect them from inhaling a great deal of scale dust. Different types of protective hoods and respirators have different protective capabilities which are measured in units of workplace protection factors, or WPF. WPF represent the ratio between the air concentration of a specific contaminant outside of the hood and the concentration of this contaminant inside of the protective hood. Therefore, the higher the WPF, the greater protection provided by the hood or respirator.

WPF for specific types of hoods and respirators are regulated by the American National Standards Institute (ANSI). ANSI WPF have been agreed upon and adopted by the National Institute for Occupational Safety and Health (NIOSH) and the Occupational Safety and Health Administration (OSHA).

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[27] ITCOEX 925
[28] Radiation Technical Services of Baton Rouge, 1993
[29] Greskevitch, MF, 1996
[30] Samimi, B, et al., 1975
[31] State of Queensland, 1999
[32] Newton, G, et al., 1987
[33] Karlsen, J, T Torgimsen, and S Langård, 1994

In 1969, ANSI released Respiratory Protection Standard Z88.2, "Practices for Respiratory Protection." This standard set the first respirator protection standard for workplace hoods and respirators. Z88.2-1969 did not yet assign exact workplace protection factors for hoods and respirators, but instead recommended that "due consideration be given to potential inward leakage in selecting [respirator] devices." In addition, it contained a list of the expected air leakages into the face piece of various respirators and hoods.[34] In 1971, the OSHA standard for workplace respiratory protection[35] was largely adopted from the 1969 ANSI Z88.2 standard.

In August 1975, the joint NIOSH-OSHA Standards Completion Program published the "Respirator Decision Logic" which listed protection factors thought to be provided by several respirators and hoods. A WPF of 1,000-2,000 was given for supplied air-line hoods and respirators[36]. This meant that only 0.05% to 0.1% of the concentration of a contaminant outside of the hood would be able to leak to the inside of the hood.

In 1980, ANSI revised the Z88.2 standard, based on advances in research and technology that were made in the ensuing years. Z88.2-1980 established assigned protection factors for multiple types and families of respirators and hoods so that respirator selection, fit, and use were standardized. The Z88.2-1980 standard included a table of assigned protection factors.

In 1987, NIOSH revised its "Respirator Decision Logic" and reduced the WPF of supplied air-line hoods and helmets to 25, indicating that supplied air-line hoods actually offered less protection than was previously thought.[37] In 1992, ANSI revised its Z88.2 Respiratory Protection Standard mandating that air-supply hoods and respirators provide a WPF of 1,000.

For the plaintiffs who wore protective hoods and respirators before 1992, we employ a WPF of 25 when calculating the workers' inhalation doses. This is equivalent to a scale dust air concentration of 0.4 mg/m^3 to 1.20 mg/m^3. For the year 1992 and thereafter, we employ a WPF of 1,000, which is equivalent to a scale dust air concentration of 0.01 mg/m^3 to 0.03 mg/m^3.

For locations away from the direct vicinity of the pipe cleaning and cutting areas, but still within the pipe yard, we use a concentration range directly due to pipe cleaning and cutting operations that is ten times smaller, i.e. of 1 – 3 mg/m^3. To this, we add resuspension of scale particulates in the yard due to activities that mechanically moved scale. Such activities include movement of trucks and forklifts, road building, rack building and shoveling scale from ground into potholes. Workers walking around, as well as wind activity, would further re-suspend particulates. We estimate that particulate concentration due to resuspension is the same as particulate concentration at a construction site[38], 0.6 mg/m^3. The air particulate concentration in the pipe yards and oil production rigs away from the pipe cleaning and cutting operations therefore ranges from 1.6 - 3.6 mg/m^3. Workers did not wear protective hoods or

[34] ANSI, 1969
[35] Federal Register, 2008
[36] US DHHS, 1987
[37] *Ibid*
[38] US DOE, 1983

respirators when working at a distance from pipe cleaning or cutting machines. A detailed discussion of our calculations and estimates of the concentration range of respirable particulates is presented in App. A.

To calculate the radioactivity (A) in the dust, we use a scale activity of A = 6,000 pCi/g for Ra-226, and of A = 2,000 pCi/g for Ra-228. As discussed in Section 2.1 of this report, these estimates are based on measurements taken by the US EPA[39], Chevron[40, 41] and Reed[42]. We assume secular equilibrium between Ra-226 and Ra-228 and their respective progeny, i.e. we apply the same activity in scale (in pCi/g) for the daughter nuclides as for their parents. For the years after 1989, when Louisiana NORM regulations first came into affect in pipe yards, we use a reduced scale activity of A = 1,313.5 pCi/g for Ra-226 and of A = 473.8 pCi/g for Ra-228 for the times workers performed pipe cleaning and cutting operations in Louisiana pipe yards. These reduced scale activities correlate with an external dose rate of 50 μR/hr. We do not apply the reduced scale activities for the times workers performed pipe cleaning or cutting activities on onshore or offshore oil production rigs, as it was not required by Louisiana law that NORM contaminated equipment be monitored at these locations.

The amount of inhaled radioactive material not only depends on the amount of this material in the air, but also on the rate at with which the particles are inhaled. For adult male workers, we use the ventilation rate (or breathing rate) for moderate exercise recommended by ICRP 66[43] of V = 1.5 m^3/h for the times the workers worked in the pipe yards and on oil production rigs. When performing less strenuous work, such as office work or work inside an auxiliary building, we apply a reduced ventilation rate of 0.925 m^3/h[44].

Different DCFs exist for different exposure assumptions and depend on the solubility and diameter of the inhaled compound. For example, smaller particles will lodge deeper within the lungs and will be retained for a longer period of time[45]. For our calculations, we assume that the respirable scale dust is relatively insoluble and that the radioactive particles are absorbed by the body at a relatively slow rate.

For our calculations, we assume and that the particles generated by pipe cleaning operations involving the use of a rattler have aerodynamic median activity diameter (AMAD) of 1 μm. The diameter of particles released during sandblasting and other abrasive blasting processes has been well documented. A 1991 study performed by CJ Tung and CC Yu[46] found that radionuclide aerosols dispersed as a result of sandblasting steam turbines at the Chin Shan Nuclear Power Station in Taiwan had an AMAD of 3 to 4 microns (μm). An additional study by C Papstefanou[47] found that the average particle size released as a result of sandblasting had an AMAD of 3.1 μm. ICRP-68 states that field measurements taken from most abrasive blasting (sandblasting) situations result in an airborne blasting dust consisting of particles with

[39] US EPA, 1987
[40] NORM Study Team, 1990
[41] Scott, LM, 1986
[42] Reed, G, B Holland, and A McArthur, 1991
[43] ICRP, 1994
[44] Yu, C, et al., 1993
[45] Cember, H, 1996
[46] Tung, CJ, and C-C Yu, 1991
[47] Papastefanou, C, 2008

an AMAD of 1 µm. In this report, we assume that the particles inhaled by the workers who utilized sandblasters have an AMAD of 1 µm. In addition, we estimate that the respirable scale dust particles due to pipe cutting with an oxyacetylene torch have an AMAD of 0.3 microns[48]. Metal oxide fumes created by welding typically have a particle size between 0.2 and 1 micron.[49]

Using information about the workers' employment histories, we then calculate the total inhalation doses the workers received by multiplying their inhalation dose rates with their total exposure times:

$Dose_{inh} = DR_{inh} * \text{exposure time}$

Where:

$Dose_{inh}$	Total inhalation dose (mrem)
DR_{inh}	Inhalation dose rate (mrem/time)
Exposure time	Total time worker was occupationally exposed to radioactive material.

We utilized the workers' social security records as well as information they or their family members shared during telephone interviews to best estimate the total amount of time each worker was occupationally exposed to radioactive material. Total annual radiation doses were calculated specifically for each year the plaintiffs worked. If a plaintiff was exposed to radioactive materials for only a portion of a specific year, we multiplied the calculated dose for that year by the fraction of time the worker was exposed. The total annual radiation doses were then added together to derive the total dose each plaintiff received over the entire time of his employment.

According to the Committee Examining Radiation Risks of Internal Emitters (CERRIE), the risk due to exposure by alpha-emitting radionuclides taken internally may be as much as 10 times higher than calculated. This is because radiation risks are predominantly determined by epidemiological studies, particularly the study of Japanese bomb survivors 50. Japanese atomic bomb survivors were exposed primarily to an instant of external gamma and neutron radiation, and many researchers have extrapolated the bomb survivor results to radionuclides taken in internally. However, radionuclides that emit beta and alpha short range radiation over long periods of time present several issues that have not been studied in detail. The uncertainties associated with internal emitting radioactive materials, according to CERRIE, might be as much as ten times greater. A more detailed discussion on the uncertainties of exposures to internal emitting radionuclides can be found in Section 6.2.3 of this report.

While working, the plaintiffs were exposed to alpha-emitting radionuclides taken internally via inhalation of scale particulates. Therefore, we multiply the upper bounding inhalation radiation dose calculated for each of the plaintiffs by a factor of 10, to account for the uncertainty in dose rate due to internal alpha emitters, following CERRIE's findings.

3.2 Dose Due to Incidental Ingestion of Scale and Sludge

[48] Newton, G, et al., 1987
[49] NIOSH, 1988
[50] Preston, DL, et al., 2003

The incidental ingestion dose rate is calculated in a manner similar to the inhalation dose rate. We first calculate the ingested amount of radioactive material, followed by the application of a DCF for ingestion to obtain the ingestion dose rate:

$DR_{ing.} = IR * A * DCF_{ing.}$

Where:

DR_{ing}	Ingestion dose rate (mrem/time)
IR	Ingestion rate (g/time)
A	Activity of Ra-226 and Ra-228 in scale or sludge (pCi/g)
$DCF_{ing.}$	Dose conversion factors for ingestion for Ra-226 and Ra-228 decay chains (mrem/pCi).

According to the US EPA's Exposure Factor Handbook Volume I, a study showed that while doing yard work or other physical outdoor activity, adults ingest outdoor soil at 480 mg/day, while the value of 200 mg/day is also used for adults. This estimate is based on the assumption that a 50 μm thick layer of soil is ingested from the inside surfaces of the thumb and fingers of one hand, as most incidental soil ingestion occurs when soil is transferred from a person's hands to their mouth[51]. The incidental soil ingestion rate for outdoor yard work does not take into account eating in dusty work places and licking dust off lips; it is entirely due to accidentally ingesting material from one's hand while working. Eating food in a dusty environment would lead to much greater ingestion rates. We utilize the ingestion rate of (480 mg/day / 24 hr/day) 20 mg/hr, as the work the plaintiffs performed was in a dusty or dirty environment.

We assume 100% of the incidentally ingested material to be scale or sludge for the times the plaintiffs operated rattlers or acetylene torches to clean and cut pipes and when working in contact with sludge on oil production rigs. However, we assume only 50% of the incidentally ingested material to be scale for the times the plaintiffs operated sandblasters, as the other half of the ingested material would be sand or other abrasive material used during the sandblasting process.

As in our inhalation dose calculations, we apply scale activities of 6,000 pCi/g and 2,000 pCi/g for Ra-226 and Ra-228, respectively. For our sludge calculations, we utilize a range of activity for Ra-226 and Ra-228 and some of their progeny: 1.35 pCi/g to 21,600 pCi/g for Ra-226; 13.5 pCi/g to 1,350 pCi/g for Ra-228; 2.7 pCi/g to 35,100 pCi/g for Pb-210; and 0.108 pCi/g to 4,320 pCi/g for Po-210. Again, we assume secular equilibrium between the parent and daughter nuclides. For the years after 1989, when Louisiana NORM regulations first came into affect in pipe yards, we use a reduced scale activity of 1,313.5 pCi/g for Ra-226 and of 473.8 pCi/g for Ra-228 for the times workers performed pipe cleaning and cutting operations in Louisiana pipe yards. We do not apply the reduced scale or sludge activities for the times workers performed pipe cleaning or cutting activities on onshore or offshore oil production rigs, as it was not required by Louisiana law that NORM contaminated equipment be monitored at these locations.

[51] Ibid

Using information about the workers' employment histories, we then calculate the total ingestion dose the workers received by multiplying their ingestion dose rates with their total exposure times:

$Dose_{ing} = DR_{ing} * \text{exposure time}$

Where:

$Dose_{ing}$	Total ingestion dose (mrem)
DR_{ing}	Ingestion dose rate (mrem/time)
Exposure time	Amount of time worker was occupationally exposed to radioactive material

Like our inhalation radiation dose calculations, we utilized the workers' social security records as well as information they or their family members shared during telephone interviews to best estimate the total amount of time each worker was occupationally exposed to radioactive material. Total annual radiation doses were calculated specifically for each year the plaintiffs worked. If a plaintiff was exposed to radioactive materials for only a portion of a specific year, we multiplied the calculated dose for that year by the fraction of time the worker was exposed. The total annual radiation doses were then added together to derive the total dose each plaintiff received over the entire time of his employment. While working, the plaintiffs were exposed to alpha-emitting radionuclides taken internally via incidental ingestion of scale and sludge. Therefore, we multiply the upper bounding ingestion radiation dose calculated for each of the plaintiffs by a factor of 10, to account for the uncertainty in dose rate due to internal alpha emitters, following CERRIE's findings.

3.3 Doses Due to External Radiation

While working in pipe yards and on onshore and offshore oil production rigs, the plaintiffs were further exposed to radiation from the scale and sludge deposited on their clothing the ground of their work areas and from NORM contaminated pipes. External radiation is directly incurred as a radiation dose, as opposed to ingestion and inhalation, for which we first calculate the uptake of radionuclides by a person. The external radiation dose rate to the whole body due to scale and sludge contamination is based on the thickness of this layer and the radioactivity in the contaminated layer.

NORM contaminated sludge splattered all over the workers' clothing as they worked over oil production wells or handled used production pipes that were recently pulled from production wells. In our calculations, we assigned a thickness of 1 millimeter for the layers of sludge deposited on the workers' clothing as they worked. For the layer of sludge that accumulated on the ground of the oil production rig platforms, we assigned a thickness of 1 centimeter. This is an underestimate as many of the workers described that sludge deposited on the floor of the rigs was thick enough to cover the top of their boots.

Scale dust would also settle on the ground of the pipe yards and oil production rigs on which the plaintiffs worked if pipe cleaning and cutting operations were performed. For the layer of scale deposited on the ground of pipe yards and production rigs, we employ a thickness range of 1 centimeter to 5 centimeters. We apply this range because many of the plaintiffs recall that their work areas were never swept clean and therefore scale dust deposited on the ground would accumulate over time. In

addition, many Louisiana pipe yards often used scale dust deposited on the ground to fill potholes and other hazardous obstacles in the ground. It is also likely that the depth of scale to which the workers were exposed would vary, slightly, over time, and we believe this range to include the true depth of scale dust to which the plaintiffs were exposed while working.

The plaintiffs who worked in pipe yards also received an external radiation dose from scale built up on the inner walls of used contaminated pipes stored in their direct vicinity while working. Pipes were often stored in large racks in pipe yards, many of which were as wide as 10 pipes across and reached eight to ten feet in height. For each of the pipes contained in the racks, we assume an outer pipe diameter of 2 7/8 inches (7.3025 cm), a scale thickness of 0.2 cm, and a pipe wall thickness of 0.551 cm. These dimensions are based on physical parameters suggested by the US EPA[52]. Because most of the radiation emitted from the contaminated pipes within the racks would be shielded by the steel walls of the pipes in front of them, we assume the workers only received a radiation dose from the first row of contaminated pipes closest to their bodies. This is an underestimate. Since the contaminated pipes are cylindrical in shape, we assume the thickness of the scale in the first row of pipes to be (0.2 cm * 2) 0.4 cm, shielded by a 0.551 cm wall of steel.

To calculate the external radiation dose that the workers received directly from pipe (as opposed to scale deposited on the ground or a vertical wall of pipes), we employed Microshield. As inputs to MicroShield, we assumed a standard production pipe: an outer pipe diameter of 2 7/8 inches (7.3025 cm), a scale thickness of 0.2 cm, and a pipe wall thickness of 0.551 cm. Each contaminated pipe is 30 feet long, and radiation measurements were taken at the center of the pipe, on contact with the outer pipe wall.

Truck drivers who transported pipe were exposed to external radiation in a different way. For this pipe configuration, we assume that the pipe joints were stacked on top of each other, which results in an actual "wall" of pipe endings behind the driver's back. This situation can be approximated with an external radiation dose from a contaminated layer of infinite depth. To calculate the radioactivity of the load, we multiply the scale activity with the volume fraction of scale in the truckload of 0.02 (the other 98 % of the volume is steel and air). This dose rate includes shielding from the truck cab. We apply this dose rate for drivers only while they are actually driving NORM-contaminated pipes, but not while loading and unloading, which is better represented by the line source calculation described above.

Some plaintiffs were also exposed to gamma radiation from radiographic pipe inspections. Gamma radiation from Ir-192 tested the pipes for leaks after pipes were cleaned. Only **eight** of the plaintiffs were present during radiographic inspections; often, welders were in the proximity of radiographic inspections while they were being performed. Radiographic inspections exposed workers to high levels of radiation and radiographers rarely used any protective equipment. This lack of protection allowed radiographers and workers in the presence of radiographic inspections to be exposed to gamma radiation. In our calculations we include a range in the distance (15 to 30 feet) between pipe welders and the radiographic inspections. It is likely that the welders were actually closer to the inspections and this is therefore an underestimate. As inputs to Microshield we assumed an outer pipe diameter of 2 7/8

[52] US EPA, 1993b

inches (7.3025 cm), and a pipe wall thickness of 0.551 cm. For the source material we used 120 Curies of Iridium-192.

In addition, the workers who cleaned pipes with rattlers were exposed to a single layer of NORM contaminated pipes as they operated the pipe cleaning equipment. With these machines, 10 to 15 NORM contaminated pipes were stored in a single row on a pipe rack located near the pipe cleaning machine. The workers stood between the single row of used pipes and the pipe cleaning machine in order to easily and efficiently roll the dirty pipes onto the machine. The row of pipes located next to the pipe cleaning machine was approximately the same height as the workers' waists.

As with our inhalation and ingestion radiation dose calculations, we utilize an activity of 6,000 pCi/g for Ra-226 and 2,000 pCi/g for Ra-228 in scale. For our sludge calculations, we utilize a range of activity of 1.35 pCi/g to 21,600 pCi/g for Ra-226, 13.5 pCi/g to 1,350 pCi/g for Ra-228, 2.7 pCi/g to 35,100 pCi/g for Pb-210, and 0.108 pCi/g to 4,320 pCi/g for Po-210. We assume all progeny to be in secular equilibrium with their parent radionuclides. In our external radiation dose calculations, we reduce the activities of Ra-226 and Ra-228 in scale for the times the plaintiffs worked in pipe yards after 1989. However, as mentioned before, many of the workers recalled that the dust on the ground of the pipe yards was never swept; only larger pieces of trash and debris were picked up off of the ground. This means that the scale dust on the ground of the pipe yard accumulated and remained on the ground over several years, and therefore the scale dust on the ground after 1989 would not be reduced in activity. Thus, our calculations for scale deposited on the ground of the pipe yard are an underestimate.
We employ the program MicroShield Version 8.02 to calculate the external radiation dose rates the workers received due to scale and sludge deposited on their clothing, in oil production pipes, and on the ground of their work areas. Scale and sludge are not included in the twelve custom source materials contained in the MicroShield database, and so we designed our own source materials to represent the radioactive scale and sludge to which the plaintiffs were occupationally exposed. Radium (Ra-226 and Ra-228 combined) in produced water has been found to co-precipitate with calcium sulfate and calcium and barium carbonates, but most often with barium sulfate[53]. Thus, we designed the constituents of the scale and sludge to which the workers were exposed after the chemical composition of barium sulfate ($BaSO_4$); one part barium, one part sulfur, and four parts oxygen. All scale dust was assumed to have a density of 2.6 grams per cubic centimeter, whereas all sludge was assumed to have a density of 1.6 grams per cubic centimeter[54].

MicroShield allows its user to select one of 16 different source geometries (such as a cylinder, sphere, disk, etc.) when performing external radiation dose rate calculations. For our calculations for sludge deposited on the workers' clothing, we selected the source geometry of an infinite slab to best represent the workers' clothing that surrounded their entire bodies as they worked. We also selected the same source geometry for our calculations for scale and sludge deposited on the ground of the plaintiffs' work areas, since many of the pipe yards and oil rigs at which the workers worked were as large as 6 acres in area. Since the workers almost always stood upright while working and gamma radiation from scale and sludge deposited on the workers' clothing and on the ground of their work area

[53] US EPA, 1993a
[54] *Ibid*

constantly emanated from all directions around the workers, we take the average of the radiation dose rates calculated for the isotropic and rotational geometries for these types of exposure.

We employ a different source geometry for the times workers were exposed to racks of used, NORM contaminated pipes while working in pipe yards and on oil production rigs. Since we cannot simultaneously use multiple source geometries in MicroShield, we assume that the vertical contaminated racks of pipes are best represented as rectangular volumes bounded by the same dimensions. Since each pipe is approximately 30 feet in length and the pipe racks would be stacked to heights that ranged between 8 to 10 feet, we assume the racks of contaminated pipes surrounding the workers to be best represented as rectangular walls that are 30 feet wide and 8 feet tall. As mentioned earlier, we assume the workers received a radiation dose from only the first row of pipes closest to their bodies and the thickness of scale within that first row is 1 cm radius and therefore 2 cm shielded by a steel pipe wall with a thickness of 0.551 cm.

Based on information shared by the workers during their personal interviews, we assume the average distance between the workers and the pipe racks was approximately 10 feet. In our calculations, we assume the pipe yard workers had one rack of contaminated pipe within their work area at all times, whereas in reality, they may have had many more racks of pipes in their direct vicinity. Since the workers stood upright and continuously moved in all directions while working, we take the average of the radiation dose rates calculated for the isotropic and rotational geometries for this type of exposure.

For the times the workers cleaned pipes using rattlers, we use the annular cylinder geometry to best represent a single, NORM contaminated pipe. We assume the single row of pipes located next to the workers as they operated the rattlers contained 15 NORM contaminated pipes and the workers stood on contact with the first pipe in the row. We assume each pipe in the row has a length of 30 feet (914.4 cm), an outer diameter of 2 7/8 inches (7.3025 cm), a scale thickness of 1 cm, and a pipe wall thickness of 0.551 cm.

We assume that the workers who cleaned pipes using a rattler were exposed to this row of pipes from only one side of their bodies and that the contaminated pipes laid perpendicular to their bodies. If we assume that all pipes in the row are touching side to side, i.e. there is no space in between adjacent pipes, we calculate the view factor of each cylindrical pipe to be 0.18[55]. This means that 18% of the entire radiation from all pipes besides the one closest to the workers is absorbed by the pipe in front of it and does not strike the worker.

Since the row of NORM contaminated pipes next to the workers who used rattlers to clean pipe is only a single layer deep, the workers received a radiation dose from all of the 15 pipes in the row. In order to calculate the total radiation dose rate received by the workers from this row of pipes, we had to account for two individual factors using the MicroShield program; 1. the distance of each pipe from the worker and 2. the amount of radiation from each pipe that was capable of penetrating through the pipe walls in front of it.

[55] Avallone, EA, and T Baumeister, 1999

The radiation emanating from a pipe decreases as the distance between the worker and the pipe increases. To account for a decrease in radiation with distance, we use MicroShield to calculate the dose the workers received from each of the 15 pipes in the single row of pipe. That is to say, we calculated the dose rate to a worker received from the center of the first pipe located 2 inches from the worker, from the center of the second pipe located 6 inches from the worker, from the center of the third pipe located 10 inches from the worker, and so on and so forth. We then multiplied each of these dose rates by 0.82, assuming that 18% of the radiation emanating from each pipe is absorbed by the pipe directly in front of it.

To calculate the amount of radiation from each of the 15 pipes that was capable of penetrating through the pipe walls in front of it, we again employed the MicroShield program. To do this, we calculated the dose rate received by the worker from the center of each pipe accounting for both distance and shielding from the pipes located in front of it. For example, when calculating the dose to a worker from the second pipe in the row, we assumed the center of the second pipe was **6.35 centimeters** away from the worker and was shielded by a **1.102** cm thick wall of steel (accounting for the **two**-**0.551** cm thick outer pipe walls of the first pipe in front of it) and a **2** cm thick wall of scale (accounting for the **two 1** cm thick layers of scale on the inner walls of the first pipe in front of it). Similarly, the dose to a worker from the third pipe in the row was calculated assuming the center of the third pipe was located **13.66 centimeters** away from the worker and the pipe was shielded by a **2.204** cm thick wall of steel (accounting for the **four-0.551** cm thick outer pipe walls of the first and second pipes in front of it) and **4** cm thick wall of scale (accounting for the **four-1** cm thick layers of scale on the inner walls of the first and second pipes in front of it). [*Note by author: This paragraph is being rewritten to reflect actual calculation.]

Because the workers stood upright as they cleaned pipes with a rattler and because they constantly changed the direction of their bodies which faced the single row of contaminated pipes as they worked, we average the dose rates calculated for the antero-posterior and postero-anterior geometries. The dose rates calculated for all 15 pipes from both pathways are then added together to obtain the total dose rate received by the workers from the row of pipes.

The MicroShield program calculates radiation dose rates for 19 different organ types using ICRP 74 DCFs. For each of the plaintiffs exposed to direct gamma radiation, we select the dose rate calculated for the target organ appropriate to their specific cancer type, as recommended by the National Institute of Occupational Safety and Health (NIOSH)[56]. If MicroShield does not calculate the dose rate to a specific organ type, we use the calculated effective dose rate. In addition, we model the height of each plaintiffs' affected organ based on the average height of an American, adult male, 5 feet and 10.4 inches (178.9 cm)[57].

Using information about the workers' employment histories, we then calculate the total external radiation dose the workers received by multiplying their external radiation dose rates with their total exposure times:

[56] NIOSH 2006a & 2006b
[57] McDowell, MA, et al., 2008

$Dose_{\gamma}$ = DR_{γ} * exposure time

Where:

$Dose_{\gamma}$	Total external radiation dose (mrem)
DR_{γ}	External radiation dose rate (mrem/time)
Exposure time	Amount of time worker was occupationally exposed to radioactive material

Like our inhalation and ingestion radiation dose calculations, we utilized the workers' social security records as well as information they or their family members shared during telephone interviews to best estimate the total amount of time each worker was occupationally exposed to radioactive material. Total annual radiation doses were calculated specifically for each year the plaintiffs worked. If a plaintiff was exposed to radioactive materials for only a portion of a specific year, we multiplied the calculated dose for that year by the fraction of time the worker was exposed. The total annual radiation doses were then added together to derive the total dose each plaintiff received over the entire time of his employment.

3.4 Total Combined Dose from All Exposure Pathways

The radiation doses to the workers from inhalation, ingestion, and external radiation pathways were summed to derive a total radiation dose for each plaintiff over the entire time they were occupationally exposed to radiation. In Tables 1a and 1b, the TEDE dose rates are listed for each work category are shown, for pipe yard and rig workers, respectively. See Section 4 for details. In Table 2a and 2b, the exposure type, time as each exposure type, total doses received and risks are displayed for each plaintiff for pipe yard and rig workers, respectively.

3.5 Underestimates in the Exposure Assessment

The following pathways were either underestimated or not accounted for in the radiation dose calculations. If these pathways were considered, the total radiation doses received by the plaintiffs would be higher.

Eating lunch in an environment with high levels of radioactive dust (not included in the incidental soil ingestion rate).

Drinking water from coolers located near cleaning machines.

Chewing tobacco while at work.

Sitting under pipe racks in the summer to get shade from the sun. We ignored the external radiation dose from the pipe above and direct contact with the ground below.

Elevated external radiation from potholes filled with scale.

Indoor radon in workers' offices or inside of auxiliary buildings.

Indoor radon at workers' homes, emanating from contaminated work clothes and shoes.

Washing of contaminated vehicles (by workers, done at home).

Workers may have worked overtime or longer hours than accounted for in our calculations.

Ra-226 to Ra-228 ratio could be higher than 3:1, which would result in significantly higher doses.

The pipe yards in which the plaintiffs worked may not have begun screening incoming shipments for pieces of equipment greater than 50 μR/hr. This would result in significantly higher doses as the activity of scale to which the plaintiffs were exposed would not have been reduced beginning in 1990.

More than just the first row of contaminated pipes stacked in a pipe rack would have contributed to the plaintiffs' external radiation doses.

Scale buildup on the inner walls of the used oil production pipes to which the plaintiffs were exposed could have been thicker than 0.2 cm. This would greatly increase the plaintiffs' external radiation doses.

Scale deposited on the ground of the pipe yards may have accumulated over several years and would therefore not be reduced in Ra-226 and Ra-228 activities after 1989.

3.6 Likelihood that Cancers Were Caused Solely by Radiation

We use NIOSH's Interactive RadioEpidemiological Program (IREP), version 5.6[58] to calculate the likelihood that the plaintiffs' cancers were caused by radiation, rather than by something else. This program was developed by NIOSH to apply the National Cancer Institute's (NCI) risk models directly to data about exposure for a specific employee. IREP is based upon radioepidemiological tables developed by the National Institutes of Health (NIH) in 1985 and more recently updated with Japanese atomic bomb survivor data. These tables act as a reference tool to provide the probability of causation estimates for individuals with cancer that were exposed to ionizing radiation. The purpose of this program is to calculate the probability of causation that occupational radiation exposure received while working at a DOE facility or elsewhere within the nuclear weapons industry caused a specific type of cancer[59].

IREP is primarily based upon risk coefficients for cancer incidence gathered from the Japanese atomic bomb survivor studies. The risk coefficients have been adjusted to account for random and systemic errors in the atomic bomb survivor dosimetry as well as for the low dose and low dose-rate situations that are more common to American workers exposed while on the job. The probability of causation, or assigned share, for this risk is calculated as "the cancer risk attributable to radiation exposure divided by the sum of the baseline cancer risk (the risk to the general public) plus the cancer risk attributable to the radiation exposure". That is this is the fraction of cancers observed in a large heterogeneous group with similar exposure histories that would not have occurred in the absence of exposure. The assigned share

[58] NIOSH and SENES Oak Ridge Inc., 2009a
[59] NIOSH and SENES Oak Ridge Inc., 2009b

is estimated with uncertainty in IREP and is expressed as a probability distribution of results. The statistical uncertainty of the risk model is accounted for with a Monte Carlo simulation where repeated samples (typically 2,000) are taken from probability distribution functions and the probability of causation is calculated for each set of samples. The upper 99-percent confidence level from the resulting probability distribution is compared to the probability causation of 50-percent to determine eligibility for compensation of Manhattan Project workers. If cancer is determined to be "at least as likely as not" caused by radiation doses received while working, i.e., with a probability of 50-percent or greater at the 99-percent confidence level, than the worker is deemed eligible for compensation. The upper 99-percent confidence level is used to minimize the possibility of denying compensation to employees with cancer likely caused by occupational radiation exposure. The following equation is utilized in IREP to determine the probability of causation or assigned share:[60, 61]

$$PC = \frac{ERR}{RR} \times 100\%$$

Where:

ERR	Excess Relative Risk - Proportion of relative risk due solely to radiation exposure
PC	Probability of Causation
RR	Relative Risk - Ratio of the total risk from exposure divided by risk due to background alone

In the event of multiple primary cancers, a probability of causation for multiple primary cancers model is used. This is calculated from the following equation provided in IREP, using skin cancer and kidney cancer as examples of two multiple primary cancers:

$$PC_{Total} = 1 - \left[\left(1 - PC_{Skin}\right) \times \left(1 - PC_{kidney}\right)\right]$$

Where:

PC_{Total}	Total probability of causation
PC_{Skin}	Probability of causation for skin cancer
PC_{Kidney}	Probability of causation for kidney cancer

The probability of causation calculated by IREP specific to each workers' cancer type were used in the equation. Doses from external and internal exposure were entered together in the model.

Calculated doses from internal exposure using ICRP 68 derived DCFs and from external exposure using ICRP 74 derived DCFs (inherent to the MicroShield program) were entered into IREP. To enter the doses that resulted from internal radiation exposures, we employed a uniform distribution, using the low and high radiation doses the plaintiffs received during the times they worked at pipe yards and/or on oil production rigs. For external radiation doses, we use a uniform distribution, using the low and high radiation doses the workers received during their time of employment at pipe yards and/or on oil

[60] *Ibid*
[61] Federal Register, 2002

production rigs. In IREP, the appropriate cancer models were selected, along with the plaintiffs' years of birth and years of diagnoses.

The IREP results for each of the plaintiffs diagnosed with cancer can be found in Table 2a and 2b of this report.

3.6.1 Radiation Exposure Compensation Act

The Radiation Exposure Compensation Act (Public Law 101-426) established the groundwork for compensating individuals involved in the Manhattan Project, the program to develop the atomic bomb.[62] RECA provided for compensation for persons who had contracted cancer of the lung, esophagus, and pharynx. Under the amended RECA (yr 2000), the Energy Employees Occupational Illness Compensation Program (EEOICPA), a former Manhattan Project worker would receive compensation "based on the radiation dose received by the employee at the Manhattan Project facility and the upper 99-percent interval of the probability of causation at 0.5 in the radioepidemiological tables published under section 7(b) of the Orphan Drug Act, as such tables may be updated under section 7(b)(3) from time to time." In 2003, the National Cancer Institute and the Centers for Disease Control produced an updated set of radioepidemiological tables that estimate the probability of causation, into the software IREP. A user must input a person's dose to a specific organ, initial year of exposure, sex, and year at diagnosis. These tables were incorporated into the software program NIOSH-IREP, and were updated with the latest radiological risk data. NIOSH-IREP is the software we employ to assess the radiological risk to the plaintiffs under the same conditions, to determine that radiation was, more likely than not, responsible for the development of their cancer at the 99th percentile.

Since NIOSH-IREP only utilizes the Japanese bomb survivor data, it underestimates the causal connection between radiation and cancer since other more recent studies are not included. Specifically, the study by Cardis et al., that combines data of nuclear workers in 15 countries, shows a significant increase in cancers for fairly low average total doses.[63]

4.0 Specific Dosimetry

The plaintiffs held several different positions and were responsible for a variety of duties while working at the pipe yards and on onshore and offshore oil production rigs. Many workers carried out similar jobs and to simplify our exposure assessment, we group the workers exposure situations into **3** categories, which combined describe the individual exposures for the workers included in this report. Based on a personal interviews and/or plaintiff depositions, we then assign each worker the corresponding amount of exposure time for each type of exposure. We differentiate the workers' exposure into the following exposure types:

Type I: Work in Various Pipe Yards

A.) Physical work in pipe yard near pipe cleaning and cutting processes
B.) Physical work in pipe yard away from pipe cleaning and cutting processes
C.) Work inside of auxiliary buildings (office buildings, warehouses, etc.) adjacent to pipe yard

Type II: Work on Onshore and Offshore Oil Production Rigs

[62] US Department of Justice, 2009
[63] Cardis E, et al., 2005

A.) Physical work as a Roustabout
B.) Physical work as a Roughneck
C.) Physical work as a Derrickman

Some workers were exposed to the same type of exposure during their entire work history, whereas others were exposed to two or more types of exposure. It should be noted that many of the plaintiffs alternated between working in both pipe yards and on oil production rigs, and they sometimes carried out work that was mainly performed in pipe yards (such as cutting or cleaning pipes) on oil production rigs.

In addition, it should be noted that some of the plaintiffs' occupational radiation exposures varied slightly from those of other plaintiffs who carried out similar work duties. The work descriptions listed below are meant to be used as general descriptions of the types of radiation exposures the workers received while performing different types of work, but the specific details of each plaintiff's individual work histories have been accounted for in their individual radiation dose calculations.

4.1 Pipe Yards

The following sections describe the work duties and subsequent occupational radiation exposures of the plaintiffs who worked in various Louisiana pipe yards.

4.1.1 Physical Work Near the Pipe Cleaning and Cutting Processes

While performing physical work in pipe yards near the pipe cleaning and cutting process (using a rattler, sandblasting machine, or acetylene torch), workers were exposed to radiation via inhalation of radioactive scale dust, incidental ingestion of radioactive scale dust, and direct gamma radiation emanating from scale deposited on the ground of the pipe yards and built up on the inner walls of used oil production pipes.

Near the pipe cleaning and cutting machines, workers were exposed to a concentration of 10 – 30 mg/m^3 of scale dust in the air. We apply a ventilation rate of 1.5 m^3/hr for physical work near the pipe cleaning machines as workers constantly lifted and carried heavy oil production pipe and additional equipment while working. When operating rattlers, we assume 100% of the particulate material in the air to be scale, whereas we assume only 50% of the particulate matter in the air to be scale when the sandblasting machines were utilized, as sandblasting machines released both scale dust and sand or other abrasive material into the air.

We apply an ingestion rate of 0.2 g/hr for scale dust that was incidentally ingested by the workers due to hand-to-mouth contact while working.

Workers were exposed to a layer of scale deposited on the ground ranging between 1 centimeter and 5 centimeters while operating the pipe cleaning machines. Scale dust would build up in thick layers directly around the pipe cleaning machines. We apply a range for the layer of scale deposited on the ground near the pipe cleaning machines as it is likely that the depth of the layer of scale would vary, slightly, throughout the entire time the plaintiffs worked at the pipe yards.

If workers operated a rattler to clean NORM contaminated pipes, they were additionally exposed to a single row of contaminated pipes. Workers received a radiation dose from approximately 15 pipes laid out in a single row located directly next to their bodies as they worked.

We apply activities of 6,000 pCi/g of Ra-226 and 2,000 pCi/g of Ra-228 in scale for all exposures that occurred near the pipe cleaning machines before 1990. From 1990 and thereafter, we apply reduced activities of 1,313.5 pCi/g of Ra-226 and 437.8 pCi/g of Ra-228 in scale which correlate to a dose rate of 50 µR/hr, due to Louisiana regulations requiring that all incoming pipe yard shipments be scanned for NORM contamination greater than 50 µR/hr. We assume that all progeny are in secular equilibrium with the parent radionuclides.

4.1.2 Physical Work at a Distance from the Pipe Cleaning and Cutting Processes

The air of the pipe yards in which the plaintiffs worked was very dusty even at a distance from the pipe cleaning and cutting areas. However, the air at a distance from the pipe cleaning and cutting operations was much less concentrated with dust, and we therefore apply a reduced air concentration. In addition, yard activities at a distance from the pipe cleaning machines led to the resuspension of scale dust in the air, resulting in a total dust air concentration that ranged between 1.6 and 3.6 mg/m^3. Since workers were performing physical work in the pipe yards, such as loading and unloading NORM contaminated pipes, we apply a breathing rate of 1.5 m^3/hr.

Radiation exposure assumptions for incidental ingestion of scale and for external exposure to scale deposited on the ground of the pipe yards at a distance from the pipe cleaning and cutting process remained the same as those for workers near the pipe cleaning and cutting process. In addition, while working at a distance from the pipe cleaning and cutting operations, many of the workers received an external radiation dose from NORM contaminated pipes stored in racks throughout the pipe yards. The plaintiffs worked an average of 10 feet from at least one pipe rack, which was approximately 30 feet long, 8 feet tall, and 10 pipe diameters wide.

We apply activities of 6,000 pCi/g of Ra-226 and 2,000 pCi/g of Ra-228 in scale for all exposures that occurred at a distance from the pipe cleaning and cutting operations. As was assumed for exposures near the pipe cleaning and cutting operations, the activities of Ra-226 and Ra-228 in scale decreased for the years after 1989 due to Louisiana NORM regulations in pipe yards. We assume that all progeny are in secular equilibrium with the parent radionuclides.

4.1.3 Work Inside Pipe Yard Auxiliary Buildings

Inside of plant buildings that were not used for the cleaning, repair of inspection of pipe, workers were not exposed to external radiation. Also, the amount of incidentally ingested material would decrease, because the conditions were less dusty, and the ingested dust would not necessarily be scale dust. For the exposure in such auxiliary buildings, we therefore only take into account inhalation of particulates. Since the distance to the pipe cleaning machine would be relatively large, we only take into account the particulate concentration that is due to resuspension of deposited scale by the movement of heavy equipment. This air particulate concentration is the same as found at a construction site, of 0.6 mg/m^3.

Because work in auxiliary buildings is usually not very physical, we apply a reduced ventilation of 0.925 m^3/hr.

As with all of our other pipe yard calculations, we apply scale activities of 6,000 pCi/g for Ra-226 and 2,000 pCi/g for Ra-228 and assume these activities were reduced to 1,313.5 pCi/g for Ra-226 and 437.8 pCi/g for Ra-228 for all years after 1989 due to NORM regulations in Louisiana pipe yards. We assume that all progeny are in secular equilibrium with the parent radionuclides.

4.2 Oil Production Rigs

The following sections describe the work duties and subsequent occupational radiation exposures of the plaintiffs who worked on various onshore and offshore oil production rigs in Louisiana.

4.2.1 Physical Work as a Roustabout

Roustabout is the term used to represent a manual laborer on an oil production rig. Roustabouts are entry level workers and are responsible for carrying out peripheral rig tasks so that higher ranking members of the rig crew are not distracted while performing well workovers[64]. Roustabouts usually work hard, long hours and are responsible for a plethora of tasks while working on the rigs. These tasks may include cleaning the rig floor, cleaning and maintaining rig equipment and tools, aiding in well workovers, and transporting pipe throughout the rig.

Sludge built up on in the inner walls of the production pipe would spray all over the Roustabouts' clothing and any exposed skin as they worked. In addition, sludge would also cover the equipment rig floor for which they were responsible of maintaining. Many of the plaintiffs who worked as Roustabouts wore gloves, but their work was often so messy that they wore through two or more pairs of gloves per day.

In our calculations, we assume that Roustabouts were exposed to sludge on their clothing and the rig equipment and floor 75% of the total time they worked. During this time, they received a radiation dose due to incidental ingestion of sludge via hand-to-mouth contact and external radiation from a layer of sludge deposited on their clothing and the rig floor. We assume they were not exposed to sludge 25% of the time they worked on the rigs, as some of their tasks were performed at a distance from the production well and did not require them to work directly with NORM contaminated equipment or on the sludge-covered rig floor.

We apply a range of sludge activities for the radionuclides contained in sludge: 1.35 pCi/g to 21,600 pCi/g for Ra-226, 13.5 pCi/g to 1,350 pCi/g for Ra-228, 2.7 pCi/g to 35,100 pCi/g for Pb-210, and 0.108 pCi/g to 4,320 pCi/g for Po-210. We assume all progeny to be in secular equilibrium with their parent radionuclides. We do not reduce the activities of Ra-226 and Ra-228 in scale and sludge for the times the plaintiffs worked on onshore and offshore oil production rigs after 1989, as Louisiana regulations did not require that equipment be monitored for NORM contamination at these locations.

[64] A well worker is the process of performing maintenance or remedial work on an oil or gas production well. This work requires removing and replacing the pipe string from the production well.

4.2.2 Physical Work as a Roughneck

Roughnecks are members of the rig crew that rank directly above Roustabouts. These workers perform many of the same tasks as Roustabouts but are more involved in the well workover process. When performing well workovers, roughnecks spend the majority of their time on the production rig floor pulling used, NORM contaminated pipes from the well hole and replacing the pipes with new or refurbished ones. During a workover, sludge contained in the used production pipe sprays all over the workers clothing and exposed skin, as well as on the rig equipment and floor.

In our calculations, we assume that Roughnecks were exposed to sludge on their clothing and the rig floor and equipment 75% of the total time they worked. During this time, they received a radiation dose due to incidental ingestion of sludge via hand-to-mouth contact and external radiation from a layer of sludge deposited on their clothing and the rig floor as well as stacks of NORM contaminated pipe. We assume they were not exposed to sludge and contaminated pipe 25% of the time they worked on the rigs, as some of their work tasks were performed at a distance from the well hole and/or did not require them to work directly in contact with the NORM contaminated equipment or rig floor.

We apply a range of sludge activities for the radionuclides contained in sludge: 1.35 pCi/g to 21,600 pCi/g for Ra-226, 13.5 pCi/g to 1,350 pCi/g for Ra-228, 2.7 pCi/g to 35,100 pCi/g for Pb-210, and 0.108 pCi/g to 4,320 pCi/g for Po-210. We assume all progeny to be in secular equilibrium with their parent radionuclides. We do not reduce the activities of Ra-226 and Ra-228 in scale and sludge for the times the plaintiffs worked on onshore and offshore oil production rigs after 1989, as Louisiana regulations did not require that equipment be monitored for NORM contamination at these locations.

4.2.3 Physical Work as a Derrickman

Derrickmen are members of the rig crew that rank directly above Roughnecks. Derrickmen hold a unique position in that they work not on the production rig floor but from an elevated platform, known as a monkeyboard, suspended approximately 90 feet above the rig floor. When performing well workovers, derrickmen are responsible for running production piping in and out of the well hole. They work from an elevated platform located above the rig floor in order to manage the top of the pipe strings entering and exiting the production wells while other workers, such as roughnecks and roustabouts, manage the bottom of the pipe strings from the rig floor. The monkeyboards from which derrickmen work are located at a height of approximately 90 feet above the rig floor because, during a workover, most used production pipes are pulled from a well 3 pipes at a time. Since each pipe is approximately 30 feet in length, a string of 3 pipes is approximately 90 feet long.

The job of a derrickman is very physically demanding. In order to reach the tops of the pipe strings pulled from the production well during a workover, derrickmen must secure themselves to the monkeyboard with a harness and lunge off of the platform to lasso in the pipe string. Once a derrickman successfully grips the pipe string, he pulls it in to the platform and stores it in the platform's fingerboard. A fingerboard consists of several steel pipes, or "fingers", that extend outward to keep the pulled production pipe in place.

NORM contaminated sludge contained within the pulled production pipes covered the derrickmen's clothing and work area as they worked from the monkeyboard. In our calculations, we assume that

derrickmen were exposed to sludge on their clothing and the monkeyboard floor 100% of the total time they worked. During this time, they received a radiation dose due to incidental ingestion of sludge via hand-to-mouth contact and external radiation from a layer of sludge deposited on their clothing and the platform floor as well as stacks of used pipes near the monkeyboard.

We apply a range of sludge activities for the radionuclides contained in sludge: 1.35 pCi/g to 21,600 pCi/g for Ra-226, 13.5 pCi/g to 1,350 pCi/g for Ra-228, 2.7 pCi/g to 35,100 pCi/g for Pb-210, and 0.108 pCi/g to 4,320 pCi/g for Po-210. We assume all progeny to be in secular equilibrium with their parent radionuclides. We do not reduce the activities of Ra-226 and Ra-228 in scale and sludge for the times the plaintiffs worked on onshore and offshore oil production rigs after 1989, as Louisiana regulations did not require that equipment be monitored for NORM contamination at these locations.

5.0 Plaintiff Profiles and Radiation Dose Calculations

The specific exposure types to which each worker was exposed are discussed in greater detail in Section 5 of this report.

For each of the exposure types, we calculate a total organ-specific radiation dose in mrem, using the methodology described in the previous section. Detailed calculations are presented in Appendices A (inhalation and ingestion of particulates) and B (direct gamma radiation). Table 2a, 2b, and 2c gives a detailed listing of the plaintiffs name, what he was diagnosed with, the range of rems he was exposed to and his assigned IREP share. The plaintiffs were assigned a table based on their occupation: pipeyard worker (Table 2a), rig worker (Table 2b) and other occupation (truck driver, tank cleaner etc) (Table 2c).

5.1 Worker 1

Worker 1 was born January 4, 1933 and was diagnosed with multiple myeloma during 2006. Worker 1 stated that he was also later diagnosed with lung cancer but the timing of the diagnosis is not clear from his medical records. During his career, Worker 1 primarily worked for HBI Incorporated as a pipeline welder from 1962-1998. Several other companies are also listed on Worker 1's Social Security Records but he stated that he performed the same type of work under similar circumstances regardless of the employer. While employed as a pipeline welder, Worker 1 was responsible for welding oil and gas pipelines during their construction and frequently worked 12-16 hour shifts. All material used during the construction of these pipelines was new, making it unlikely that Worker 1 was exposed to NORM during these times. However, Worker 1 was frequently in the vicinity of radiographic inspections of newly completed welds. Inspections occurred more or less constantly and Worker 1 stated that he was typically one pipe joint away (~30 feet) during this time. Worker 1 was not completely certain as to what methods were used for inspection of the pipe, though he described a device that was put around each weld prior to inspection and mentioned that he specifically remembered gamma ray devices were used on occasion.

Over the course of his career, Worker 1 was exposed to direct gamma radiation from the radiographic inspection of pipeline welds. His calculated low dose is 17.15 rem while his high dose is calculated as 102.89 rem. These values are due in large part to the fact that Worker 1 was

approximately 30 feet away from radiographic inspections. Worker 1's IREP share is 26.83 %, indicating that work experience was a substantial and contributing factor to his cancer.

5.2 Worker 2

Worker 2 was born March 21, 1964 and was diagnosed with chronic granulocytic leukemia in April of 1994. Worker 2 passed away on August 26, 1994, just four months after his initial diagnosis from his battle with cancer.

Worker 2 worked for a variety of companies throughout his career in several pipe yards. His performed tasks include cleaning pipes in his earlier years and later moving on to pipe inspection towards the end of his working years. Worker 2 performed these duties when he was employed between the years of 1984 and 1994 for companies such as AD Surratt Pipe Inspection Company, Tuboscope Vetco International, and Acuren Inspection, Inc. Worker 2 frequently worked between 40 and 50 hours a week, Monday through Friday. In speaking with his widow, she recalled that he frequently came home from work covered in a thick layer of black filth (scale), and that his clothes, boots and skin were soaked with materials from the pipe yard. She also stated that he would often complain that his hands/skin hurt and burned at the days end from being covered in materials throughout the day of work. It is unclear exactly how Worker 2 was inspecting pipes at the pipeyard and whether or not he was receiving an additional gamma dose of radiation during this process. He also received a dose of radiation directly from the dirty pipes within the pipe yard, and this calculation was not included. Therefore, it should be noted that the values for Worker 2's exposure to radioactive materials may actually be slightly higher than what is represented below.

Worker 2's work in the pipeyard industry between 1984 and 1994 has resulted in exposure to NORM via the ingestion and inhalation of scale and direct gamma radiation from scale groundshine and while cleaning pipes. The calculated low dose for all of Worker 2's exposures is 118.65 rems while his high dose is calculated as 1868.78 rems. His IREP share is 99.73% indicating it is more likely than not that Worker 2's leukemia was caused by his exposure to radioactive materials on the job.

5.3 Worker 3

Worker 3 was born March 24, 1964 and was diagnosed with acute promyelocytic leukemia in January of 2008. Worker 3 has had chemotherapy, and is currently struggling to find and maintain employment due to pain and complications from his cancer.

Worker 3 performed a variety of tasks during his career throughout many employment opportunities with oil and pipeyard companies. His performed tasks include working as a truck driver for oil-filled trucks, as a pipe cleaner in a pipeyard, and later as a truck mechanic who worked on trucks that were hauling sludge/oil from the oil fields. Worker 3 performed these duties when he was employed between the years of 1990 and 2008, until he was diagnosed with cancer, for companies such as Ambar Incorporated, Quail Tools, BR Welding Supplies and Swift Transportation Company. Worker 3 frequently worked many hours in a week, ranging from 50 to 80 hours depending on his current employer. He recalls being dirty at the end of each work day from scale/sludge debris at each job. While cleaning pipes for Quail Tool, he would handle dirty pipes with no gloves and would often cough throughout the day from the inhalation of airborne materials being cleaned from the pipes. He also recalls being even dirtier

at times when working as a truck driver/mechanic of large trucks hauling oil field sludge, as he would get himself into tight spaces around and under the truck and near the hatch that closed to contain all of the materials inside. He specifically noted that his boots were often completely soaked in sludge materials from the truck throughout the entire day, and recalled that his feet would sometimes burn at night time when he returned home from work. Calculations were not included for the additional gamma dose that Worker 3 obtained from his dirty clothes in the workplace. Therefore, it should be noted that Worker 3's numbers for exposure to radioactive materials on the job are actually slightly higher than what is presented below.

Worker 3's work in the oil and pipeyard industry between 1990 and 2008 has resulted in exposure to NORM via the ingestion and inhalation of scale, the ingestion of sludge and direct gamma radiation from scale, sludge and cleaning pipes. The calculated low dose for all of Worker 3's exposures is 12.34 rems while his high dose is calculated as 455.65 rems. His IREP share is 97.49% indicating it is more likely than not that Worker 3's leukemia was caused by his exposure to radioactive materials on the job.

5.4 Worker 4

Worker 4 was born July 3, 1960 and died April 29, 2011. Worker 4 was diagnosed with lung cancer with malignant plural effusion during 2008. It should be noted that Worker 4 smoked approximately 1-1.5 packs of cigarettes per day for much of his life.

Worker 4 worked for a variety of companies near the Harvey Canal but always had the title of "pipe welder" or "pipefitter" regardless of employer. From 1977-2009, Worker 4 worked in a variety of shops helping to fabricate a variety of structures from new and used pipe (including used oilfield tubulars). Worker 4 also worked reconditioning used tubulars by welding new box and pin sections onto pipe joints. As a regular part of his job, Worker 4 would frequently cut NORM contaminated tubulars with an oxy/acetylene torch and would only wear a paper dust mask and face shield or shaded goggles for eye protection. Although Worker 4 was not a radiographer, as a welder he was frequently in the vicinity of radiographic inspections. Worker 4's son (who frequently worked along side his father) recalled that inspections typically involved panoramic radiography of welds, whereby an isotopic source is placed into the bore of a tubular. During these inspections, Worker 4 and other workers would be required to stand a minimum of 20' from the source although workers would sometimes inadvertently get closer. During the course of the day, Worker 4 would get covered with dust and his son recalls that he would frequently work in the vicinity of a variety of operations including cutting, welding and cleaning of NORM contaminated tubulars

During the course of his career, Worker 4 was exposed to alpha radiation via the inhalation of scale as well as direct gamma radiation pipe radiography and while welding NORM contaminated pipes. Worker 4's calculated low dose is 927.57 rems while his high calculated dose is 32933.65 rems. His IREP share is calculated to be 99.63% indicating that it is more likely than not that Worker 4's cancer was caused by on the job exposure to radioactive materials.

5.5 Worker 5

Worker 5 was born March 5, 1952 and was diagnosed with colon cancer around 2000. Worker 5's medical records are not entirely clear as to the precise timing of his diagnosis, however he underwent a colon resection in 2000, a procedure that likely would have followed shortly after a cancer diagnosis.

Worker 5 began his career in the oil and gas industry in 1969 working for various subcontractors. He recalled that the exact nature of his work was highly varied and that at different times he worked as a pipe cleaner in dedicated pipeyards, a pipefitter/welder in pipeyards and refineries and later as an independent fabricator/welder. Early in his career, Worker 5 was primarily involved in descaling NORM contaminated tubulars. He recalled that he worked for a variety of employers helping to clean tubulars in a dedicated pipeyard. Pipeyard locations varied, however Worker 5 recalled that the environment was always dusty and required using an automated pipe rattler. At the time, he specifically remembers that he did not wear a respirator or other protective equipment. Worker 5 gradually took on other responsibilities and eventually started work as a welder but continued to descale tubulars. As a welder, Worker 5 performed a variety of tasks with new and used tubulars, including welding and cutting them with an oxy-acetylene torch. Worker 5 also occasionally performed work in oil and gas refineries, helping with general pipefitting tasks. Near the end of his career, Worker 5 began contracting for pipefitting/welding jobs and was self employed. The tasks he performed were similar to those from earlier in his career with the exception that he not descale any NORM contaminated tubulars. Worker 5 has been on disability since 1989 and has not worked in the oil or gas industry since.

Worker 5 was subject to the inhalation and incidental ingestion of scale dust as well as direct gamma radiation from scale built up on the ground and in NORM contaminated tubulars. The calculated low dose for Worker 5 is 97.9 rems while the high dose is calculated as 268 rems. Worker 5's IREP share is 88.52 %, indicating it is more likely than not that his colon cancer was caused by exposure to radioactive materials on the job.

5.6 Worker 6

Worker 6 was born April 17, 1941 and was diagnosed with colon cancer during September 2004. This cancer soon metastasized to his brain and Worker 6 succumbed to his illness on April 13, 2005.

According to Worker 6's eldest daughter, he worked primarily as a pipe cleaner between 1968 and 2001. Although his Social Security records show a variety of employers listed during this period, Worker 6 worked for a single company that underwent frequent changes in ownership. Worker 6's daughter occasionally visited him on the job and remembers the work environment and tasks as he would describe them. She recalls that Worker 6 worked cleaning tubulars (but did not remember the specific equipment) and that he used cutting torches and welding equipment as a fairly regular part of his job. She also recalls that whenever she visited the yard it was very dusty and that her father's work clothing had to be washed separately because of the dust. While descaling tubulars, Worker 6 did not wear any specialized protective gear such as a dust mask or respirator. Worker 6 would also work very long hours, typically leaving home at 6:00 am and returning at 6:00 pm, 6 days per week. Worker 6's daughter recalls that her father performed all of his work in or near Harvey, LA.

While working as a pipe cleaner between 1968 and 2001, Worker 6 was exposed to alpha radiation from the ingestion and inhalation of scale dust as well as direct gamma radiation from scale

build up on the ground and racks of NORM contaminated tubulars. Worker 6's calculated low dose is 273.51 rems while his high dose is calculated to be 905.77 rems. His IREP share is 90.29%, indicating it is more likely than not that Worker 6's cancer was caused by his occupational exposure to radioactive materials.

NOTE: Worker 6's daughter mentioned that her father told her about asbestos exposure when she was young but she did not remember the specifics. This exposure information was not included in any of the risk calculations for Worker 6.

5.7 Worker 7

Worker 7 was born October 14, 1928 and was diagnosed with multiple myeloma during 2009 at the age of 81. Worker 7 passed away just weeks after his diagnosis with cancer and multiple years of surviving with Parkinson's Disease. During his career, Worker 7 worked for Intracoastal Terminal as a pipe cleaner for three years from 1982 to 1984. Following that, Worker 7 worked a long career of 35 years for Avondale Shipyards. With Avondale Shipyards, Worker 7 started out as a roustabout and completed general shipyard duties on barges and at wellheads for the first five years of employment. In 1959, Worker 7 took on a new position as one of the mechanics in the shipyard. For the next 31 years, Worker 7 worked on boats in the shipyard. The majority of his time was spent working on the tugboats that guided the barges in and out of the shipyard, but 25% of the time he was working directly on the actual barges. His work environment was often the inside of the boat on the very bottom level focused on the engines, valves and gears of the barges and boats. Worker 7's son recalls that Worker 7 was always covered in a dirty, black material. He rarely wore a respirator or gloves, and his hands were often stained black from work. He also recalls his father stating that the work environment was not optimal due to the lack of ventilation in the bottom of the boats and the inhalation of whatever materials were being worked on at the time. For both the pipeyard and the shipyard, Worker 7 typically worked ten to twelve hours a day, five to six days a week.

Over the course of his career, Worker 7 was exposed to direct gamma radiation from groundshine from the scale and NORM contaminated tubulars in the pipeyard, and the sludge in the shipyard. He was also exposed to alpha radiation from the inhalation of the scale in the pipeyard, and the ingestion of the scale and sludge from both work environments. His calculated low dose is 369.1 rem while his high dose is calculated as 6336.4 rem. Worker 7's IREP share is 98.08%, indicating that it is more likely than not that Worker 7's cancer was caused by his exposure to radioactive materials while working for Intracoastal Terminal and Avondale Shipyards throughout his career.

5.8 Worker 8

Worker 8 was born October 2, 1937 and was diagnosed with adenocarcinoma of the prostate in late 2003. Worker 8 was employed as a truck driver for much of his career and was ocasssionally required to deliver and pick up oilfield tubulars. From 1965-1966 and 1985-1986 Worker 8 worked for Cactus Pipe and Supply and Intracostal Tubular Services as a truck driver. During the course of a typical work day, Worker 8 would deliver and pick up pipe from various yards. Worker 8 recalled that although he did not physically load and unload pipe himself he was required to remain in close proximity to his truck during the process. Worker 8 would stay with his truck (and within the boundaries of the pipeyard) from anywhere between 30 minutes to 4 hours at a time, depending on the number of other trucks

waiting to be unloaded/loaded. It is important to note than the majority of the pipeyards visited by Worker 8 engaged in descaling operations and that he was subject to inhalation and ingestion of scale dust as well as direct gamma radiation while in the yard. Additionally, Worker 8 was subjected to direct gamma radiation from loads of NORM contaminated tubulars while driving his truck.

During the course of his career, Worker 8 was exposed to alpha radiation via the inhalation and ingestion of pipe scale as well as direct gamma radiation from scale built up on the ground and contaminated pipes on his truck. The calculated low dose for Worker 8 is 12.54 rems and his high dose is calculated as 20.67 rems. His IREP share is 11.23%, indicating that work experience is a substantial and contributing factor to Worker 8's cancer.

5.9 Worker 9

Worker 9 was born January 31, 1967 and was diagnosed with chronic lymphocytic leukemia (CLL) during September 2008. Medical records mention a preliminary diagnosis of small lymphocytic lymphoma at the same time, however medical documents from January 2011 state that Worker 9 was diagnosed with CLL.

Throughout his career Worker 9 held a variety of jobs, however his involvement in the oil and gas industry centered on fishing and slickline operations from 1984 to 1999. Fishing operations are typically performed on rigs where tools or other debris has been dropped down hole and must be retrieved. In these instances, a "work string" that is made up of tubulars with a smaller diameter than the main casing is lowered into the bore. The work string enables operators to use a variety of tools to perform a range of downhole operations. Worker 9 recalled that much of his responsibility while working on fishing operations involved handling work string which had been down hole and had been contaminated with mud. Since the work sting was not production tubing and did not have produced fluids or waters flowing through it, there would not have been NORM scale built up in it as is the case with production tubing. However, Worker 9 recalled that sludge was ubiquitous and that he would frequently become covered with it while on the job. Worker 9 also performed work as a slickline operator. This work is similar to fishing operations in that a tool or other hardware is lowered down hole except that a cable is used in place of the work string. Regardless of the specific task, Worker 9 stated that he would work between 40 and 65 hours per week and did not use a respirator or other protective gear.

Worker 9 was exposed to NORM contaminated drilling mud and sludge while working for a variety of employers as a slickline and fishing operator. Incidental ingestion of sludge as well as direct gamma radiation emanating from built up sludge on his clothing contributed to Worker 9's calculated low dose of 1.68 rems and a high dose of 556.05rems. This range of doses results in an IREP assigned share of 97.38%, indicating it is more likely than not that Worker 9's cancer was caused by his exposure to radioactive materials on the job.

5.10 Worker 10

Worker 10 was born May 3, 1950 and was diagnosed with multiple myeloma during 1998. Throughout his career Worker 10 worked a variety of jobs including pipe descaling for Tuboscope during

1976, pipe thread inspection for Vetco-Gray Tool from 1982-1983 and pipeyard security for Van Leeuwen Pipe and Tube Corporation in 1989. It should be noted that the length of time spent at each of these employers given by Worker 10 during his interview does not match his Social Security records and that calculations are based on values he provided.

During his time at Tuboscope, Worker 10 removed scale build up from the inside of used tubulars by sandblasting. Worker 10 described inserting a nozzle into the bore of each tubular in order to remove scale buildup. He recalled that during this time his work area was very dusty and that he did not wear any type of dust mask or respirator. He also recalled that there was a thick buildup of scale in his work area and that he stood approximately two feet away from a rack which held used tubulars. It should be noted that although some literature cites an AMAD of 3 μm for sandblasting particles, exposure calculations for Worker 10 assumed an AMAD of 1 μm, in line with previous RWMA reports. While employed by Vetco-Gray Tool, Worker 10 inspected recently cut threads on tubulars using mechanical gauges. Tubulars were already cleaned, however Worker 10 performed this work in a pipeyard where descaling operations were taking place. Worker 10 also worked briefly for Van Leewuen Pipe and Tube Corporation as a security guard, helping to patrol a yard where descaling operations were taking place. Worker 10 recalls that descaling typically took place in the yard and that he would sometimes be in close proximity to racks of used tubulars during his shift. Regardless of his employer, Worker 10 stated that he typically worked 40 hours per week with occasional overtime.

Worker 10 was exposed to alpha radiation via the inhalation and ingestion of pipe scale as well as direct gamma radiation from racks of NORM contaminated tubulars and scale build up near descaling operations. Based on his work history and interview, Worker 10's low dose is calculated as 25.49 rems while his high dose is calculated as 514.57 rems. His IREP share is 81.94% indicating it is more likely than not that Worker 10's cancer was caused by his on the job exposure to radioactive materials.

5.11 Worker 11

Worker 11 was born October 10, 1946 and was diagnosed with lung cancer during 1995. Throughout his career, Worker 11 worked descaling tubulars and occasionally inspected and cut tubulars for a company that often changed names along with ownership. While employed by Universal Tubular Services/ICO-Ultra Sonics Inspection/ICO Inc/ICO Worldwide LP from 1985-2002, Worker 11 worked in pipeyards throughout the South helping to descale NORM contaminated tubulars with an automated wire brush. He recalls that he typically worked six to seven days per week and between nine and eleven hours per day. Although Worker 11 worked in a variety of yards across the South (including in Texas, Oklahoma and Alabama) conditions were similar in that the air was typically dusty and the work area around each descaling machine had a thick scale build up. Worker 11 recalls that the scale on the ground would occasionally be nearly five inches thick due to the fact that there was little time during the day for cleaning the work area. Although descaling tubulars was his primary job, Worker 11 also used an oxy/acetylene torch to cut tubulars that were damaged and he occasionally assisted with radiographic inspections of recently cleaned tubulars. Worker 11 estimates that he performed each of these activities no more than a few hours per week.

Throughout his career, Worker 11 was exposed to alpha radiation via the inhalation and ingestion of pipe scale particulates as well as gamma radiation from built up scale in his work space, NORM contaminated tubulars, and radiography. Worker 11's low dose is calculated as 783.30 rems

while his high dose is calculated as 30938.29 rems. This large dose is due in part to the fact that the lungs (and the associated dose conversion factors) were selected as the target organ resulting in a relatively larger dose from inhalation of particulate. Worker 11's IREP share is 99.39% indicating it is more likely than not that his cancer was caused by exposure to radioactive materials on the job. It should also be noted that Worker 11 smoked about a half pack of cigarettes per day for 30 years and that this has been taken into account for the determination of his IREP assigned share.

5.12 Worker 12

Worker 12 was born July 30, 1922 and was diagnosed with gastric cancer in April of 1996. Worker 12 passed away on October 19, 1997, just over a year after his initial diagnosis from his battle with cancer.

Worker 12 worked for a variety of companies throughout his career in several pipe yards. His performed tasks included welding NORM contaminated pipes for each company. Worker 12 served as a pipe welder when he was employed between the years of 1947 and 1965 for companies such as Brown and Root, Ayer Marine Service, Berwicjk Bay Shipyard, Harms Marine Corporation, Patterson Shipyard, Avondale Shipyard and Berry Brothers Oilfield Service. Worker 12 frequently worked between 50 and 60 hours a week, Monday through Friday and occasionally Saturday. In speaking with his daughter, she recalled that he frequently came home from work covered in a thick layer of black filth (sludge), and that his clothes, boots and skin were soaked with black residue from welding materials on the job site. She remembered that he would return home so dirty, that he would strip of his work clothes before coming inside. Because of the filth, he later was given work uniforms to wear on the job and leave on-site at the end of the day. She also remembers that his hands were stained a dark black from the great amount of time spent at work welding dirty materials. When referring to "welding", his daughter said that her father wasn't always necessarily welding pieces together, but that he was often repairing broken/cracked pipes that were dirty with residue.

Worker 12's work as a welder in the oilfield industry between 1947 and 1965 has resulted in exposure to NORM via the ingestion and inhalation of sludge and direct gamma radiation from sludge and NORM contaminated tubulars. The calculated low dose for all of Worker 12's exposures is 278.8 rems while his high dose is calculated as 1233.3 rems. His IREP share is 95.5% indicating it is more likely than not that Worker 12's gastric cancer was caused by his exposure to radioactive materials on the job.

5.13 Worker 13

Worker 13 was born November 1, 1946 and was diagnosed with chronic lymphocytic leukemia (CLL) and stage 3-B non-Hodgkin's lymphoma (NHL) during November, 2007. Worker 13 worked a variety of jobs throughout his career but primarily worked as a welder. For approximately half of each year from 1966 to 1979, Worker 13 would work within a pipe yard fabricating structures using NORM contaminated tubulars. He would frequently use an oxy/acetylene torch to cut used tubulars and was in the vicinity of radiographic pipe inspections, however he was not issued a radiation monitoring badge or respirator. Worker 13 stated that he worked in a variety of pipe yards and remembers descaling operations typically took place within these yards. Regardless of where he was employed, Worker 13 stated that he would usually not take a job unless he could work 80 hours/week. During his interview, Worker 13 stated that during the summer months he would often work on off shore oil rigs, helping to

perform general welding duties on the rig. He stated that during his time off shore he was frequently covered with sludge.

During his career, Worker 13 was exposed to alpha radiation via the ingestion of sludge and inhalation of pipe scale as well as direct gamma radiation from radiographic inspections, NORM contaminated tubulars, and sludge build up his clothing. Worker 13's calculated low dose is 516.1 rems while his high dose is calculated as 19412.1 rems. His IREP share is 99.43% indicating that Worker 13's non-Hodgkin's lymphoma was more likely than not caused by his occupational exposure to radioactive materials.

Although Worker 13 was diagnosed with NHL he was also diagnosed with CLL, a cancer which is sometimes considered to have no link to radiogenic exposures. However, a review by Richardson et al. (2005) finds that the current understanding of CLL pathogenesis describes a process whereby mutational events (which can be produced by ionizing radiation) play an important role in carcinogenesis. CLL is typically considered non-radiogenic in origin partly because the link between CLL incidence and exposure to ionizing radiation is difficult to identify via epidemiologic methods. The long asymptomatic period and protracted period of morbidity associated with CLL make positive associations between CLL and radiation difficult (Richardson et al., 2005). CLL may also be obscured by competing causes of death (Richardson et al., 2005). Richardson et al. (2005) state that studies on the order of one to two decades are likely not long enough to observe effects of radiation on CLL due to the fact that the time between initial exposure and follow up is not sufficient to allow for the induction, latency and morbidity period associated with CLL. Ultimately the authors (Richardson et al., 2005) state that CLL occurrence is like other forms of cancer in that its incidence will be increased by exposure to ionizing radiation. At a fundamental level, the authors (Richardson et al., 2005) state that if CLL has no radiogenic link then it must be an exception to the general principles of radiation carcinogenesis and at the level of DNA damage there is no basis for the assumption that no link exists.

5.14 Worker 14

Worker 14 was born on November 21, 1943 and after struggling with chronic kidney disease (CKD) died on December 25, 2010. This is a non-cancerous disease however CKD is often a preceding condition to Kidney Cancer and studies have found that radioactive exposure is linked to the development of CKD (Moulder & Cohen 2005).

During his career, Worker 14 worked one year (1974) in the railroad industry for Industrial Railroad Service Inc. where he laid tracks in pipe yards. While laying railroad tracks, Worker 14 was exposed to the dust in the pipeyard. Worker 14 worked a span of five years (1982, 1987-1990) for Intracoastal Tubular Services as a pipe cleaner.

Worker 14's wife recalled that he would come home dusty and covered in grease from the pipe yard each night.

During his career, Worker 14 was occupationally exposed to direct gamma radiation from scale on the floor of the pipe yards (groundshine) and from cleaning pipes. His total minimum radiation dose for is calculated to be 155.2 rems while the total maximum radiation dose is calculated to be 1273.19

rems. Worker 14's IREP share is 94.79% indicating that exposure to radiation is more likely than not a contributing factor for the development and cause of his cancer.

5.15 Worker 15

Worker 15 was born January 25, 1949 and was diagnosed with lung cancer early in 2009, requiring removal of part of his lung. It should be noted that Worker 15 is a former cigarette smoker and that this has been accounted for IREP assigned share determination.

Worker 15 worked for a variety of employers during his career but performed similar tasks. Worker 15 stated that he was often contracted to firms and began working as a tank cleaner in 1976 and that his primary task was to clean the inside of tanks recently drained of used drilling mud. These tanks were located in a variety of places including onboard ships and near land based rigs. Although Worker 15's main task was cleaning tanks, he briefly descaled tubulars and worked in the Avondale Shipyard. It should be noted that he also occasionally worked outside of the oil industry and was sometimes employed cleaning tanks that did not contain NORM. Worker 15 stated that he was sometimes unemployed between jobs but this was usually not the case. Later in his career he took on a more supervisory role but still entered tanks frequently in order to inspect them before and after cleaning was performed. Regardless of where he was working or what task was performed, Worker 15 recalled that he frequently worked long hours, sometimes 70-80 hours per week.

Worker 15 describes the insides of used mud tanks as being covered with sludge that would have to be squeegeed off. He stated that the only time he wore a full face respirator was during the late 1980's and early 1990's. The majority of the time spent inside tanks was with minimal personal protective gear. Worker 15 stated that he received training for work in confined spaces and that he was frequently briefed beforehand on the occurrence or NORM in mud tanks. He also stated that he would be scanned with a handheld radiation detector after washing up and before leaving the jobsite.

While inside used mud tanks, either inspecting or cleaning them, Worker 15 was subject to the ingestion of sludge, as well as direct gamma emanating from sludge built up on interior tank surfaces and his clothing. Worker 15 was also subject to the inhalation and ingestion of scale dust while briefly cleaning pipes and while working in the Avondale Shipyards, albeit at a relatively low concentrations. The calculated low dose for all of Worker 15's exposures is 69.1 rems while his high dose is calculated as 876.2 rems. This results in an IREP assigned share of 89.97%, indicating it is more likely than not that Worker 15's lung cancer was caused by exposure to radioactive materials on the job. Worker 15's dose would be even higher if we accounted for the fact that he was likely totally surrounded by NORM contaminated sludge while in tanks; current calculations assume tanks had sludge built up only on the floor and walls. It should be noted that Worker 15 believes he may have been periodically exposed to asbestos between 1981 and 1986 while removing fireproof brick from boiler rooms onboard ships and that this exposure has not been factored into his IREP share determination.

5.16 Worker 16

Worker 16 was born May 8, 1923 and was diagnosed with chronic myelogenous leukemia (also known as chronic myeloid leukemia) in 1985, later succumbing to his disease in 1988. During his career Worker 16 worked for Tube-Kote Inc. (which later became Tuboscope Vetco International) between

1957 and 1983. Worker 16 held a variety of positions at the company, eventually working his way from Pickler, to Pipe Coater to Coating Inspector. Worker 16's son worked with his father several summers and has a good recollection and understanding of what type of work his father did and what the conditions were like when he was there. Worker 16's son recalls that Worker 16 initially worked in pickling operations, helping to remove scale build up from pipes by dipping them in an acid bath and that later Worker 16 operated a machine that would coat recently cleaned tubulars. Worker 16's son recalls that during the final six years of his father's employment, Worker 16 inspected recently coated tubulars. It should be noted that the entire time Worker 16 was working for Tube-Kote/Tuboscope Vetco International, he was in the vicinity of pipe descaling operations. Worker 16's son recalls that descaling in this particular yard was done by sandblasting. Worker 16's son also stated that Worker 16 used an X-ray machine to inspect pipe coating thickness, however based on available information it is unlikely that machines used to measure/inspect coating thickness utilize a radiographic source. Instead it is more likely that machines employing ultrasonic methods were used; these machines do not contribute to Worker 16's radiation dose totals. Regardless of his assignment, Worker 16 would typically work between 40 and 48 hours per week, sometimes working an extra shift. He would also eat his lunch in a break room that was under the same roof as coating/descaling operations and would only occasionally wear a dust mask.

While employed by Tube-Kote/Tuboscope Vetco, Worker 16 was occupationally exposed to direct gamma radiation from pipe racks near his work area as a pickler and pipe coater, as well as alpha radiation via ingestion and inhalation of scale particles his entire time with the company. Worker 16's calculated low dose is 102.02 rems while his high dose is calculated as 1161.02 rems. His IREP share is 99.36%, indicating it is more likely than not that Worker 16's leukemia was caused by his occupational exposure to radioactive material.

5.17 Worker 17

Worker 17 was born October 3, 1956 and was diagnosed with bilateral renal tumors during August, 2008. During his career (1975-2005), Worker 17 worked as a supervisor for a company listed under various names including Patterson Truck Lines, Patterson Tubular Services and Cudd Pressure Control Incorporated. Worker 17 mentioned that he either worked at yards located in Houma, LA or Morgan City LA and conditions were similar regardless of the location. While employed as a supervisor, Worker 17 worked hands on directing the loading, unloading and transport of new and used tubulars. Though he was formally a supervisor, Worker 17 frequently worked alongside laborers handling shipments of pipe and was outdoors in the yard. During the course of his workday Worker 17 would sometimes be in close proximity to pipe descaling operations and the resultant dust and scale build up as well as direct gamma radiation from racks of contaminated pipes. From 1992-1995 Worker 17 stated that he worked almost entirely in an office on site and only occasionally entered the yard. Once he returned to his duties in the yard he was tasked with the extra responsibility of measuring the radiation level of incoming shipments of used pipe. Worker 17 recalled that it was not uncommon for the yard to refuse shipments because they exceeded standards.

Throughout his career with Patterson Truck Lines, Patterson Tubular Services and Cudd Pressure Control Incorporated, Worker 17 was exposed to alpha radiation from the ingestion and inhalation of scale, as well direct gamma radiation from scale on the ground (groundshine) and contaminated drill

pipes. The low calculated dose for Worker 17 is 169.82 rems while his high calculated dose is 14684.48 rems. His IREP share is 99.62%

5.18 Worker 18

Worker 18 was born September 20, 1957 and was diagnosed with non-Hodgkin's lymphoma during August 2003. Although preliminary documents mention the occurrence of bone marrow cancer, there is no discussion of this in Worker 18's medical records as of February 2009, three months prior to his death.

Throughout his career Worker 18 worked a variety of jobs within the oil industry including work as a roustabout, crane operator, pipeline installer and later as a manager/foreman for a company involved with cleaning mud tanks. Worker 18's wife recalls that early in his career he was employed by several oilfield service companies and did work similar to that of a roustabout. Worker 18 frequently worked on land based oil rigs but ocasssionally went out to near shore rigs for no more than a few days at a time. Worker 18's wife mentioned that he sometimes worked as a crane operator during the same period he was assigned roustabout duties, though she was not sure as to the relative amount of time spent on each task. Later in his career, Worker 18 ocasssionally worked on pipeline installation crews, helping to install oil and gas pipelines. Worker 18's wife did not recall the exact nature of his work as a pipeline installer except that he performed some welding and worked installing new pipe, not cleaning existing lines. It should be noted that throughout his career, Worker 18 performed a variety of tasks within any given year and had a range of responsibilities. Worker 18's most recent employment was as a manager/foreman for a company that cleaned mud tanks. Worker 18's wife recalled that as a supervisor, Worker 18 was not responsible for physically cleaning the tanks himself.

While working as a roustabout Worker 18 was subject to the ingestion of radioactive drilling sludge as well as direct gamma radiation from sludge on his clothing. While working as a pipeline installer, he was exposed to direct gamma radiation from radiographic sources during pipe inspection activities. Worker 18's calculated low dose is 47.32rems while his high dose is calculated as 146.96rems. His IREP share is 56.74% indicating it is more likely than not that Worker 18's cancer was caused by exposure to radioactive materials on the job.

5.19 Worker 19

Worker 19 was born July 22, 1948 and was diagnosed with distal rectal carcinoma during 2009. Throughout his career Worker 19 worked a variety of jobs, some of which were in the oil industry and included pipe descaling as well as off shore pipeline installation. Worker 19 stated that while employed by McDermott Incorporated he worked on board a barge laying oil pipeline. While on the barge, Worker 19 was part of a crew that performed radiographic inspection of recently completed welds. He described inspection procedures common in the oil industry, including double wall radiography of pipe utilizing a "crank out" gamma source. During this period Worker 19 worked long hours, typically 14 hours on/7 hours off and 28 days on/7 days off.

Worker 19 stated that he worked for Tuboscope for approximately 3-4 years helping to descale pipe as well as machine threads and inspect recently cleaned tubulars with a "Sonoscope" machine. It should be noted that this type of machine relies on an induced magnetic field to identify flaws within

tubulars and does not rely on gamma sources or X-rays. Worker 19 recalled that he typically worked up to 60 hours per week and would spend approximately 25% of his time cleaning tubulars and the remainder operating the Sonoscope machine. He could not recall whether or not there was significant scale build up in his work area however he did remember that the work environment was very dusty. While working at the Tuboscope facility Worker 19 also recalled that he would frequently come home covered in dust and that he would eat his lunch in the yard.

Worker 19 was exposed to alpha radiation via the inhalation and ingestion of scale while descaling tubulars at Tuboscope. He was also exposed to gamma radiation from scale build up near cleaning operations and racks of contaminated pipe at Tuboscope facilities. Worker 19 was also subject to gamma radiation while assisting with pipe radiography on board pipe laying barges. Worker 19's calculated low dose is 23.60 rems while his high dose is calculated as 109.85rems. His IREP share is 32.20%, indicating that Worker 19's cancer was significantly influenced by his occupational exposure to radioactive materials.

5.20 Worker 20

Worker 20 was born October 13, 1958 and was diagnosed with malignant neoplasm of the larynx in August 2009. However, Worker 20's medical records indicate that he was initially diagnosed in 2004 but did not seek treatment at the time. These records have since been destroyed by Hurricane Katrina and are not available for reference.

Worker 20 worked for various employers between 1977 and 1999 during which time he performed several tasks, mostly relating to work on board and off shore oil rigs including roughnecking, operating rig based cranes, rig based pipe inspection as well as general help on board the rig. It is important to note that Worker 20 did not keep a consistent work schedule and often worked a variety of jobs for numerous employers throughout his career. He also did not work at all during the late 1980's and mid 1990's due to health issues. During the majority of his time working on rigs, Worker 20 would frequently work a schedule of 12 hours on, 12 hours off for up to three weeks at a time. While roughnecking or working as a general rig hand, Worker 20 would frequently handle and work near used drill pipe becoming covered with sludge. He also occasionally worked cleaning the inside of recently emptied mud tanks for a short period during the late 1970's. Later in his career as a rig based crane operator, Worker 20 recalls that he would frequently help other workers on the rig floor and as a result would often be just as dirty. Worker 20's most recent employment was that of an offshore drill rig mechanic. He recalled that when servicing equipment on rigs he would work more or less continuously until the job was finished and would frequently get covered with used drilling mud and would work around used drill pipe. During the vast majority of his career, Worker 20 wore only basic safety equipment including steel toed boots and safety glasses. He only occasionally wore a dust mask while with Mallard Bay Drilling during the early 1990's.

Over the course of his career, Worker 20 was occupationally exposed to alpha radiation via the ingestion of sludge as well as direct gamma radiation from stacks of used drilling pipe as well as sludge on rig floors, his clothing and inside empty mud tanks. Based on his work history and interview, Worker 20's low radiation dose is calculated to be 17.5 rems and his dose is calculated as 684.4 rems. His IREP share is 82.47% indicating it is more likely than not that Worker 20's cancer was caused by on the job exposure to radioactive materials.

5.21 Worker 21

Worker 21 was born February 13, 1959 and was diagnosed with Colon cancer in 2005. Worker 21 passed away on May 5, 2010, five years after his diagnosis. Between the years of 1979 and 1993, Worker 21 worked for a variety of different companies such as Avondale Shipyards, Circle Barge Drilling Co., Plimsoll Marine Inc., Nola Shipyard Inc., Payne & Keller Gulf Coast Inc, Todd Shipyards Corp., Gulf Industrial Contractors, Brown & Root Inc., Rig Hammers Inc., and Manninos P&M Texaco Service Inc. At these companies, Worker 21 worked as a roustabout and completed general shipyard duties for the entirety of his career.

During his career Worker 21 was occupationally exposed to direct gamma radiation from sludge on the floor of shipyards and alpha radiation from the ingestion of sludge at shipyards as well. His total minimum radiation dose is calculated to be 0.5 rems while the total maximum radiation dose is calculated as 50.9 rems. Worker 21's IREP share is 61.97% indicating that exposure to radiation is more likely than not a contributing factor for the development and cause of his cancer.

5.22 Worker 22

Worker 22 was born September 20, 1958 and was diagnosed with T cell lymphoblastic lymphoma during July 2005. Worker 22 subsequently died from his illness but it is not clear from available records when this occurred. During his career Worker 22 worked for a variety of employers, however his exposure to NORM occurred while working as a pipe cleaner with Martin Oil Country Tubular Inc. from 1988 through 1996. A relation of Worker 22 recalls that during his employment Worker 22 would typically work 8 hours per day, 5 days per week cleaning used oilfield pipe with an automated wire brush. The relation of Worker 22 recalls that when they occasionally visited the yard the environment was generally very dusty and that the layer of pipe scale was several inches thick in some places. The relation of Worker 22 recalls that Worker 22's clothing was so dusty that it had to be washed separately from other clothing and that he specifically mentioned the use of VARSOL on the job. Worker 22 typically did not wear any sort of dust mask, though he did eat his lunch in a separate dining area away from the main yard.

It is also worthwhile to note that the relation of Worker 22 stated that Worker 22 was issued a radiation monitoring badge but Worker 22 told her that badges were rarely collected and readings were not properly recorded. The relation of Worker 22 still has one of these badges but this issue has not been investigated further.

While employed as a pipe cleaner by Martin Oil Country Tubular Inc., Worker 22 was occupationally exposed to NORM contaminated pipes and pipe scale. During the course of pipe cleaning operations, Worker 22 ingested and inhaled pipe scale. He was also exposed to groundshine radiation and direct gamma radiation emanating from nearby pipe racks. Based on Worker 22's occupation history and interview with the relation of Worker 22, the low calculated dose to Worker 22 is 259.96 rems while the high dose is 841.12 rems. His IREP share is 89.53%, indicating that it is more likely than not that Worker 22's cancer was caused by on the job exposure to NORM.

5.23 Worker 23

Worker 23 was born April 8, 1940 and was diagnosed with colon cancer in 2004 and cholangiocarcinoma (cancer of a bile duct near the liver) in 2008. Worker 23 passed away soon thereafter. Worker 23's widow stated that throughout his career, Worker 23 worked for a variety of employers including a period from 1977 to 1992 when he worked as a truck driver. During this time Worker 23 would routinely pick up and deliver new and used oilfield tubulars to onshore drill rigs and pipeyards. According to Worker 23's widow, Worker 23 would work up to 60 hours per week and would usually come home covered with mud and dirt. She recalls that the tubulars Worker 23 hauled were a mix of new and used, and that he would frequently load and unload his own materials. Regardless of whether or not he was personally loading or unloading pipe, Worker 23 would remain close to his truck and within the confines of pipeyards during the entire process. These yards typically had pipe descaling facilities.

During his time as a truck driver, Worker 23 was exposed to direct gamma radiation while loading/unloading NORM contaminated tubulars as well as when driving a truck loaded with used tubulars. Worker 23 was also subjected to alpha radiation via inhalation of scale particles while in pipeyards participating in descaling operations and from the ingestion of sludge from handling contaminated tubulars. The total low dose to his colon from these exposures is calculated as 89.70 rems while the high dose is calculated as 267.86 rems. Worker 23's IREP share for colon cancer is 70.65%. The total low dose to his liver from previously mentioned exposures is 105.95 rems while the high dose is 1303.91 rems. Worker 23's IREP share for liver cancer is 98.49%. The IREP shares for Worker 23's two independent cancers indicate that both were more likely than not to have been caused by exposure to radioactive materials on the job. The combined probability of these two cancers is 99.56%.

5.24 Worker 24

Worker 24 was born April 10, 1947 and died on September 25, 2007 shortly after being diagnosed with Chronic Myelocytic Leukemia in 2006. Worker 24 performed a variety of tasks during his career and from 1969 to 1984 he operated a hot oiling truck for a range of employers.

Hot oiling trucks service on shore oil production rigs and are used to remove paraffin buildup in well bores, flow lines and other equipment. These trucks operate by heating oil (often provided by production onsite) and circulating it though rig equipment wherever paraffin has build up. This hot oil allows paraffin to become less viscous and it then flows out along with the circulated oil. It is important to note that this work involves coming into contact with production equipment which is likely contaminated with scale (and NORM) in addition to paraffin. Operators of hot oil trucks are required to come into direct contact with rig equipment contaminated with sludge in order to hook up their machinery. Operators are likely to ingest sludge during these instances as well as be exposed to direct gamma radiation emanating from sludge deposited on their clothing and from scale built up in nearby equipment. For Worker 24's exposure calculation, we assume that he was only exposed to NORM containing equipment one third of the time he was working, since the nature of hot oiling trucks would have required him to operate the equipment at a distance from the rig, as well as drive the rig from site to site (it did not carry NORM contaminated materials onboard).

Worker 24's widow had a good recollection of the type of work Worker 24 performed, however she never worked with him and her only knowledge of his job duties was whatever Worker 24 described to her. Worker 24's widow stated that Worker 24's work schedule was variable in that he would

sometimes drive to an oil rig, operate for a full day (at least 8 hours) and return home in the evening. Other times Worker 24 would remain onsite, operating for several days at a time. According to Worker 24's widow, Worker 24 did not wear any personal protective gear onsite, other than a set of work gloves.

Worker 24's work with hot oiling trucks resulted in the incidental ingestion of NORM contaminated sludge, as well as direct gamma radiation emanating from scale filled equipment and sludge. His total low dose is calculated as 12.1 rems while his high total dose is calculated as 964.2 rems. This dose results in an IREP share of 94.39%, indicating it is more likely than not that exposure to radioactive materials on the job resulted in Worker 24's cancer.

5.25 Worker 25

Worker 25 was born July 24, 1944 and was diagnosed with colon cancer, specifically intramucosal adenocarcinoma of the ascending colon, during January 2008. Worker 25 was also diagnosed with liver cancer, however this metastasized from his colon and is not considered as an independent cancer for our calculations.

Throughout the course of his career, Worker 25 worked as a machinist for a variety of companies between 1963 and 2002. It should be noted that although Worker 25 was hired by a variety of employers, all work was done at pipeyards in Louisiana. Worker 25's daily tasks involved refurbishing NORM contaminated pipe which required him to machine new threads onto tubulars. No welding or cutting with an oxy-acetylene torch was performed. Work was typically done in a shop setting and according to Worker 25, the environment was extremely dusty with scale build-up that was occasionally as much as one foot thick. Worker 25 did not wear a dust mask and would work long hours, typically no fewer than 80 hours per week and occasionally up to 100 hours per week.

Throughout his career as a machinist, Worker 25 was exposed to alpha radiation via the inhalation and ingestion of pipe scale as well as gamma radiation via scale on the ground and nearby racks of contaminated drill pipe. Based on his work history and interview, Worker 25's calculated low radiation dose is 739.73 rems while his high dose is calculated as 1869.19 rems. His IREP share is 95.49% indicating that it is more likely than not that Worker 25's cancer was caused by his exposure to radioactive materials on the job.

5.26 Worker 26

Worker 26 was born August 4, 1964 and was diagnosed with testicular cancer in June of 2005. Worker 26 has undergone treatments and is currently in remission.

Worker 26 worked as a roustabout and instrumentation specialist for sixteen years for Anadarko E&P Company and DCP Midstream. For the first few years on the job, his primary role was that of a roustabout. However, in the following years, he was trained to be one of the instrumentation specialists in the plant. Worker 26 was responsible for the maintenance and fixing of the tanks, valves and pipes within the plant. These tanks were filled with NORM condensate that came directly from the well heads in the field. Many of the times, his assistance was required when the valves clogged and the tanks would be overflowing. While fixing the equipment, he recalled standing in the sludge material up to his knees

and being completely covered in liquid residue. He sometimes wore gloves on his hands, however these were soaked through for the better part of each work day. He also recalled being so filthy with work material, that he would often have to go home halfway through the work day to change his clothes as the skin on his legs would become irritated and sensitive from wearing soaking wet work pants. Worker 26 said that a typical work week was on 50 hours per week on average, however it wasn't uncommon for him to frequently work 70 or 80 hours in a busy work week.

Worker 26 said that regulations became much stricter after he left his position with DCP Midstream. He said that people doing the same position that he held for sixteen years were later required to wear a protective suit, when he had been exposed to all of those same NORM materials with no protection at all for the duration of his employment. He also recalled an instance towards the end of his career with DCP Midstream when he was at work and an environmental investigator came in and ran a Geiger counter throughout the work site. He said that he as well as the other employees were scared and concerned with the high levels of radioactive material that the Geiger counter picked up on, when they had been unaware of just how dangerous their work environment was.

Worker 26's work in the oil industry between 1990 and 2005 has resulted in exposure to NORM via the ingestion of sludge and direct gamma radiation from sludge. The calculated low dose for all of Worker 26's exposures is 51.1 rems while his high dose is calculated as 162.3 rems. His IREP share is 43.87%, indicating that his exposure to radioactive materials is a substantial and contributing factor for the development of his cancer.

5.27 Worker 27

Worker 27 was born March 15, 1955 and was diagnosed with liver cancer early in 2006. Within a few months the cancer had metastasized to his lungs and on September 28, 2006, Worker 27 died due to the cancer. It should be noted that Worker 27's medical records indicate he was in otherwise good health and did not abuse alcohol.

Worker 27 was involved in the oil industry the majority of his career and worked a variety of jobs. Most recently he was employed as a line operator and prior to that worked as an offshore roughneck and tubular descaler. Earlier in his career, he also worked in the Avondale Shipyards as well as with a company that provided general services to onshore oil rigs work. Worker 27's widow has a fairly good recollection of the type of work Worker 27 performed most recently; however she did not remember the specifics of his earliest employment. For the brief time Worker 27 was employed at the Avondale Shipyards we assume only that he inhaled and ingested dust at relatively lower concentrations than individuals who actually operated pipecleaning equipment. Shortly after leaving the Avondale Shipyards, Worker 27 went to work for Soloco LLC. Because Worker 27's widow did not recall exactly the type of work Worker 27 performed with the company, we assume that he performed general labor helping to service land based rigs. Soloco LLC is currently an oilfield services company and it is likely that Worker 27 would have had at least some exposure to sludge while on the job.

Later in his career, Worker 27 was employed as a roughneck on offshore oil rigs. Worker 27's widow recalled that Worker 27 would be on the job between 7-10 days, though he would occasionally go through periods where he worked only 2-3 days at a time. While working for all other employers (those not located offshore), Worker 27's widow recalls that Worker 27 typically would work

approximately 45 hours per week. Worker 27's widow never visited Worker 27 on the job, but she does recall that he often came home dirty and smelling of petroleum regardless of where he was working. She also specifically remembers that Worker 27 wore a fitted respirator while employed as a line operator; this likely greatly reduces his incidental ingestion of sludge during that time.

Worker 27 was exposed to NORM via inhalation and incidental ingestion of particulates in pipeyards as well as ingestion of sludge while onboard or while working with oil rigs or related equipment. He was also exposed to direct gamma radiation emanating from scale built up in pipeyards as well as sludge on oil rigs and on his clothing. The calculated low dose from these exposures is 229.8 rems while the high dose is calculated as 8726.2 rems. Worker 27's IREP share is 99.79% indicating it is more likely than not that his cancer was caused by exposure to radioactive materials on the job.

5.28 Worker 28

Worker 28 was born January 2, 1926 and was diagnosed with prostate cancer in 2000. The cancer soon metastasized to other organs including his brain and brain stem. Worker 28 eventually died on December 31, 2004 due to metastic disease of the brain and brain stem.

Worker 28 performed a variety of tasks during his career including many involving the oil and gas business. His widow recalled that he performed different tasks but that his main jobs included working as a roughneck on land based oil rigs, descaling pipe and driving heavy trucks. Worker 28 performed these duties whenever he was employed between 1945 and 1998 by "Beebe" or any variation on that name. It should be noted that early in his career, Worker 28 occasionally worked outside of the oil industry and that his actual tasks within the oil industry likely varied on a daily basis as he did not have a set schedule. Worker 28's widow estimated that the majority of Worker 28's time was spent working as a roughneck on land based rigs and that the remaining time was divided between descaling used tubulars and trucking. Regardless of the specific task, Worker 28 frequently worked more than 40 hours per week and would sometimes be on the job 60 hours per week. Although Worker 28's widow rarely visited her husband at work, she recalled that he frequently came home from work covered in a mix of mud, dust and oil and that descaling was performed either in a dedicated pipe yard or onsite, at the rig. She stated that he may have worn a paper dust mask while descaling pipe because the area was generally very dusty but was not positive on the specific protective equipment used. Worker 28's widow was also not certain what materials Worker 28 was transporting while driving trucks or where he was driving to/from, thus we assume no NORM exposure during those times.

Worker 28's work in the oil industry between 1945 and 1998 has resulted in exposure to NORM via the inhalation and ingestion of scale dust, ingestion of sludge and direct gamma radiation from scale, sludge and NORM contaminated tubulars. The calculated low dose for all of Worker 28's exposures is 75.9 rems while his high dose is calculated as 349.3 rems. His IREP share is 73.09% indicating it is more likely than not that Worker 28's prostate cancer was caused by his exposure to radioactive materials on the job.

5.29 Worker 29

Worker 29 was born March 17, 1955 and died March 7, 1997 after being diagnosed with Acute Myelogenous Leukemia approximately one year prior. Worker 29's formal job title was

"pipefitter/boilermaker" and from 1973 to1992 he worked as a subcontractor for a variety of companies. According to Worker 29's widow and his brother, Worker 29's main task was to clean large tanks at petroleum refineries and tank farms (also located at refineries) as part of "turnaround" operations where tanks would be cleaned prior to receiving new chemicals. Worker 29 entered these tanks to help remove residue left over from various chemicals stored inside, typically by shoveling out whatever residue remained on the tank floor. Worker 29's widow recalls that Worker 29 would return from work smelling strongly of petroleum products and that he would store his clothing (and full face respirator) outside of the home due to the odor. Worker 29 sometimes worked with his brother, who recalled occasionally working in tanks which previously contained Butadiene. Worker 29 wore heavy protective clothing for protection from corrosive materials and likely would have worn a respirator while inside each tank (though Worker 29's brother was not sure of the specific type of respirator used, it varied depending on the job). Worker 29's brother also stated that while working with Worker 29 in the early 1970's for the GATX Corporation, they helped fabricate storage tanks on site. Worker 29's brother recalls that during this process, Worker 29 was likely in the vicinity of radiographic inspections that frequently took place. However, Worker 29 was not a radiographer and Worker 29's brother stated it was not typical to work in the immediate vicinity of inspection operations for a prolonged period of time. Worker 29's brother also mentioned that as far as he knows, Worker 29 did not receive confined spaces training.

Worker 19's widow confirmed that Worker 29's primary job was cleaning tanks as a pipefitter/boilermaker. She stated that the only other job he held was working in the family's general store beginning in the late 1980's. This work accounts for apparent gaps in Worker 29's employment history because this income was not listed in his Social Security records. Worker 29's widow also confirmed that Worker 29 did not take on any part time jobs working in pipe cleaning yards or performing other oil related work.

To calculate Worker 29's radiographic exposures, we assume he was near radiographic inspections 50% of the time he was working for GATX Corporation between 1973 and 1976. From personal interviews, we know that Worker 29 worked between 40 and 72 hours per week and that inspections would sometimes take place 10-15 feet away from a worker. Given this, we calculate a total low dose of 26.71 rems and a high dose of 91.25rems to the red bone marrow, yielding an IREP share of 64.86% indicating it is more likely than not that Worker 29's Leukemia was caused by his exposure to radioactive materials on the job.

Worker 29 was likely exposed to toxic and/or carcinogenic chemicals while performing tank turnarounds. Worker 29's brother specifically remembers working with Worker 29 in tanks previously containing Butadiene (also known as 1,3-Butadiene), a known human carcinogen that has been linked to leukemias.[65] Due to the fact that Worker 29 performed turnarounds in petroleum refineries and tank farms it is likely he also had contact with benzene, a known human carcinogen linked to leukemias.[66] Unfortunately, there is no record of the specific chemicals Worker 29 was exposed to, the exact type of

[65] U.S. EPA, Integrated Risk Information System, 1,3-Butadiene (CASRN 106-99-0), Revised 11/05/2002.
[66] U.S. EPA, Integrated Risk Information System, Benzene (CASRN 71-43-2), Revised 04/17/2003.

respirator used for each situation and the air concentration of chemicals in each tank. This set of circumstances makes it difficult to precisely determine the risk associated with Worker 29's work around these chemicals.

5.30 Worker 30

Worker 30 was born on October 12, 1959 and was diagnosed with Lymphoblastic Leukemia September of 2003. Sadly, Worker 30 died in March of 2004, only six months after his diagnosis. During his career between the years of 1988 and 1995, Worker 30 worked for a variety of companies such as Bayou Scale Contractors Inc, Liberty Services, Teledyne Movible Offshore and Transocean Offshore. Worker 30 worked as a roustabout and completed general shipyard duties for the entirety of his career at these companies.

Over the course of his career, Worker 30 was exposed to direct gamma radiation from sludge in the shipyards and alpha radiation from ingestion of sludge at the pipeyards as well. His total minimum radiation dose is calculated to be 0.26 rems while the total maximum radiation dose is calculated as 525.70 rems. Worker 30's IREP share is 97.94% indicating that exposure to radiation is more likely than not a contributing factor for the development and cause of his cancer.

5.31 Worker 31

Worker 31 was born August 30, 1961 and was diagnosed with a malignant neoplasm of the stomach during 2009. During his career Worker 31 worked in a variety of fields, including pipe cleaning operations in 1980 for a company he recalled as "PSI" though no such name is listed in his Social Security records. Worker 31 only performed pipe cleaning for six months and worked approximately 40 hours per week during that period. He recalls that used oilfield pipe was cleaned using a wire brush and that pipes were loaded onto a cleaning machine from a horizontal rack. According to Worker 31 the pipeyard was very dusty and he typically ate his lunch in the yard. Worker 31 did not remember if there was scale built up on the ground, however groundshine radiation from scale was included in dose calculations since it is typical of his type of work environment.

While working in pipe descaling operations for a period of approximately six months, Worker 31 was exposed to alpha radiation from the inhalation and ingestion of pipe scale as well as direct gamma radiation from scale built up on the ground and from scale contaminated drill tubulars. Worker 31's low dose is calculated as 6.26 rems while his high dose is calculated to be 16.82 rems. His IREP share is 29.94%, indicating that work experience is a substantial and contributing factor to Worker 31's cancer.

5.32 Worker 32

Worker 32 was born October 16, 1958 and was diagnosed with thyroid cancer in 2006. Worker 32 has had numerous surgeries and the cancer has spread within his neck.

Worker 32 performed a variety of tasks during his career throughout many employment opportunities with oil companies and working offshore on oil rigs. His performed tasks include working as a roughneck on offshore oil rigs, as a roustabout working in oil field wells, and occasionally as a rattler when he would clean the pipes on an offshore rig. Worker 32 performed these duties during the period of time he was employed between the years of 1979 and 1984 for companies such as Owen Drilling

Company, TransContinental Drilling Company, Penrod Drilling Company and Tyler Drilling Company. Worker 32 frequently worked many hours in a week, ranging from 50 to 85 hours depending on his current employer. He recalled that he often came home from work covered in a thick layer of oily sludge, and that many days clothes were so dirty from work that workers discarded the days clothing to the trash before leaving and would obtain new work clothing the next day. He stated that he did wear gloves, but that these gloves were so saturated that his hands were covered in oily sludge and residue all day long.

Worker 32's work in the oil industry between 1979 and 1984 has resulted in exposure to NORM via the ingestion of sludge and direct gamma radiation from sludge and NORM contaminated tubulars. The calculated low dose for all of Worker 32's exposures is 2.77 rems while his high dose is calculated as 80.68 rems. His IREP share is 36.73% indicating that his work experience is a substantial and contributing factor to Worker 32's cancer.

5.33 Worker 33

Worker 33 was born June 24, 1953 and was diagnosed with pancreatitis in 1998. This is a non-cancerous disease, however some studies suggest that pancreatitis is a preceding condition to pancreatic cancer (Albert et al. 1993; 2006).

Worker 33 was employed as a manual pipe cleaner during his career throughout many employment opportunities with various pipeyard companies. His performed tasks included manually cleaning production pipes with a wire brush (inside and out) and occasionally counting/tallying pipes within the yard. All of this work took place within a pipeyard where descaling operations were under way. Worker 33 performed these duties when he was employed between the years of 1973 and 1988 for companies such as Tom Hicks Transfer Company, Brown and Root, Inc., and Superior Construction Company. Worker 33 frequently worked between 45 and 55 hours throughout a normal work week consistently with each place of employment. He recalled that the pipeyard was constantly dusty and that there was always scale build-up/debris in his work area and throughout the yard. He also noted that he ate lunch on a daily basis within a "shed" in the pipeyard that was also dirty with material from the work site.

Worker 33's work in the pipeyard industry between 1973 and 1988 has resulted in exposure to NORM via the ingestion and inhalation of scale and direct gamma radiation from scale. The calculated low dose for all of Worker 33's exposures is 154.68 rems while his high dose is calculated as 452.46 rems. Although pancreatitis is a non-cancerous disease, literature suggests that pancreatitis is a disease that is and can be affected/caused by direct radiation (Levy et al. 1993). Therefore, with the calculated range of rems that Worker 33 experienced throughout his working career with NORM contaminated material, it can be assumed that his work experience has contributed significantly and/or caused his pancreatitis.

6.0 Radiation Health Effects

6.1 Principle Effects of Radiation

There are two principle concerns that accompany exposure to radiation. One is the formation of genetic defects and the second is induction and promotion of cancer. In both cases, irradiation of cells produces

physical and chemical changes. On one hand, the genetic materials in the reproductive cells of parents are damaged. The resultant mutation may be manifest in birth defects or heritable diseases in immediate offspring or may be carried through successive generations to remote offspring. Radiation damage to chromosomes cause changes leading to the induction of various kinds of cancer in the effected organs.

There are many important factors bearing upon understanding of the effects of radiation dose. These include the total dose, the rate at which the dose was delivered, the dose pattern (e.g. intervals between exposure), and the nature of the radiation contributing to the dose. For example, gamma rays can penetrate through the body and deposit only a fraction of their energy. Interactions are thinly distributed over relatively remote cells and organs. On the other hand, alpha-emitting radionuclides, deposited internally, deliver a highly localized radiation dose with a total range of approximately 20 μm (0.0008 inches). Effects are relatively much more likely with alpha particle irradiation. The ICRP accounts for this high energy transfer of alpha particles with a quality factor of 20 in converting rads to rems; for gamma radiation, a rad equals a rem. Another important factor is the stage of cell division. The cell is more susceptible to damage at the last stage of division. Children could be more susceptible because cells are reproducing more rapidly while growing and more cells are in the susceptible stage. This is the same reason why radiation therapy has greater effect on cancerous cells that are multiplying more rapidly. Other factors affecting radiation effects include sex, age at exposure, time of conception (relative to irradiation), location of exposed genes, and genetic susceptibility. The ICRP[67] recently published a treatise on the possible genetic inherited susceptibility to cancer that could modify the effects of radiation exposure. The path and organ dose due to the internal deposition of radionuclides is highly variable. The attendant physical and chemical characteristics result in variable deposition and retention patterns at specific locations in the body. Certain organs and cells can be much more affected than others.

6.1.1 Genetic Effects

One expects that the consequences of irradiation of germ cells in the female are greater than those in the male. Females are born with the entire inventory of germ cells that will form mature oocytes throughout her reproductive life. Therefore those germ cells accumulate any radiation dose over many years. Male sperm is constantly reproduced and would be subject to only short-term exposure.

Mutations in germ cells are characterized by changes within the genes that make up chromosomes in a cell nucleus. The genes consist of specific sequences of deoxyribonucleic acid (DNA) and protein. The genes are components of the chromosomes and determine the hereditary factors and the entire organization and function of the chromosomes and the cells. Genetic diseases occur because of changes in the structure or regulation of DNA within the chromosomes and cells of an organism. These mutations can occur naturally or by action of physical and chemical agents.

Virtually any identified birth defect has genetic alterations that could be a consequence of radiation damage. All mutations are expected to have some harmful effect. Genetic problems are generally classified to three categories: single gene disorders, chromosomal aberrations, and multifactorial disorders. Single gene disorders usually are more drastic and are immediately manifest in offspring.

[67] ICRP, 1998

Major anomalies might include hydrocephalus (fluid in the cerebral ventricles of the brain) and achondroplasia (bone deformities and dwarfing).

Single gene defects are inherited by autosomal transmission (22 pairs of non-sex chromosomes) or by X-linked chromosomes. One copy of the autosomal gene is contributed by the mother and the other by the father. The autosomal traits can be either dominant (immediately expressed) or recessive. Expression of recessive traits requires combination with another copy. A son's X-linked gene will come from the mother and a daughter will receive the X-chromosome from both the father and mother. X-linked traits are expressed only in a daughter and can be either dominant or recessive.

Chromosomal aberrations due to radiation damage are well known and include abnormal numbers of chromosomes, and broken and/or rearranged chromosomes. The chromosomal abnormalities can be passed on at the union of the egg and sperm.

The multifactorial disorders are believed to involve more than one gene and are expected to be a consequence of environmental factors such as drugs, toxins, viral or bacterial agents, and radiation dose. The environmental factors include conditions within which the fetus or embryo are developed. The mother can take in teratogenic radionuclides and the effects transferred to the developing embryo. There is a genetic component, but the other factors contribute to the diseases or abnormalities. The term is used or qualified in reference to a single disorder (e.g. clubfeet) because of the multitude of possible contributing factors.

Newly recognized mechanisms and genetic disease suggest other means of disorders beyond the three described above. In one case there is a combined effect with the existence of both normal cells and cells carrying a mutation. It also appears that the parental origin (mother or father) will determine the genetic manifestation. Other observed phenomena depend upon whether the altered cells originated from both the mother and father.

It is now understood that the cytoplasm within a cell, outside of the nucleus with the genes and chromosomes, also carries genetic information that is passed on through cell division. There is a strictly maternal line of transmission and the abnormalities can be transmitted to her children.

Any of the mechanisms under investigation include abnormalities caused by irradiation even though the means of transmission and manifestation differ.

6.1.2 DNA Damage

Deoxyribonucleic acid (DNA) is bound in double helical chains by hydrogen bonds between the bases forming the material in the chromosomes of the cell nucleus. There are two base pairs, the purine bases adenine and guanine, and the pyrimidine bases thymine and cytosine. The adenine base pairs with the thymine and the guanine pairs with the cytosine. One DNA strand has the complementary sequence of the other. Each gene has a unique sequence of the bases. The genes are linked in linear arrays to form chromosomes in the cell nucleus. A large number of genes, 60,000 to 70,000 are required to control normal functions. Most genes are present in only two copies with each on a separate chromosome. One copy is inherited from the mother and one from the father.

Damage to DNA is the primary event that leads to the development of cancer and hereditary disease. Double strand breaks in the DNA are the most likely cause of mutation in somatic or germ cells.

Ionizing radiation can cause different kinds of damage. The complexity of the damage increases with an increase in the radiation Linear Energy Transfer (LET). Ionizing radiation deposits energy in cells as tracks of ion pairs. The intensity and density of ionizations is a function of the LET of the radiation. Typical low-LET x-ray and gamma radiation can cause about 70 ionizations across an 8 μm cell diameter cell nucleus. A high-LEt alpha particle, such as from Ra-226, will cause over 23,000 ionizations within the nucleus of a single cell[68]. This damage causes mutations and chromosomal changes. Radiation damage transforms cells to a stage in the development of metaplasia that can lead to neoplasia or cancer.

In an attempt to repair single-stranded DNA damage, the DNA replication may bypass the damaged sites by inserting an incorrect base opposite the lost or altered base. Mutations and chromosomal rearrangements are a consequence. The repair of complex DNA double-strand breaks is inherently error-prone and is most likely to be dependent upon dose, dose rate and radiation quality.

The radiosensitivity of normal cells, studied for survival after irradiation in cultures, varies by about a factor of two. In low irradiation dose conditions, this is extended to a factor of three to four[17]. This variation may have a genetic basis.

Cancers induced following lower radiation doses appear as a consequence of gene/chromosomal mutations. The dose-dependent radiation induced mutations add to other tumor-initiating events. It is reasonable to assume the same variable sets of cellular factors serve to suppress or enhance malignant development. The dose response could be dependent upon a change in the post-irradiation processes. The radiation cancer risk might be reduced by error-free DNA repair. However if post-irradiation mutation rates are persistently high, as with genomic instability, then cancer induction would be enhanced.

Qualification of the risks associated with lower radiation doses require information from epidemiology, the shape of the dose-response curve, and the damage mechanisms that could be extrapolated to lower doses.

6.1.3 Radiation Induced Cancer

It is known that radiation dose can lead to the induction of cancer. For over 60 years, the International Commission on Radiation Protection, a body of experts in this field, has produced a series of documents providing the progressive knowledge of radiation effects to enable proper radiation protection. In the United States, since 1931 the National Council on Radiation Protection and Measurements has published similar reports, and continues to do so. In 1959, the Federal Radiation Council was formed to advise the President on radiation matters affecting health for all Federal agencies and for cooperative State Programs. With the formation of the US EPA in 1970, that program became the responsibility of the US EPA. Since the mid 1980s the US EPA has provided a related series of documents to assist Federal and State agencies in their implementation of radiation protection programs. The US EPA has recently (Sept., 1999) updated their published cancer risk coefficients. A successive series of reports by the

[68] UNSCEAR, 2000

Committee on the Biological Effects of Ionizing Radiations (BEIR) of the National Research Council have continued to update the knowledge on the health effects of radiation. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has similarly been issuing successive reports on radiation effects since 1955.

The nature of radiation interactions on cellular components is similar to those that have been described above that can cause genetic defects. Cancer induction is a complex process and the mechanisms of all of the complex factors involved in the process have not been fully developed. A simple summary of the expected processes is that radiation dose causes mutations with altered genes and chromosomes; there can be changes in the gene expression without mutation; and there can be induction of cancer causing viruses. It is believed that cancer induction is a multi-step process that requires two or more intracellular events to transform a normal cell to a cancerous cell. It is also recognized that there is a latency period between the delivered dose and the expression of cancer.

Three successive steps involve initiation, promotion, and finally progression. Initiation involves dose-dependant radiation effects that are usually irreversible. Initiation also requires cell proliferation with changes passed on to daughter cells. Accompanying non-cancer producing conditions and events influence cancer promotion. Tissues tend to become increasingly malignant with the passage of time.

Tumorigenesis is a multi-stage process. First the chromosomal DNA in a normal target is damaged. With the failure to correctly repair that damage, a specific neoplasia initiating mutation can appear. This promotes growth to metaplasia followed by conversion to a malignant phenotype leading to the tumor. According to the National Academy of Sciences, radiation is not only an initiator of cancer, but also a promoter.[69]

A radiation-induced cancer cannot be distinguished from cancer caused by some other carcinogen. The risk of cancer depends upon a number of factors: the kind of cancer, the age and sex of the exposed person, the amount of dose to a particular tissue and organ, the kind of radiation, whether the rate of exposure is brief or chronic, the presence of other carcinogens, the presence of promoting biochemicals, and individual variations and genetic susceptibility.

Cells that survive irradiation, with the loss of repair capacity, are prone to cancer. As a result some individuals can become more radiosensitive. Loss of repair gene function leads to cancer proneness due to increased genetic instability.

It is unanimously agreed that leukemia and virtually all forms all forms of solid cancers in humans can be induced by ionizing radiation.[70] Lymphoma is a group of diseases that involve lymphoid tissue. Multiple myeloma is a malignancy of bone marrow with abnormal plasma cells.

6.1.4 Radiation Protection Standards

The standards for protection against radiation have progressed in accordance with the progress of scientific understanding of the nature and extent of the effects. It has been more recently understood

[69] National Research Council, 1990
[70] Gofman, JW, 1981

that a given amount of radiation dose, through long term chronic irradiation, is more damaging than that of short-term exposure. With improved scientific knowledge, the risk of cancer induction per unit of dose has increased. Estimated cancer risks changed from BEIR III (1980) to those reported in BEIR IV (1990). The level of risk for leukemia increased by a factor of 4.4 for males and a factor of 5.0 for females. The risk for non-leukemia cancers increased by factors ranging from 4.8 to 18.3 for males and 4.6 to 12.7 for females.

6.2 Radiation Risk Analysis for Cancer

This analysis focuses on the risk of the plaintiffs developing cancer, due to both the background risk and the excess risk due to the radiation dose that they received.

6.2.1 Cancer Dose

The cancer dose is the radiation dose that on average leads to one fatal cancer in an irradiated population. The cancer dose depends on age, gender, and cancers included. There is a range of risk estimates in the literature, all of which lead to different cancer doses. In this report, we discuss risk estimates from BEIR V[71], Gofman[72], and Pierce[73], all of which ultimately use data from Japanese bomb survivors in Hiroshima and Nagasaki. However, we employ the IREP program for calculating the likelihood that radiation was responsible for the plaintiffs' cancers. IREP calls this likelihood the assigned share. Combining all radiation pathways, we determine whether it is more likely than not that the pipe yard workers' cancers were caused due to his radiation exposure.

For analysis purposes, we carried out calculations for the pipe yard workers under two different dose methods. We employed dose coefficients from ICRP-30, which assumed a 50-year exposure period and further assumed that his doses, which spanned several years, occurred at the average age while exposed to radioactive materials while working in the pipe yards. This is so we could compare his radiation dose to the allowable dose to a nuclear worker regulated by the Nuclear Regulatory Commission, even though the pipe yard workers were not nuclear workers. However, in order to determine the likelihood that radiation caused the pipe yard workers' cancers, we used the more recent dose coefficients from ICRP-72, that appear on the ICRP CD. This allows us to take into account the workers' ages when each radiation exposure occurred and their commitment period, the time between their exposures to radiation and their cancer diagnoses.

6.2.1.1 Excess Lifetime Risk to Develop Fatal Cancer

The excess risk is the additional risk to develop fatal cancer due to the radiation dose received by the pipe yard workers. This risk is in addition to any background risk to develop fatal cancer. The excess risk of cancer to any organ depends on the TEDE that a worker received, and on the age at which the TEDE was received. Gender would also play a role in the risk analysis. The excess risk of developing cancer in a specific organ depends on the dose to that organ.

[71] National Research Council, 1990
[72] Gofman, JW, 1981
[73] Pierce, DA, et al., 1996

6.2.1.2 Risk Ratio and Likelihood that Specific Cancers Were Caused by Radiation

The Risk Ratio (RR) is defined as the ratio between the total risk and the background risk:

RR = (excess risk + background risk) / background risk

This is a measure to estimate how much more likely it is for a worker to develop cancer due to the radiation dose received while working compared to another person who was only exposed to background radiation. Evidently, the RR has a lower limit of 1 in case of no excess radiation dose. An RR of 2 means that a person's risk to develop cancer has effectively doubled because of the radiation that he received. The dose that leads to an RR of 2 is also referred to as the doubling dose. Obviously, doses that are below the doubling dose lead to an RR between 1 and 2, and doses above the doubling dose to an RR of >2.

Likelihood (cancer was caused by radiation) = Excess risk / (excess risk + background risk)

This likelihood can range between 0 (no relationship between cancer and radiation) to 1 (cancer certainly caused by radiation). It is a measure of the probability that a worker's cancer was effectively caused by the radiation dose he received. In previous reports, we employed risk models from BEIR V, Gofman[74] and Peirce[75]. Like IREP, all are based on Japanese bomb survivor studies. In this report we only employ IREP, which incorporates the latest Japanese bomb survivor data. A more recent study shows that NHL and has been associated with radiation[76].

6.2.2 The Linear-No-Threshold Hypothesis and Bystander Effects

Extensive research has been done in an attempt to quantify the health effects from inhalation, ingestion, and external exposure to radionuclides. The consensus of the international scientific community has accepted the linear no-threshold hypothesis, which posits that dose-effect relationships derived from experiments with high doses of radiation can be scaled linearly to calculate effects from low doses. It also states that there is no "safe" threshold of radiation, that each additional exposure, no matter how small, increases a person's risk of cancer. The hypothesis is based on the understanding that radiation-induced cancer is caused by mistakes in the genetic code produced when radiation comes in contact with DNA. For every additional radioactive disintegration, there will be an increased probability that a cancer-causing DNA mutation will occur. The linear no-threshold hypothesis is also based on epidemiological evidence of Japanese bomb survivors[77]. A significant increased incidence of cancers occurred down to a dose of 5 rems, and an increased incidence occurred down to the lowest doses.

Bystander Effect. Japanese bomb survivors were subjected to external gamma and neutron radiation, but not to internal exposure due to ingestion and inhalation of radionuclides. However, recent studies

[74] Gofman, JW, 1981
[75] Pierce, DA, et al., 1996
[76] Berrington, A, et al., 2001
[39] Pierce, DA, et al., 1996

suggest that the theory of a proportional dose-response mechanism without threshold significantly underestimates the effects of low-dose radiation. Whereas at high doses, mutagenic effects do seem to be proportional to the radiation received, low doses have shown a different relationship. In one study, the mutagenic effect in a cell culture in which only 10 % of all cells were penetrated with one α-particle was found to be almost the same as when all cells were exposed, due to a strong bystander effect[78]. Other studies have shown that irradiation of other parts of the cell, but not the DNA, also causes mutations, and that mutations are caused in non-irradiated cells by transferring them into culture from irradiated cells.[79] This effect has been observed with both alpha- and gamma- radiation.[80] The bystander effect is thought to be caused by proteins excreted from cells in response to radiation. The bystander effect does not follow a linear dose-response relationship; culture from cells irradiated with low doses causes more mutations in non-irradiated cells than culture from cells irradiated with high doses.[81]

This recent research shows that the linear no-threshold hypothesis may not be sufficiently conservative, as at low doses the effect per dose unit may be significantly greater than at high doses. Therefore, the use of the linear no-threshold hypothesis may significantly underestimate doses from relatively low levels of radiation, particularly in certain circumstances. Unfortunately there is not sufficient data from human studies to prove or disprove the significance of the bystander effect in real-life situations.[82]

6.2.3 Risk Uncertainties for Internal Radiation

According to the Committee Examining Radiation Risks of Internal Emitters (CERRIE)[83], the risk due to exposure by radionuclides taken internally may be as much as 10 times higher. CERRIE was established by the Environment Minister of Great Britain in 2001 for the express purpose of investigating internal risks and consisted of scientists with a broad range of views on the subject. The pipe yard workers were exposed to radionuclides taken internally by inhalation and ingestion, in addition to direct gamma external radiation.

Radiation risks are predominantly determined by epidemiological studies, particularly the study of Japanese bomb survivors.[84] Residents of Hiroshima and Nagasaki were exposed primarily to an instant of external gamma radiation and neutrons. From that epidemiological study, that is still ongoing, international committees like the International Commission on Radiological Protection (ICRP) have extrapolated the bomb survivor results to radionuclides taken internally. But radionuclides that emit beta and alpha short range radiation over long time periods present several issues that have not been studied in detail.

In order to calculate radiation dose and risk from internal emitters, the ICRP follows four steps:

(1) using metabolic models, ICRP first estimates radionuclide concentrations in each organ,

[78] Zhou, H, et al., 2001
[79] Lorimore, A, PJ Coates, and EG Wright, 2003
[80] Little, JB, 2003
[81] Lorimore, A, PJ Coates, and EG Wright, 2003
[82] Brenner, DJ, et al., 2003
[83] CERRIE, 2004
[84] Preston, DL, et al., 2003

(2) using dosimetric models, these radionuclide concentrations are converted to an absorbed dose (grays or rads), i.e., to an average energy deposited per unit mass of tissue,

(3) using a radiation weighting factor to account for different types of radiation (factor of 20 for alpha particles), the absorbed dose is converted to an equivalent dose (sieverts or rems), and finally,

(4) the equivalent dose is converted to an effective dose by weighting the individual organs to take into account the differing radiosensitivities.

In the past several years, new experimental data and theories have raised questions regarding the uncertainty introduced by each of these steps, particularly, steps (2) and (3). The data and theories, all related to internal emitters, are centered on four issues: genomic instability, bystander effect, multisatellite mutations and the SET theory.

Genomic instability relates to the damage to genomic DNA that results in "detrimental effects in the progeny of the irradiated cell, many cell divisions after the initial insult."[85] There is some evidence that low doses of radiation can lead to much greater frequency of mutations down the road than induced by the direct action of radiation.

Bystander effects are damage to cells that are not directly along a radiation track, but to adjacent cells. Bystander effects have been seen in laboratory experiments and are not linearly related to radiation dose. The data are sparse for whole animals.[86]

Minisatellite mutations are characterized by very high mutation rates and were first observed among the barn swallow breeding close to the Chernobyl reactor. Compared to barn swallows in Italy and the Ukraine, the mutation rates were ten times higher.[87]

The second event theory or SET propounds that a second radiation hit, within a specific time window after the first, enhances the mutagenic effectiveness of radiation. According to SET, this might be the case for Sr-90/Y-90 and certain Pu radionuclides.[88] The CERRIE recommended additional studies of the phenomena.

Taken together, the uncertainties of internal emitters, according to CERRIE, might be as much as ten times greater.

6.2.4 Risk Uncertainties for Exposure at Middle Age

A recent paper in the Journal of the National Cancer Institute[89] shows that the cancer risk due to radiation exposure in middle age do not decrease with increasing age at exposure. The paper, based on data from Japanese bomb survivors, shows that the cancer risk may be twice as high as previously estimated. While it has been thought that the cancer risks due to childhood exposure has been high due to rapidly growing cells, the same theory would suggest the cancer risk less for adults. For older persons, initiation of cancer may not be the factor, but rather, the promotion of preexisting malignant cells. This information has not been incorporated into this report since the information has just become available.

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[85] CERRIE, 2004
[86] *Ibid*
[87] *Ibid*
[88] *Ibid*
[89] Shuryak, I, Sachs, R.K. and Brenner, D.J., "Cancer Risks After Radiation Exposure in Middle Age," JNCI, October 26, 2010.

7.0 Rules and Regulations

As an Agreement State under the federal Atomic Energy Act, the State of Louisiana enacted regulations for radioactive materials. The enabling legislation, setting up the regulatory agency (the Board of Nuclear Energy) and its charge, was enacted by the Louisiana Legislature in 1962. This legislation was called the Nuclear Energy Act. The Board of Nuclear Energy was divided into the Atomic Energy Development Agency and the Division of Radiation Control. Since May 1967, which is when the State assumed regulatory authority from the U.S. Atomic Energy Commission (i.e. became an "Agreement State"), the Louisiana Division of Radiation Control has had sole responsibility for the control of radiation.

The first regulations were promulgated in 1966, and took effect on May 1, 1967. All radioactive materials, not just source and special nuclear materials, were regulated by the Division of Radiation Control. While the term NORM was not specifically defined in the regulations, Ra-226 was specifically regulated. Exemption limits were specified, but these were far below the levels present in the pipe yards in which the plaintiffs worked. Though the Division never enforced the Ra-226 regulations, general licenses were issued and carried over until February 1989 when the State issued a "Declaration of Emergency"[90] and specifically enacted regulations for NORM material. Whether the regulations were enforced before 1989 or not, Louisiana pipe yards were required to satisfy radiation regulations such as the posting of radioactive areas, protecting worker safety (also regulated by OSHA) and controlling soil contamination, specifically, maintaining total radium concentrations less than 5 pCi/g in potential residential areas and 15 pCi/g in industrial areas. The soil contamination limits for operating facilities was relaxed to 200 pCi/g in more recent regulations, but the soil contamination limit for decommissioned sites released for unrestricted use remained the same.

The first rules that specifically addressed NORM in relation to oil fields and pipe yards were promulgated by a "Declaration of Emergency" February 1989. In September 1989, the Division of Radiation Control issued the current regulations regarding radioactive materials associated with oil and gas producing operations through the Department of Environmental Quality (DEQ) under Title 33 Part XV, Radiation Protection. The regulations state that a license is required for the possession, use, transfer, ownership and acquisition of radioactive material, including NORM.

Our calculations assume that all of the pipe yards in which the plaintiffs worked adhered to these regulations beginning September 1989 (even though the regulations were repealed and re-promulgated only in 1992).

According to the regulations, licenses are differentiated into general and specific licenses. For a general license, a licensee must fulfill certain requirements in order to be allowed to process NORM. The licensee has to comply with these conditions, but does not have to apply for a license. In contrast, specific licenses can only be obtained through an application process. Section 1408 requires that licensees notify the Office of Environmental Services by filing NORM Form RPD-36 with the Office of Environmental Services, Permits Division. Section 1410 pertains to pipe yards, granting a general license to "*receive, process, process, and clean tubular goods or equipment which are contaminated with scale*

[90] Louisiana Register, 1989

or residue but do not exceed 50 microroentgens per hour". For the decontamination of pipe that exceeds 50 µR/h, a specific license is required. We do not know whether the pipe yards in which the plaintiffs worked held a specific license.

According to Section §1410, the general license is linked to a series of conditions, which have to be fulfilled in order for the license to be valid. These conditions are:

Notification of DEQ within 90 days of the effective date of the regulations that facility (ITCO) intends to receive equipment contaminated with scale or residue that does not exceed 50 µR/hr.

Program is approved by the DEQ to screen incoming shipments to ensure that 50 µR/h-limit is not exceeded by individual pieces of equipment

Program is submitted to ensure worker protection

Program is submitted to control soil contamination

Program is submitted to prevent release of NORM beyond site boundary

Program is submitted to ensure that soil contamination does not exceed 200 pCi/g of Ra-226 or Ra-228, or an exposure rate 50 µR/h at 1 m above the ground

Plan for cleanup of existing facilities with NORM contaminated soil in excess of 200 pCi/g Ra-226 or Ra-228, or 50 µR/h at 1 m above the ground; must be submitted to DEQ within 180 days of effective date of regulation

Soil on site must be cleaned to below 5 pCi/g of Ra-226 or Ra-228 before release of the site for unrestricted use.

For most of these conditions, we have no knowledge whether the pipe yards complied. Noncompliance with a necessary condition for the general license is equivalent to violating the license (and, by extension, Louisiana State law). As of currently, we have not seen documents that show compliance with any of the other conditions. All programs had to be submitted to DEQ, Office of Environmental Services, Permits Division, for approval.

Chapter 15 of the radiation regulations pertains to the transportation of radioactive material. Material can only be transported by persons/companies that have a license for transportation, unless the activity of the transported material is below 2,000 pCi/g. Since many pipe joints contained scale with concentrations greater than 2,000 pCi/g Ra-226, the pipe yards were required to hold this specific license. It is not clear if they pipe yards held specific transportation licenses.

The plaintiffs who worked in pipe yards were not considered nuclear workers. The external radiation requirements of 50 µR/hr (if enforced) ensured that pipe yard workers received an external radiation dose of less than 100 mrem/yr, the allowable dose for a member of the public. But pipe yard workers

received a much greater dose from inhalation of radioactive particulates that were not seriously considered when regulations were drafted.

8.0 Non-Radiological Exposures

8.1 Respirable Particulates

The Occupational Health and Safety Administration's (OSHA) regulation standards in 29 CFR for "Particulates not otherwise regulated" (PNOR) in Table Z-1, and for "inert and nuisance dust" in Table Z-3, are 5 mg/m^3 for respirable dust. As seen in this report, we calculated the air particulate concentrations near the pipe cleaning and cutting operations to be 10 – 30 mg/m^3, or 2-6 times above this limit. Respirable dust includes particles that are small enough to penetrate the nose and upper respiratory system and deep into the lungs. These particles are often small enough to make it past the body's clearance mechanisms of cilia and mucous. Dust is respirable at diameters below 10 µm, with those under 2 µm being the most likely to be retained.[91]

In April 1987, an industrial hygienist, Lindsay Booher, visited the ITCO pipe yard to observe the working environment to which the ITCO workers were exposed[92]. Booher noted that levels of "nuisance dust" were exceeded at the ITCO yard. This means that the workers' health were endangered in two separate ways by the very high dust concentrations they were exposed to at work: the sheer amount of it, and the radionuclides within this dust.

The correlation between exposure to respirable particulates and increased morbidity and mortality is well documented. Health effects for which statistically significant associations with exposure to of less than 10 µm (PM_{10}) were found to include overall mortality, mortality due to cardiopulmonary and cardiovascular diseases and lung cancer, and morbidity due to chronic obstructive pulmonary disease (COPD), bronchitis, asthma, dyspnea, breathlessness, cough, production of phlegm and pneumonia.

This directly applies to the work situation at the pipe yards and oil production rigs at which the plaintiffs worked regarding the general connection between inhalation of particulates and adverse health effects. The major difference is that in epidemiological studies, the subjects are usually exposed to much lower particulate concentrations than the plaintiffs in this report. Under "normal" circumstances, it is very rare that someone is exposed to particulate concentrations of more than 0.1 mg/m^3. In contrast, we assume a scale dust concentration of 10-30 mg/m^3 near the pipe cleaning machines, and of 1.6 – 3.6 mg/m^3 in other parts of the pipe yards.

Numerous references cite a relationship between health effects and dusty conditions at the pipe yards and oil production rigs. The sources for the risk estimates (with measured health outcome in parenthesis) are:

Cardiopulmonary disease (mortality): Pope et al. 2002

[91] US Department of the Interior, 1987
[92] The ITCO pipe yard is one of the pipe yards from which we derived our particulate air concentration range.

COPD (hospital admissions): Samet et al. 2000
Bronchitis and Asthma (morbidity): Kuenzli et al. 1997
Cough/phlegm and dyspnea (morbidity): Zemp et al. 1999
Myocardial infarction (onset): Peters et al. 2001
Sinusitis (hospital admissions): Gordian et al. 1996

In addition to the studies cited above, the book by Dr. John Gofman collects dose-response studies and quantitatively demonstrates the relationship between radiation and ischemic heart disease.[93]

8.2 Varsol Exposure

Many of the plaintiffs were exposed to the chemical Varsol, a degreasing agent used to clean pipe threads, while working at the pipe yards and oil production rigs. Varsol is a trade name for Stoddard solvent, and was developed and produced by Exxon. Stoddard solvent is a distillation fraction of crude petroleum that contains at least 200 products, many of which are gasoline range hydrocarbons. The mixture is generally composed of 30-50 percent straight-chain and branch-chain paraffins, 30-40 percent naphthenes, and 10-20 percent aromatic hydrocarbons.[94, 95]

Varsol is 4-percent 1,2,4-trimethylbenzene and 0.1-percent ethylbenzene, both of which are known to be toxic for inhalation, ingestion and dermal contact.[96] It is colorless, insoluble in water, volatile, and smells like kerosene or gasoline. Stoddard solvent is used as a dry-cleaning solvent and a metal degreaser. It is also used industrially as a thinning agent in paints, coatings and waxes and as a solvent in printing ink, photocopier toner, adhesives, rubber products, waxes, polishes, and pesticides.[97, 98] Varsol was used at many of the pipe yards and oil production rigs to clean the grease covered pipe ends and thread protectors.

Inhalation is the primary route of exposure to Stoddard solvent due to its high volatility, although dermal absorption can be enhanced by cuts or abrasions on the skin and through prolonged dermal contact with the liquid. Stoddard solvent enters the bloodstream quickly following inhalation. It is then absorbed by tissues throughout the body, and may enter the brain. It is primarily stored in fat due to its lipophilicity. Its transport throughout the body following dermal absorption is not known, although it is thought to be similar to that following inhalation. Due to Stoddard solvent's similarity to other refined petroleum solvents, metabolism is likely to occur in the liver and excretion would occur through the respiratory tract and kidneys. Acute exposure can lead to irritation of the respiratory tract and neurologic effects. Stoddard solvent is a moderate skin irritant and exposure can lead to dermatitis, lesions, and defatting of the skin.[99, 100]

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[93] Gofman, JW, 1999
[94] Agency for Toxic Substances and Disease Registry (ATSDR), 2000
[95] ATSDR, 1995
[96] ExxonMobil
[97] ATSDR, 2000
[98] ATSDR, 1995
[99] ATSDR, 2000
[100] ATSDR, 1995

Due to the complexity of Stoddard solvent's composition, the International Agency for Research on Cancer (IARC) has not evaluated the carcinogenic potential. Epidemiologic studies of painters and dry-cleaning workers, who were exposed to Stoddard solvent as well as other mixed petroleum products, have not yielded consistent findings. Some studies have found increased incidences of respiratory tract, bladder, and kidney cancers. Exposure has been associated with neuropsychiatric disorders, hepatotoxicity (toxicity of the liver), kidney damage, and changed in blood-forming capacity.[101, 102]

NIOSH recommends that workers exposed to refined petroleum products have medical surveillance examinations for blood count, urinalysis, and testing of the liver, nervous system, and kidneys. The Occupational Safety and Health Administration (OSHA) has established a time-weighted average standard for Stoddard solvent of 2,900 mg/m^3 in air for an 8-hour workday during a 40-hour workweek. NIOSH recommends an exposure limit of 350 mg/m^3 for a 10-hour workday, with a ceiling level of 1,800 mg/m^3. The American Conference of Governmental Industrial Hygienists (ACGIH) recommends a threshold limit value time-weighted average of 525 mg/m^3 for an 8-hour workday.[103, 104] In addition, work with Varsol should only be conducted in a well ventilated area and impervious (non-cloth) gloves should be utilized to limit dermal absorption. It is recommended that respiratory protection be worn if airborne concentrations are unknown or exceed the recommended exposure limit.[105] The odor threshold for Stoddard solvent is less than 2 mg/m^3, although after six minutes it can no longer be detected due to olfactory sense fatigue.[106] We have not seen evidence that any of the pipe yards and/or oil production rigs at which the plaintiffs worked monitored the air for Varsol concentrations.

[101] ATSDR, 2000
[102] ATSDR, 1995
[103] ATSDR, 2000
[104] ATSDR, 1995
[105] ExxonMobil
[106] ATSDR, 1995

9.0 Tables and Figures

Table 1a. TEDE Dose Rates for different pipe yard work situations (exposure types)

Radiation Pathways	Type A (mrem/hr)	Type B (mrem/hr)	Type C (mrem/hr)
Inhalation of particulates through 1989	47	13.3	12.7
Inhalation of particulates after 1989	10.5	2.1	2.7
Ingestion of particulates through 1989	1.12	1.12	
Ingestion of particulates after 1989	0.25	0.25	
Groundshine through 1989	3.56 - 10.05	3.56 - 10.05	
Groundshine after 1989	.78 - 2.2	.78 - 2.2	
External radiation (pipe cleaning rack) though 1989	.61-.85		
External radiation (pipe cleaning rack) after 1989	.13-.18		
External radiation (pipe storage rack) though 1989		0.073	
External radiation (pipe storage rack) after 1989		0.016	
Total Dose rate through 1989	52.3 - 59.5	18.1 - 24.5	12.7
Total Dose rate after 1989	11.6 - 13.1	3.1 - 4.6	2.7

A.) Physical work in pipe yard near pipe cleaning and cutting processes

B.) Physical work in pipe yard away from pipe cleaning and cutting processes

C.) Work inside of auxiliary buildings (office buildings, warehouses, etc.) adjacent to pipe yard

Table 1b. TEDE Dose Rates for different drill rig work situations (exposure types)

Radiation Pathways	Type A (mrem/hr)	Type B (mrem/hr)	Type C (mrem/hr)
Incidental Sludge Ingestion	.00093 - 5.74	.00093 - 5.74	.00093 - 5.74
External radiation (sludge on clothing)	0.35	0.35	0.35
External radiation (NORM contaminated pipe)		.03 - .2	.03 - .2
Groundshine from sludge	0.3 - 2.38	2.38	0.3 - 2.38
Total Dose Rate	.65 - 8.47	.68 - 8.67	.68 - 8.67

Exposure Types
A = Physical work as a Roustabout
B = Physical work as a Roughneck
C = Physical work as a Derrickman

Table 2a. Cancer Types, Total Radiation Doses, and Assigned Shares for Coleman vs. H.C. Price Co. Pipe yard Plaintiffs

Plaintiff Name	Primary Cancer Type	Total Radiation Dose		IREP Assigned Share
		Low (rem)	High (rem)	
Worker 2	CGL	118.65	1868.78	99.73%
Worker 3	APL	12.34	455.65	97.49%
Worker 4	Lung	927.57	32933.65	99.63%
Worker 5	Colon	97.9	268	88.52%
Worker 6	Colon	273.51	905.77	90.29%
Worker 7	MM	369.1	6336.4	98.08%
Worker 10	MM	25.49	517.57	81.49%
Worker 11	Lung	783.30	30938.29	99.39%
Worker 12	Gastric	278.8	1233.3	95.5%
Worker 13	CLL, NHL	655.0	20153.1	99.43%
Worker 14	CKD*	155.2	1273.19	94.79%
Worker 16	ML	101.02	1161.02	99.36%
Worker 17	Kidney	169.82	14684.48	99.62%
Worker 19	Rectal	23.60	109.85	32.20%
Worker 22	TLL	259.96	841.12	89.53%
Worker 25	Colon	739.73	1869.19	95.49%
Worker 27	Liver	229.8	8726.2	99.79%
Worker 31	Stomach	6.26	16.82	29.94%
Worker 33	Pancreatitis*	154.68	452.46	NON-CANCER

* Indicated a non-cancer ailment

Cancer Type Abbreviations:

MM: Multiple Myeloma
CGL: Chronic Granulocytic Leukemia
APL: Acute Promyeloctic Leukemia
CLL: Chronic Lymphocytic Leukemia
NHL: Non-Hodgkin's Lymphoma
CKD: Chronic Kidney Disease
ML: Myelogenous Leukemia
TLL: T-Cell Lymphoblastic Lymphoma
CML: Chronic Myelocytic Leukemia
AML: Acute Myelogenous Leukemia
LL: Lymphoblastic Leukemia

Table 2b. Cancer Types, Total Radiation Doses, and Assigned Shares for Coleman vs. H.C. Price Co. Rig Plaintiffs

Plaintiff Name	Primary Cancer Type	Total Radiation Dose		IREP Assigned Share
		Low (rem)	High (rem)	
Worker 9	CLL	1.68	556.05	97.38%
Worker 18	NHL	203.87	355.70	73.54%
Worker 20	Larynx	17.5	684.4	82.47%
Worker 21	TLL	259.96	841.12	89.53%
Worker 15	Lung	69.1	876.2	89.97%
Worker 26	Testicular	51.1	162.3	43.87%
Worker 28	Prostate	75.9	349.3	73.09%
Worker 30	LL	0.26	525.7	97.94%
Worker 32	Thyroid	2.77	80.68	36.73%

Cancer Type Abbreviations:

MM: Multiple Myeloma
CGL: Chronic Granulocytic Leukemia
APL: Acute Promyeloctic Leukemia
CLL: Chronic Lymphocytic Leukemia
NHL: Non-Hodgkin's Lymphoma
CKD: Chronic Kidney Disease
ML: Myelogenous Leukemia
TLL: T-Cell Lymphoblastic Lymphoma
CML: Chronic Myelocytic Leukemia
AML: Acute Myelogenous Leukemia
LL: Lymphoblastic Leukemia

Table 2c. Cancer Types, Occupation, Total Radiation Doses, and Assigned Shares for Coleman vs. H.C. Price Co. Other Plaintiffs

Plaintiff Name	Occupation	Primary Cancer Type	Total Radiation Dose		IREP Assigned Share
			Low (rem)	High (rem)	
Worker 1	Pipeline Worker	MM	17.15	102.89	26.83%
Worker 8	Truck driver	Prostate	12.54	20.67	11.23%
Worker 23	Truck driver	Colon Cholangiocarcinoma	81.04 97.31	252.28 1288.38	69.66% 98.38% Combined: 99.54%
Worker 24	Truck driver	CML	12.1	964.2	94.39%
Worker 29	Tank Cleaner	AML	26.71	91.25	64.86%

Cancer Type Abbreviations:

MM: Multiple Myeloma
CGL: Chronic Granulocytic Leukemia
APL: Acute Promyeloctic Leukemia
CLL: Chronic Lymphocytic Leukemia
NHL: Non-Hodgkin's Lymphoma
CKD: Chronic Kidney Disease
ML: Myelogenous Leukemia
TLL: T-Cell Lymphoblastic Lymphoma
CML: Chronic Myelocytic Leukemia
AML: Acute Myelogenous Leukemia
LL: Lymphoblastic Leukemia

Table 3. Representative Radionuclide Activities of Ra-226 and Ra-228 and Various Progeny in Sludge*

	Ra-226 (pCi/g)	Ra-228 (pCi/g)	Po-210 (pCi/g)	Pb-210 (pCi/g)	Reference
Minimum	1.35	13.5	0.108	2.7	IAEA[107]
Maximum	21,600	1,350	4,320	35,100	IAEA[108]

*The above table includes only the radionuclides for which an activity was given by IAEA. However, all radionuclides of the Ra-226 and Ra-228 decay chains were considered in our sludge calculations.

[107] IAEA, 2003
[108] *Ibid*

Fig. 1. Ra-226 and Ra-228 Decay Chains

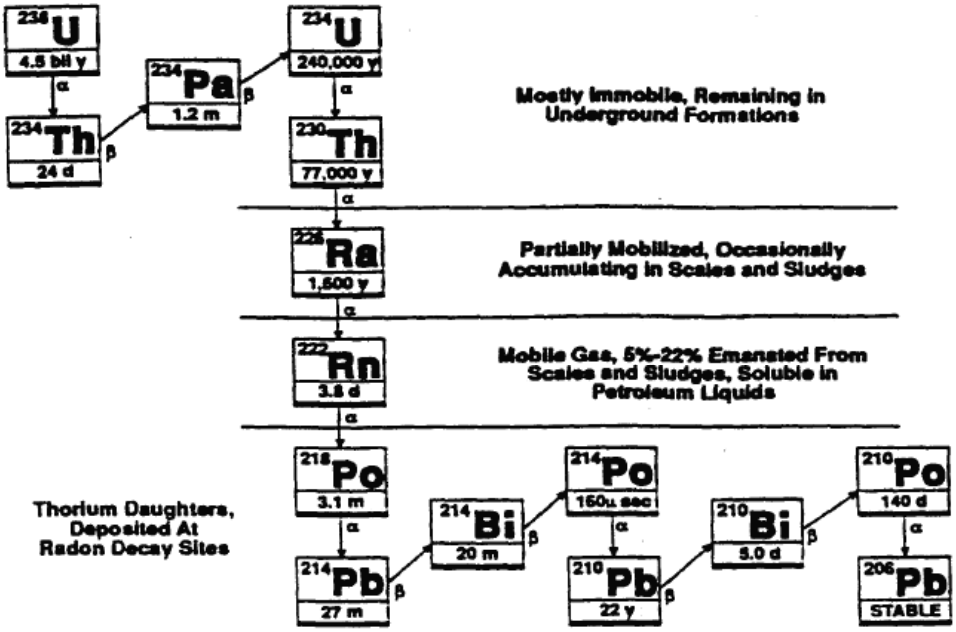

Fig. 2. Air Rattlers for Straight Tubes

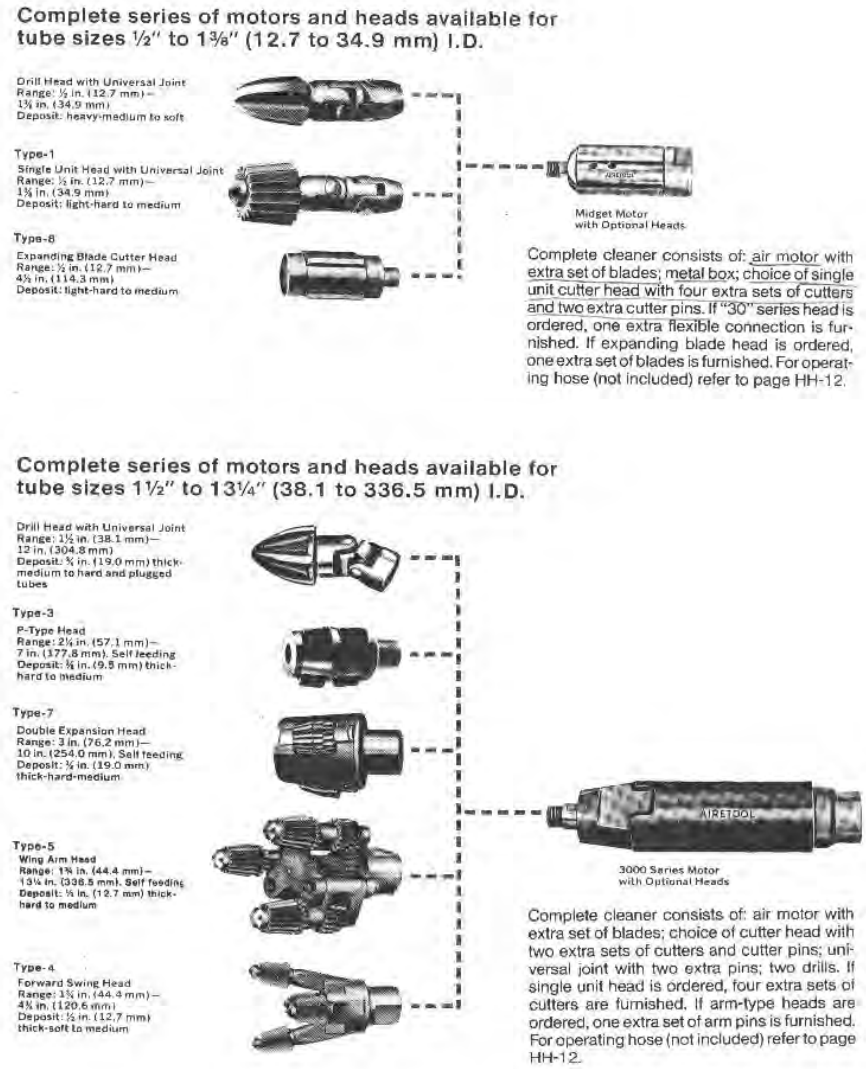

Figure 2. Air rattlers for straight tubes.

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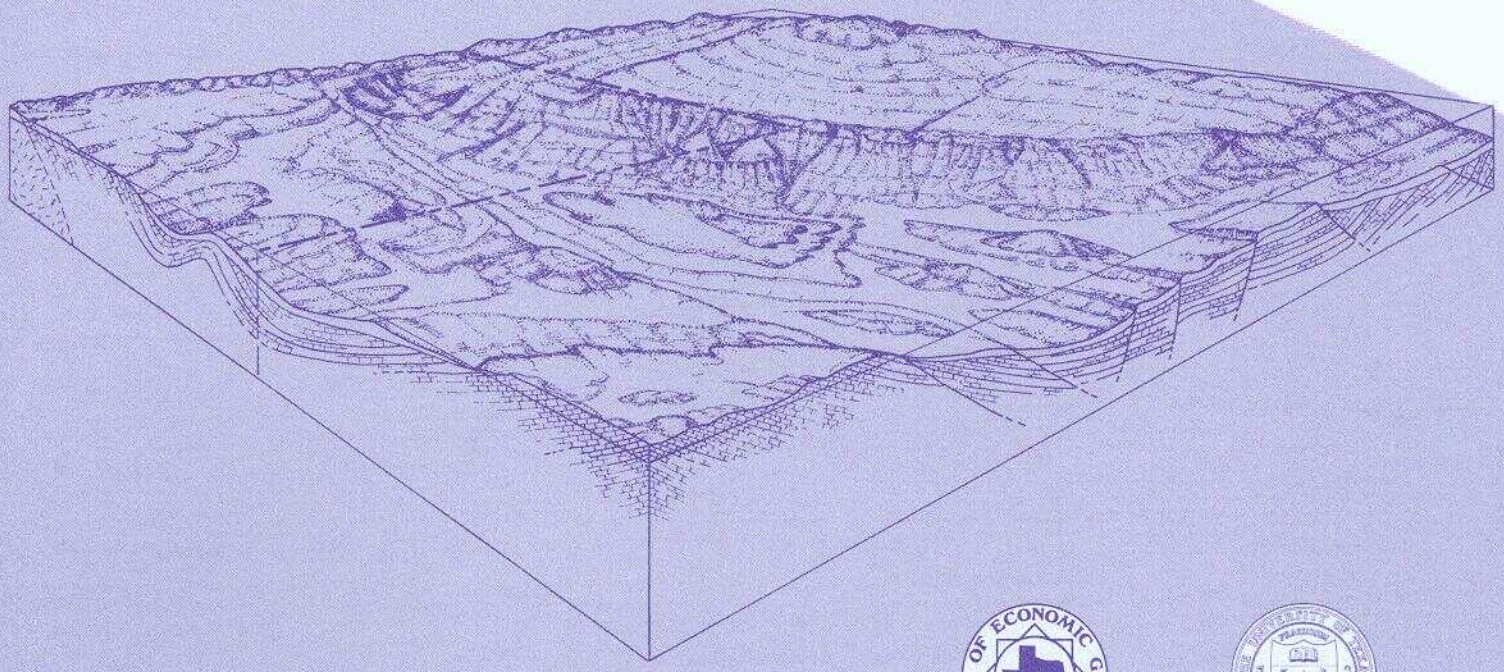
Report of Investigations No. 201

Stratigraphic Analysis of the Upper Devonian Woodford Formation, Permian Basin, West Texas and Southeastern New Mexico

John B. Comer



1991

Bureau of Economic Geology • W. L. Fisher, Director
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Contents

Figures

Plates (in pocket)

Abstract

The Upper Devonian Woodford Formation is an organic-rich petroleum source rock that extends throughout West Texas and southeastern New Mexico and currently is generating oil or gas in the subsurface. The Woodford is a potential hydrocarbon reservoir in areas where it is highly fractured; the most favorable drilling targets are fractured siltstone or chert beds in densely faulted regions such as the Central Basin Platform, southernmost Midland Basin, and parts of the Northwestern Shelf. Stratigraphic analysis was undertaken to determine how the Woodford was deposited and why its petroleum source potential is so great.

The Woodford consists of two lithofacies, black shale and siltstone. Black shale, the most widely distributed rock type, is very radioactive and contains varvelike parallel laminae, abundant pyrite, and high concentrations of marine organic matter. Siltstone, typically a basal facies, in deep basin and proximal shelf settings, exhibits disrupted stratification, graded layers, fine-grained Bouma sequences, and a subequal mixture of silt-sized quartz and dolomite. Black shale is mostly pelagic and represents an anaerobic biofacies, whereas siltstone is the result of bottom-flow deposition and represents a dysaerobic biofacies.

The depositional model developed herein for the Woodford was based on stratigraphic sequence, patterns of onlap, and lithologic variations, together with published information about global paleogeography, paleoclimate, and eustasy. During the Late Devonian, the Permian Basin was a low-relief region located on the western margin of North America in the arid tropics near 15 degrees south latitude. Worldwide marine transgression caused flooding of the craton and carried water from a zone of coastal upwelling into the expanding epeiric sea. Strong density stratification developed, due partly to accumulation of hypersaline bottom water that formed locally in the arid climate. Anaerobic conditions resulted from poor vertical circulation and from high oxygen demand, which was caused by the decay of abundant organic matter produced in the nutrient-rich surface waters. Continuous, slow deposition of pelagic material was interrupted by episodic, rapid deposition of silt and mud from bottom flows generated during frequent tropical storms.

This report documents the composition, distribution, and structure of the Woodford Formation in a major hydrocarbon-producing basin. Petrologic and organic geochemical data helped explain the origin of the unit and provided information necessary for predicting potential locations and lithologies of commercial petroleum reservoirs within the Woodford. Combining comprehensive stratigraphic, petrologic, and geochemical data was useful for developing a depositional and exploration model of Devonian black shale in West Texas and New Mexico. Similar studies should be conducted elsewhere to enable discovery of unconventional hydrocarbon reserves in black shales.

Keywords: Upper Devonian, Woodford, black shale, siltstone, source rocks, unconventional reservoirs, depositional model, paleogeography

Introduction

This report presents a stratigraphic analysis of the Woodford Formation (Upper Devonian) in the Permian Basin of West Texas and southeastern New Mexico (fig. la, b). The study is part of a larger project undertaken to determine how and why these enigmatic, organic-rich marine rocks were deposited and to document their petroleum-generation history. The part of

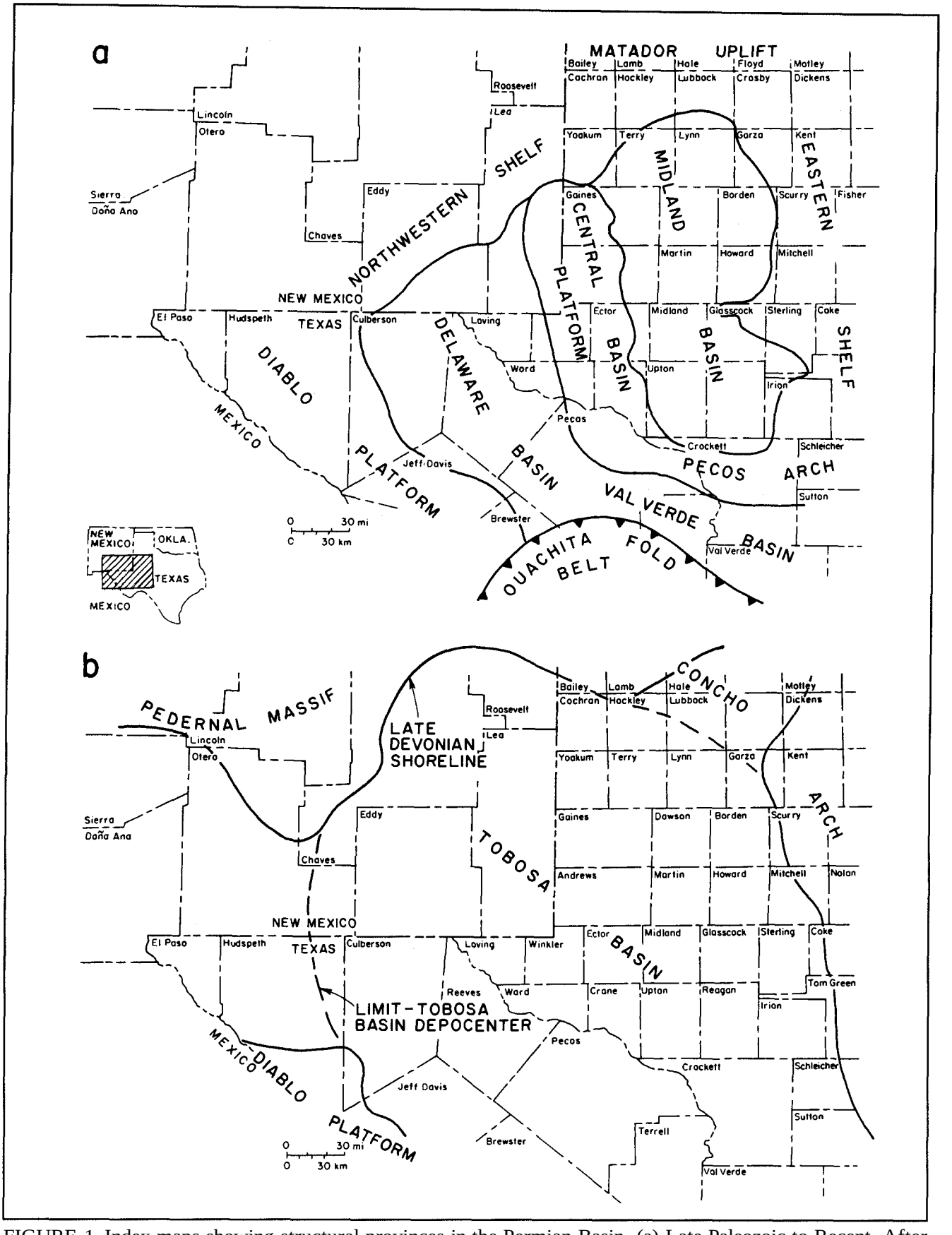


FIGURE 1. Index maps showing structural provinces in the Permian Basin, (a) Late Paleozoic to Recent. After Walper (1977) and Hills (1984). (b) Late Devonian. After Galley (1958) and Wright (1979).

the project involved in this study entailed mapping, conducting lithologic studies of cores and outcrops, and reconstructing paleogeography and depositional environments.

The Woodford Formation has long been recognized by geologists working in the region as an important stratigraphic marker because of its black shale lithology, anomalously high radioactivity, and widespread distribution (Ellison, 1950; Wright, 1979). The organic-rich formation typically yields shows of oil from cuttings and cores and produces a gas response on mudlogs. The Woodford, acknowledged as a principal petroleum source rock in the Permian Basin (Galley, 1958; Jones and Smith, 1965; Horak, 1985), contains some intervals of "oil shale" as well (>10 gal of retortable oil per ton of shale). It is also a low-grade, subeconomic uranium and heavy metal deposit (Swanson, 1960; Landis, 1962; Duncan and Swanson, 1965).

The economic potential of black shales has prompted several studies of shale deposition. Previous publications describe and interpret the origin of Devonian black shales in the eastern United States (for example, Cluff, 1980; Ettensohn and Barron, 1981; Broadhead and others, 1982; Schopf, 1983; Ettensohn and Elam, 1985; Pashin and Ettensohn, 1987), but no comparable work has been published on equivalent strata in the southern Midcontinent. Developing a comprehensive depositional model of the Woodford was complicated in that no modern analog is available for comparison. During the Late Devonian a euxinic sea, in which broad expanses of marine black shale had been deposited, occupied most of the Midcontinent of North America. However, virtually no large euxinic epeiric seas on stable cratons and passive continental margins adjacent to the open ocean exist in the modern world. Why cratonic euxinic seas developed must be understood before the origin of the Woodford can be fully explained. Although global controls, such as deglaciation and ocean ridge expansion (Heckel and Witzke, 1979; Johnson and others, 1985), can account for the worldwide transgression in the Late Devonian, regional controls must be used to account for the strongly stratified water columns and widespread bottom anoxia that developed in North America. The depositional model described later herein shows that it was the unique relationship among geography, geomorphology, tectonics, climate, and oceanography that produced the uncommon environment and unusual lithology of the Woodford Formation.

Methods

Data for the project were obtained from 558 well logs, 13 cores, and 3 measured sections. Well control is plotted on the structure and isopach maps (pls. 1, 2), and the location of cores, measured sections, and cross sections is shown in figure 2. An index of well names and locations is on open file at the Bureau of Economic Geology, and the core and measured section localities are listed in appendix A.

Plates 1 and 2 were contoured using the well data shown on each map. In areas of poor control, elevation of the Woodford (pl. 1) was inferred using the *Tectonic Map of Texas* (Ewing, 1991), which was contoured on top of the Ellenburger Formation (Lower Ordovician) in West Texas and on top of the Silurian-Devonian carbonate section in southeastern New Mexico. Faults mapped in this report were redrawn from Ewing's map.

Outcrops in the Hueco, Franklin, and Sacramento Mountains were described to compare these well-studied measured sections in the west with the poorly known rocks in the subsurface. Outcrops were chosen that had been mapped previously and for which paleontological analysis had established relative ages.

The Woodford Formation was identified from well logs, primarily by high radioactivity on the gamma-ray log (pls. 3 through 7), and by its stratigraphic position between carbonates. Although other highly radioactive strata lie in the Permian Basin, the Woodford is the most laterally persistent and typically exhibits the strongest radioactivity anomaly.

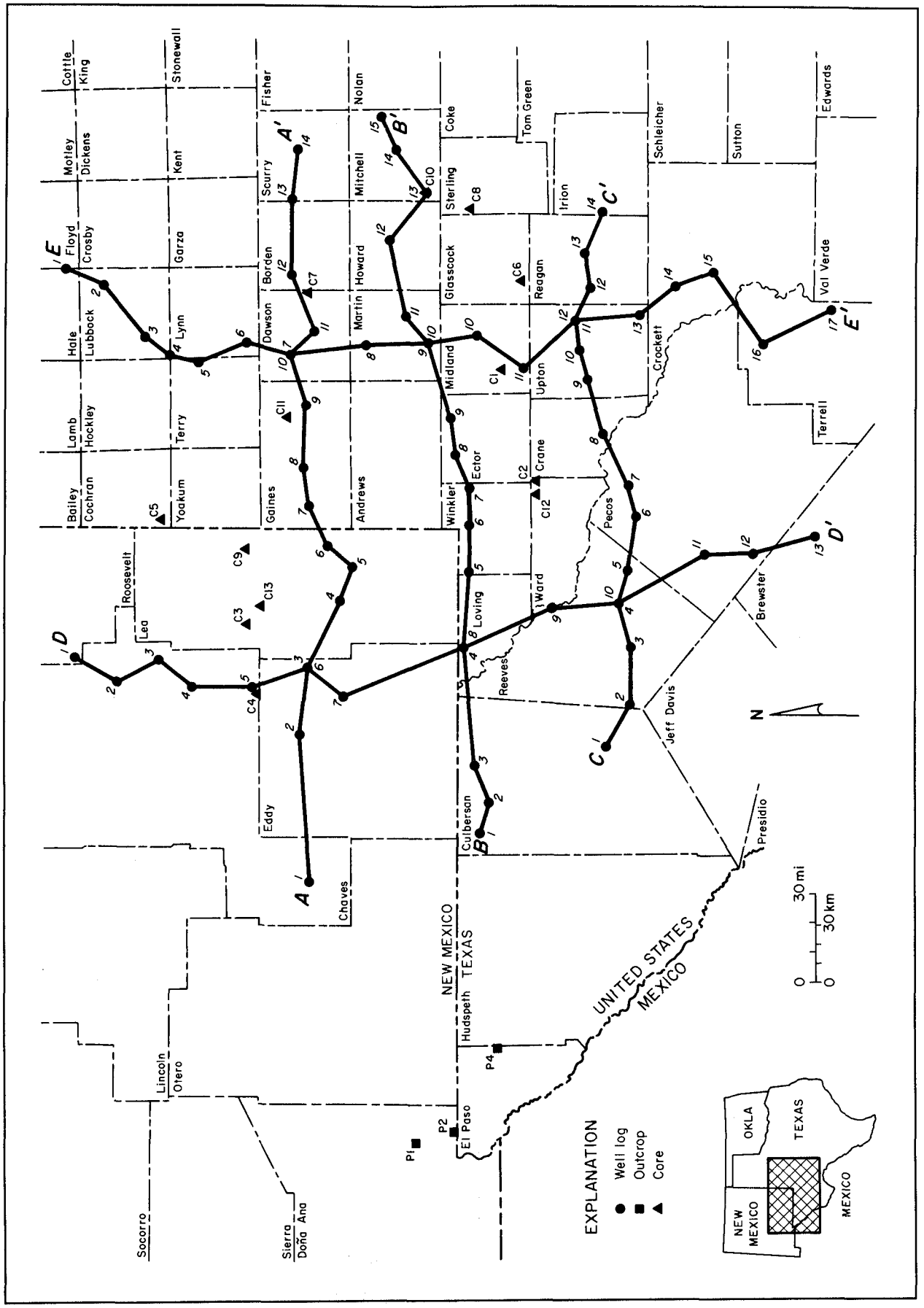


FIGURE 2. Map showing lines of cross sections (pls. 3 through 7) and locations of cores and measured sections (app. A).

The Woodford was more difficult to identify where it is overlain by radioactive, fine-grained carbonates or shales (for example, pl. 5, logs 9 through 14; pl. 6, logs 9 through 13; pl. 7, logs 10 through 12 and 16, 17) and where the lower part of the formation is much less radioactive than the upper part (for example, pl. 4, logs 9, 11; pl. 7, logs 7, 8). In such sections, the upper and lower contacts were picked from cores, if available, or on sonic, resistivity, and neutron logs. Typically the Woodford Formation exhibits low sonic velocity, low resistivity, and low neutron-induced radiation.

In cores and outcrops, the Woodford and correlative formations were identified by their high radioactivity and unique lithology. A radioactivity profile (counts per second [CPS]) was made for each core and outcrop using a hand-held scintillometer (Ettensohn and others, 1979). Discrepancies between log depth and core depth were corrected by comparing the radioactivity profile and the wireline gamma-ray log. Lithologically, Woodford black shale contrasts sharply with the light-colored Silurian-Devonian carbonates below and Mississippian carbonates above. Where differences in color and composition are less obvious, continuous, varvelike parallel laminae and abundant pyrite distinguish the Woodford.

Petrologic analysis was conducted using slabbed cores, outcrops, slabbed hand specimens, and thin sections (app. B). Uncovered thin sections were X-rayed to identify the clay minerals and to distinguish calcite and dolomite, and selected thin sections were point counted (app. C).

Woodford lithofacies were correlated in the subsurface using gamma-ray logs (pls. 3 through 7). The two dominant lithofacies, black shale and siltstone, are readily identified because siltstone is markedly less radioactive than black shale (app. B; C5, C9).

Total organic carbon (TOC), vitrinite reflectance (% R_o), and kerogen morphology data (app. D) were valuable in interpreting the sediment provenance, paleogeography, climate, and oceanography during Woodford deposition. Recognition of pelagic and terrigenous sediment was aided by distinguishing between amorphous kerogen, which derives from organic matter of aquatic origin, and structured kerogen, which is mostly the debris of land plants (Hunt, 1979; Tissot and Welte, 1984). Large concentrations of organic matter, recorded in the rocks as high TOC values, indicate high primary productivity, rapid sedimentation, or anoxic conditions; kerogen type records relative influences of terrigenous, paralic, or marine sources and indirectly reflects depositional processes, paleosalinity, paleoclimate, and proximity to land (Byers, 1977; Hunt, 1979; Demaison and Moore, 1980; Tissot and others, 1980; Tissot and Welte, 1984; Stein, 1986; Pedersen and Calvert, 1990). Vitrinite reflectance, which records maximum paleotemperature (Dow, 1977; Hunt, 1979; Tissot and Welte, 1984), allows inferences to be made about structural evolution, thermal events, and burial history of the basin during and after the Late Devonian and constrains models of mid-Paleozoic tectonics and paleogeography.

Stratigraphy

Nomenclature

The name Woodford was first used by Taff (1902) to describe exposures of chert and black shale along the southern flank of the Arbuckle Mountain anticline in Carter County, Oklahoma. Both Woodford Chert and Woodford Shale are established as formation names (Keroher and others, 1966), but the term Woodford Formation also appears in the literature. In this report, "Woodford Formation" is used because of the wide variety of lithologies that compose the interval in the southern Midcontinent. The most readily apparent and dominant lithology is black shale; however, chert, dolostone, sandstone, siltstone, and light-colored shale are common (Harlton, 1956; Amsden and others, 1967; Amsden, 1975, 1980).

Correlation and nomenclature of Devonian and Mississippian formations are well known regionally (fig. 3), but within the Permian Basin, stratigraphy and correlation of Silurian, Devonian, and Mississippian strata are poorly

known. Throughout this report, therefore, carbonate rocks underlying the Woodford are referred to as Silurian-Devonian (undifferentiated), and those overlying the Woodford are referred to as Mississippian (undifferentiated), unless faunal or lithologic data indicate a specific system, series, or stage.

Age and Correlation

The Woodford Formation is mostly Late Devonian (Frasnian-Famennian) in age, although beds of latest Middle Devonian (Givetian) and earliest Mississippian (Kinderhookian) appear at some localities (Hass and Huddle, 1965; Amsden and others, 1967; Amsden and Klapper, 1972; Amsden, 1975, 1980). Ellison (1950) found Late Devonian conodont assemblages but no Mississippian fossils in the Woodford Formation in the Permian Basin, and he documented the correlation between the Woodford in the Permian Basin and the Percha Formation in southeastern New Mexico and West Texas (fig. 3). The Late Devonian age of the Percha and Sly Gap Formations (fig. 3) has been established by faunal analysis (Stevenson, 1945; Laudon and Bowsher, 1949).

The Woodford is stratigraphically equivalent to several Devonian black shales in North America, including the Antrim Shale in the Michigan Basin, the Chattanooga and Ohio Shales in the Appalachian Basin, the New Albany Shale in the Illinois Basin, the Bakken Formation in the Williston Basin, and the Exshaw Formation in the Western Canada Basin (Meissner, 1978; Cluff and others, 1981; Roen, 1984; Burrowes and Krause, 1987). Correlative rocks exposed in uplifts in the southern Midcontinent include the Houy Formation in the Llano Uplift of Central Texas; the Chattanooga Shale in the Ozark Uplift of northeastern Oklahoma, southern Missouri, and northern Arkansas; the middle division of the Arkansas Novaculite in the Ouachita Mountains of southeastern Oklahoma and west-central Arkansas; the upper part of the Caballos Novaculite in the Marathon region of West Texas; the Percha Formation in the Hueco and Franklin Mountains of West Texas; and the Sly Gap Formation in the Sacramento Mountains of southeastern New Mexico (King and others, 1945; Stevenson, 1945; Laudon and Bowsher, 1949; Graves, 1952; Cloud and others, 1957; Huffman, 1958; Hass and Huddle, 1965; Amsden and others, 1967).

Previous Work

Western Outcrop Belt

Throughout the Franklin, Hueco, and Sacramento Mountains, Middle and Upper Devonian rocks unconformably overlie massive beds of the Lower Silurian Fusselman Dolomite (King and others, 1945; Stevenson, 1945; Laudon and Bowsher, 1949; LeMone, 1971; Lucia, 1971). In the Franklin and Hueco Mountains and at Bishop Cap, New Mexico, the Fusselman is overlain by the upper Middle to lower Upper Devonian Canutillo Formation, which is overlain conformably by the Upper Devonian Percha Formation (King and others, 1945; Rosado, 1970) (app. B; Pl, P4). The Canutillo consists of dark cherty and noncherty dolostone (Rosado, 1970), and the Percha is black, fissile, nonfossiliferous shale (Stevenson, 1945). The Canutillo-Percha contact is sharp, and the lithologic transition abrupt.

In the Sacramento Mountains, the Fusselman is overlain by the upper Middle to lower Upper Devonian Onate Formation, which is overlain by the lower to middle Upper Devonian Sly Gap Formation (Stevenson, 1945; Laudon and Bowsher, 1949; Kottlowski, 1963; Rosado, 1970; Bolton and others, 1982). Locally, rocks assigned to the Percha overlie the Onate or the Sly Gap (Pray, 1961; Bolton and others, 1982). The Onate-Sly Gap contact was found to be conformable by Stevenson (1945) but locally eroded and disconformable by Pray (1961). Kottlowski (1963) suggested that the Onate may be a basal facies of Sly Gap because the contact is gradational or only slightly erosional. The Onate consists of interbedded gray-brown shale, siltstone, fine sandstone, and carbonate (Stevenson, 1945), and the most common lithology is dolomitic siltstone (Kottlowski, 1963). The Sly Gap is fossiliferous and consists of thinly interbedded, mostly tan to pale-yellow shale, siltstone, and limestone, along with a few dolomitic beds (Stevenson, 1945; Rosado, 1970). The Sly Gap is distinguished from the Onate in the field by color; and the Sly

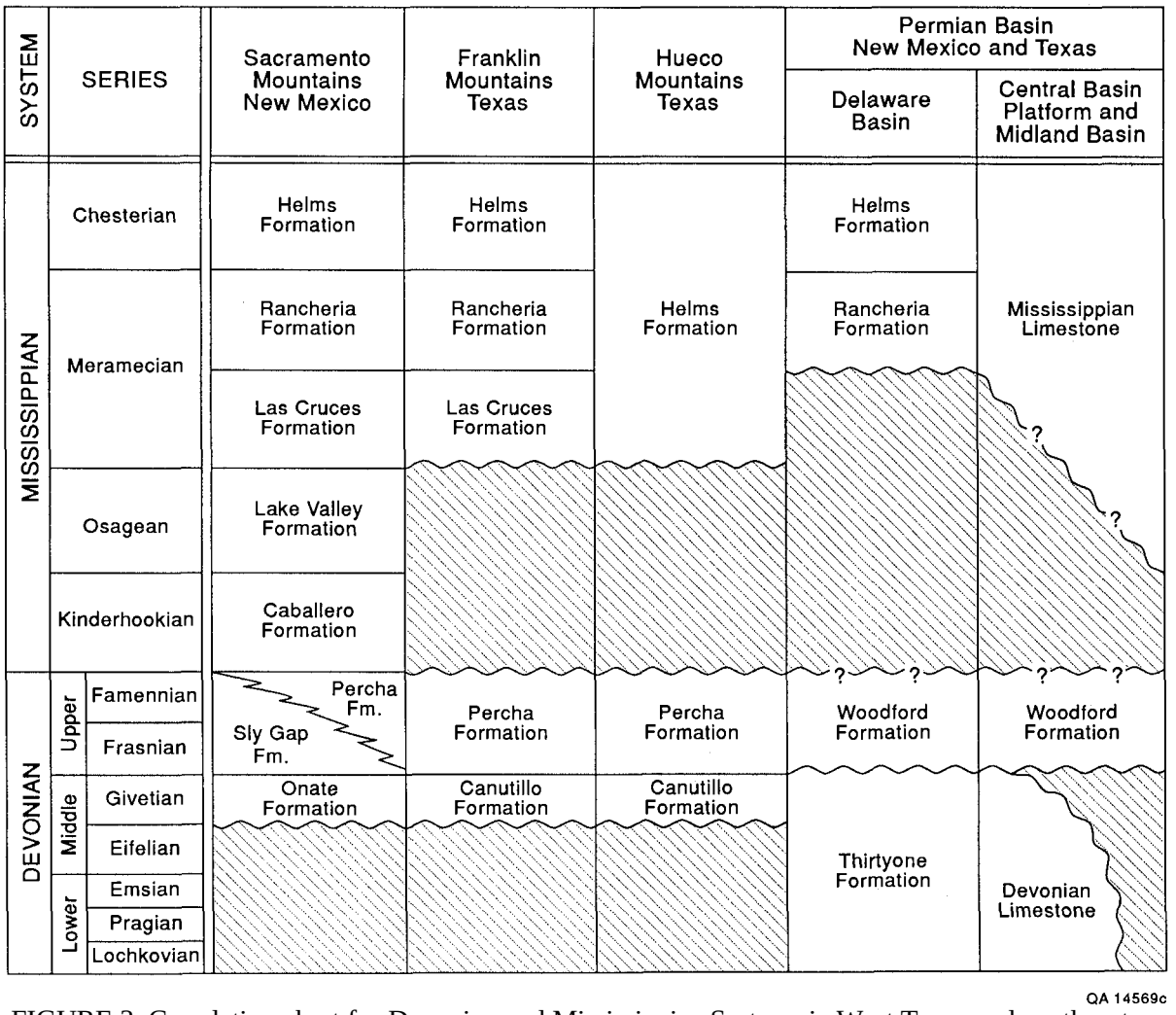


FIGURE 3. Correlation chart for Devonian and Mississippian Systems in West Texas and southeastern New Mexico. Adapted from Rosado (1970), LeMone (1971), Hoenig (1976), Bolton and others (1982), Lindberg (1983), and Hills (1984).

Gap has more shale and fewer massive, resistant beds than does the Onate (Stevenson, 1945). In the Sacramento Mountains, the Sly Gap gradually thins to the east and south and contains more black shale than do exposures farther west (Stevenson, 1945), reflecting a facies relationship with the Percha (Rosado, 1970).

At most localities in the Franklin, Hueco, and Sacramento Mountains, the Percha and Sly Gap Formations are overlain disconformably by Mississippian limestones (King and others, 1945; Rosado, 1970) (app. B; P2, P4). At Bishop Cap, New Mexico (app. B; Pl), and locally in the Sacramento Mountains, Upper Devonian rocks are overlain conformably by the Kinderhookian Caballero Formation (Rosado, 1970; Bolton and others, 1982) (fig. 3).

Central Texas

In the Llano region of Central Texas, the Houy Formation disconformably overlies rocks of Early to Middle Devonian and Early Ordovician age (Cloud and others, 1957). Rocks below the unconformity are carbonates, and most are cherty. In upward succession, the Houy consists of a lower or basal chert breccia (Ives Breccia Member), black shale (Doublehorn Shale Member), and an upper, unnamed phosphatic unit. The Ives Breccia consists mostly of angular fragments and unbroken nodules of chert and locally contains angular blocks of dolostone, all of which appear to be little-moved lag deposits (Cloud and others, 1957). The Doublehorn Shale is fissile, radioactive, spore-bearing black shale, and the upper phosphatic unit contains phosphatic

debris such as fish bones, pellets, and conodonts. The Houy is predominantly Late Devonian, but locally the lowermost Houy may be Middle Devonian and the upper phosphatic unit partly Early Mississippian (Kinderhookian) (Cloud and others, 1957).

The Houy is conformably overlain by the Kinderhookian Chappel Limestone (Cloud and others, 1957). However, the upper Houy has thin beds, interrupted faunal zones, and intervals containing mixed Mississippian and Devonian fossils, all of which make correlation, age, and vertical continuity difficult to determine (Cloud and others, 1957).

Northeastern Oklahoma and Northern Arkansas

In the Ozark Uplift, the Chattanooga Shale rests disconformably on rocks ranging in age from Devonian to Ordovician (Huffman, 1958). The Sylamore Sandstone Member constitutes the lower part of the formation at many localities, and its age is late Middle Devonian to late Kinderhookian (Freeman and Schumacher, 1969; Pittenger, 1981). The black shale interval, sometimes called the Noel Shale Member (Huffman and Starke, 1960), is predominantly Late Devonian but ranges in age from early Late Devonian to Kinderhookian (Amsden and others, 1967). The Sylamore is submature to supermature quartzarenite that contains minor phosphate, glauconite, and locally abundant dolomite (Pittenger, 1981). Quartz was reworked from contemporaneous exposures of the Middle Ordovician Bergen Sandstone (Pittenger, 1981). Locally the basal layer of the Sylamore is chert breccia (Amsden and others, 1967). The Noel is black, fissile, radioactive shale and is the most abundant Chattanooga lithology. The Chattanooga is overlain disconformably by limestones and cherts of the Mississippian Boone Group. The Boone is predominantly Osagean but ranges in age from middle Kinderhookian to early Meramecian (Sutherland and Manger, 1979).

Ouachita Fold Belt

The middle division of the Arkansas Novaculite in Oklahoma and Arkansas is from Late Devonian to Kinderhookian age and represents, at least partly, a lateral facies of the Woodford (Hass, 1951; Amsden and others, 1967). Likewise, the upper Caballos Novaculite in West Texas is a Late Devonian (Graves, 1952) lateral facies of the Woodford. Faunal data are scarce and contact relationships problematic, but vertical lithologic continuity suggests that the Woodford-equivalent interval in the novaculite formations is bounded conformably by the underlying and overlying beds. The upper Caballos contains mostly white novaculite, and the middle division of the Arkansas Novaculite contains interbedded dark-gray and greenish-gray shales and dark-gray novaculite (Hass, 1951; Amsden and others, 1967).

Central and Southern Oklahoma

In central and southern Oklahoma, the Woodford Formation rests disconformably on rocks of late Early Devonian to Ordovician age (Amsden, 1975, 1980). The Woodford is mostly Late Devonian but ranges in age from Givetian to Kinderhookian (Hass and Huddle, 1965; Amsden and others, 1967; Amsden and Klapper, 1972; Amsden, 1975, 1980). A basal clastic unit, the Givetian to early Famennian Misener Sandstone, is present in some areas (Amsden and Klapper, 1972). Woodford black shale is Frasnian to Kinderhookian (Hass and Huddle, 1965; Amsden and others, 1967).

Rocks underlying the Woodford are predominantly carbonates, and some are cherty. In southern Oklahoma, the Misener is sandstone, siltstone, green shale, dolostone, or chert breccia, whereas in north-central Oklahoma it is mostly mature quartzarenite containing minor glauconite and phosphate and locally abundant dolomite (Harlton, 1956; Amsden and others, 1967; Amsden and Klapper, 1972; Amsden, 1980; Francis, 1988). Quartz was derived with little transport from Middle Ordovician Simpson sandstone in north-central Oklahoma and from the Ouachita province in southern Oklahoma (Amsden and Klapper, 1972). Black shale is the most widespread Woodford lithology. It is fissile, spore-bearing, and highly radioactive, and in the Arbuckle Mountains it is interbedded with chert (Amsden and others, 1967; Amsden, 1975, 1980). Woodford chert is dark and rich in radiolarians and marine organic matter (Comer and Hinch, 1987). The Misener-Woodford sequence is stratigraphically equivalent to the

Sylamore-Chattanooga sequence in the Ozark Uplift, and the lower boundary of both sequences is diachronous, onlapping parts of the northern Oklahoma shelf and the Ozark Uplift (Freeman and Schumacher, 1969; Amsden and Klapper, 1972; Amsden, 1980).

In the Arbuckle Mountains, the Woodford is conformably overlain by the Sycamore Formation. The Sycamore consists of poorly fossiliferous, fine-grained, silty limestone interbedded with dark shale, and its age spans the Early to Middle Mississippian (Kinderhookian to Meramecian) (Ham, 1969). In the subsurface, the Woodford is overlain by Mississippian rocks (mostly limestones), but the stratigraphic relationship is problematic. In basinal regions, evidence of unconformity is obscure, although the contact is probably disconformable (Ham and Wilson, 1967; Frezon and Jordan, 1979). Locally the contact appears to be gradational, and the unconformity, if present, represents only a minor stratigraphic break (Frezon and Jordan, 1979).

Permian Basin

In the Permian Basin, lithologic, electric-log, and sparse faunal data indicate that the Woodford unconformably overlies rocks ranging in age from Devonian to Ordovician (Lloyd, 1949; Ellison, 1950; Peirce, 1962; McGlasson, 1967, Munn, 1971; Hoenig, 1976). The Woodford is overlain disconformably by Mississippian limestone (fig. 3) and locally by rocks as young as Early Permian (Lloyd, 1949; Wright, 1979). Lloyd (1949) assigned the Mississippian limestone section in the subsurface to the Meramecian Rancheria Formation on the basis of a few fossils and lithologic similarity to rocks exposed in the Sacramento Mountains. Older, Osagean and Kinderhookian rocks have not generally been recognized in the basin, although Kinderhookian strata were postulated to exist in a small area of eastern Chaves, southwestern Roosevelt, and northwestern Lea Counties, New Mexico, on the basis of lithologic similarity to the Caballero Formation in the Sacramento Mountains (Lloyd, 1949).

Ellison (1950) divided the Woodford Formation into three units using radioactivity, log response, and lithology. The lower unit was calcareous and cherty, and it had the lowest radioactivity; the middle unit had the most resinous spores and the highest radioactivity; and the upper unit had few spores and intermediate radioactivity (Ellison, 1950). The middle unit was the most widespread, comprising the black shale lithology characteristic of the Woodford throughout the basin, and the lower unit was the most areally restricted. A correlation may exist between Ellison's lower Woodford unit and the Ives Breccia Member and between the middle Woodford unit and the Doublehorn Shale Member of the Houy Formation in Central Texas (Wright, 1979).

Formation Boundaries

The lower boundary of the Woodford and its stratigraphic equivalents represents a major regional unconformity that extends across the southern Midcontinent and records a major period of uplift and erosion that is at least partly Devonian (Galley, 1958; Amsden and others, 1967; Ham and Wilson, 1967; Ham, 1969). During this regressive episode, older Devonian and Silurian strata were removed over broad areas of the Midcontinent, and rocks below the unconformity became locally deeply eroded (Ham and Wilson, 1967; Ham, 1969; Amsden, 1975). In basinal regions, such as the Anadarko Basin, the unconformity marks the end of early Paleozoic shallow-water carbonate sedimentation and the beginning of deep-water carbonate and clastic deposition (Ham, 1969). The Woodford and correlative formations are diachronous and represent onlapping sediments (Freeman and Schumacher, 1969; Amsden and Klapper, 1972) deposited during worldwide Late Devonian marine transgression (Johnson and others, 1985). The coarse sandstone and breccia occurring locally above the unconformity are lag deposits derived from older formations (Cloud and others, 1957; Amsden and others, 1967; Amsden and Klapper, 1972; Amsden, 1975, 1980; Pittenger, 1981), and the black shale represents strongly reduced mud laid down on the anoxic floor of an epeiric sea (Ellison, 1950; Wright, 1979).

The upper boundary of the Woodford represents only a minor stratigraphic break (Ham and Wilson, 1967; Frezon and Jordan, 1979; Click, 1979; Mapel and others, 1979). It is disconformable at some localities (for example, the

Ozark Uplift and parts of the western outcrop belt and Oklahoma subsurface) and conformable at others (for example, Central Texas, the Arbuckle Mountains, and the Ouachita Fold Belt). The local occurrence and minor stratigraphic expression of disconformities indicate low-lying land masses in the latest Devonian or earliest Mississippian and an episode of minor epeirogenic uplift, slight sea-level fluctuations, and brief interruption of marine sedimentation (Stevenson, 1945; Ham and Wilson, 1967; Frezon and Jordan, 1979; Mapel and others, 1979).

Distribution

Distribution of the Woodford Formation in the Permian Basin is illustrated in plates 1 through 7. The area contoured in plates 1 and 2 was not extended to the western outcrop belt because of limited well control in Chaves, Eddy, Otero, and Lincoln Counties, New Mexico, and Culberson, Hudspeth, and El Paso Counties, Texas.

Relief on the present-day Woodford surface is more than 20,000 ft in the subsurface (pl. 1) and more than 25,000 ft if elevations in the western outcrop belt are included. Most of the relief in the basin developed as a result of deformation during the late Paleozoic Ouachita orogeny (Galley, 1958; Muehlberger, 1980), whereas relief in the outcrop belt and Diablo Platform was strongly influenced by later Laramide deformation (Muehlberger, 1980).

The Woodford Formation ranges in thickness from 0 to 661 ft (pl. 2) and is thickest in structural lows and thinnest or absent on structural highs. Thicknesses shown on plate 2 were not corrected for dip and do not everywhere represent true stratigraphic thicknesses. The Woodford is more nearly flat-lying in basin and shelf settings farthest from major faults (for example, on the Eastern Shelf and in most parts of the Midland Basin and Northwestern Shelf).

Northwestern Shelf and Matador Uplift

The Woodford Formation is present at most localities on the Northwestern Shelf but is absent on and north of the Matador Uplift (fig. la; pls. 1, 2, 7) (Ellison, 1950; Wright, 1979; Dutton and others, 1982; Ruppel, 1985). In northern Lea County, New Mexico, elevation of the Woodford increases northward, but the pattern is broken by several faults (pl. 1). These faults trend north-south or northwest-southeast, generally parallel to the Central Basin Platform and the axis of the Delaware Basin.

The Woodford thins northwestward across Eddy County, New Mexico, away from the Delaware Basin (pls. 2, 6), the gradual thinning coinciding with the increase in elevation (pl. 1). In eastern Chaves and northern Eddy Counties, New Mexico, thin and thick areas are irregularly distributed and are not clearly related to structure (pl. 2). In the northernmost part of the map, Woodford thickness appears to be structurally controlled because isopach contours are oriented east-west, parallel to the structural trend of the Matador Uplift (pl. 2).

Eastern Shelf

The Woodford Formation was previously thought not to extend onto the Eastern Shelf (Ellison, 1950; Wright, 1979), but in the present study no clearly defined eastern limit for the Woodford was found (pls. 1, 2). The formation is absent in northeastern Crockett County, in most of western Irion County, and in a large area that includes parts of Scurry, Borden, and Garza Counties. However, the formation is present across Sterling, Mitchell, and most of Scurry Counties.

The wide spacing of structural contours in the eastern part of the map (pl. 1) documents a gradual increase in elevation of the Woodford from the Midland Basin onto the Eastern Shelf. The Woodford also thins gradually in the same direction (pls. 2 through 5). On the Eastern Shelf, the Woodford is thin, and the distribution is somewhat irregular and patchy (note thicknesses in Scurry, Mitchell, and Sterling Counties, pl. 2). These structural and isopach trends are uninterrupted except in southern Irion and northern Crockett Counties, where large-scale faults cut the section.

Central Basin Platform and Pecos Arch

The Central Basin Platform and Pecos Arch are the diverging structural highs in the center of the map that meet in Crane and northeastern Pecos Counties (fig. la; pls. 1, 2). Faults bounding the Pecos Arch trend east-west, whereas those along the Central Basin Platform trend northwest-southeast. Some of the largest faults, those having throws of a few thousand feet, are normal or high-angle reverse faults, although some show evidence of strike-slip motion (Galley, 1958; Walper, 1977; Muehlberger, 1980; Hills, 1984).

The Woodford is absent from the Pecos Arch and from many of the faulted structures on the Central Basin Platform (Ellison, 1950; Galley, 1958) (pls. 1, 2, 7). Elevations of the Woodford or the unconformity representing the Woodford range from 980 ft below sea level in northern Pecos County to more than 7,000 ft below sea level in eastern Winkler County. The Woodford thins over the Central Basin Platform in most places, but in some areas, such as southern Ector and Winkler Counties, the thickness steadily increases westward (pl. 2).

Delaware Basin

The Woodford Formation reaches its maximum thickness of 661 ft in the Delaware Basin structural low in western Winkler County (pls. 1, 2). The Woodford is more than 600 ft thick in central and southwestern Winkler, southeastern Loving, and northern Ward Counties. The top of the deepest Woodford is more than 16,000 ft below sea level in eastern Loving County and more than 15,000 ft below sea level in east-central Reeves County (pl. 1). Several isolated thick areas whose distribution is fault controlled appear in Reeves County (pl. 2); in the north-central part of the county, thickness locally exceeds 500 ft, and in central and southeastern areas, 400 ft.

Midland Basin

The axis of the Midland Basin is approximately outlined by the closed -9,000-ft structural contours east of the Central Basin Platform in Texas (pl. 1). The deepest Woodford is nearly 9,800 ft below sea level in northeastern Gaines County (pl. 1). Within the basin thickness trends are subtle (pl. 2); the Woodford at its thickest is 135 ft in north-central Martin County. Two thick areas are indicated by the closed 100-ft isopach contours in Dawson, Gaines, Andrews, and Martin Counties. Between the thick areas lies an east-west trend of relatively thin Woodford (50 to 100 ft). Another narrow thin trend (<50 ft) lies in southern Martin and southeastern Andrews Counties. These trends parallel structural and isopach trends along the Matador Uplift and Pecos Arch and are at a high angle to those along the Central Basin Platform immediately to the west.

Val Verde Basin

The Woodford is present in the Val Verde Basin of southern and southeastern Pecos, southern Crockett, northern Terrell, and northern Val Verde Counties (fig. la; pls. 1, 2, 7). In northern Brewster and southern Pecos Counties, the Woodford Formation, along with a carbonate sequence typical of the Paleozoic section of the craton, lies beneath allochthonous rocks of the Ouachita Fold Belt (pls. 1, 2, 6 [D–D´, well 13]).

Two structural trends are present in the Val Verde Basin (pl. 1). In south-central Pecos County, faults and structural contours trend northwest-southeast, and elevation of the Woodford Formation increases from central Pecos County south westward and westward. In Terrell, southern Crockett, Val Verde, and eastern Pecos Counties, faults trend east-west, and elevation of the Woodford increases northward from the Ouachita Fold Belt to the Pecos Arch.

In central Pecos County, the Woodford was inferred to be more than 21,000 ft below sea level (pl. 1) on the basis of the elevation of the Ellenburger Formation (Ewing, 1991), and it was inferred to be more than 300 ft thick (pl. 2) on the basis of nearby thickness trends. In central Terrell County, the Woodford was inferred to be more than 20,000 ft below sea level, and even deeper burial is likely beneath the Ouachita overthrust (pl. 1). Thicknesses in this part of the basin locally exceed 400 ft and may be 300 ft or more in central Terrell County beneath the Ouachita allochthon (pl. 2).

Diablo Platform and Western Outcrop Belt

The Diablo Platform (fig. la, b) is a major structural boundary between the Permian Basin to the northeast and the Chihuahua Tectonic Belt to the southwest that has been strongly affected by Laramide deformation (Muehlberger, 1980). Most of the faults along the platform trend northwest-southeast and follow Proterozoic basement faults (Walper, 1977; Muehlberger, 1980).

The Woodford is absent in the southeastern part of the Diablo Platform, southwest of the map area (Wright, 1979), but it is present in the northeastern part (Rosado, 1970) (pls. 1,2). The highest observed subsurface elevation (128 ft below sea level) is in northwestern Culberson County (pl. 1). The highest overall elevation (>5,000 ft above sea level) is in the western outcrops. From the Delaware Basin, elevation of the Woodford gradually increases westward across Reeves and Culberson Counties toward the Diablo Platform (pl. 1), and the formation gradually thins in the same direction (pl. 2).

Lithofacies

Two lithofacies were identified in the Woodford Formation—black shale and siltstone. Black shale is pyritic and has parallel laminae; siltstone, a hybrid rock composed of silt-sized quartz and dolomite grains, is medium to dark gray and has discontinuous and disturbed bedding. Distinguishing between lithologies can be difficult because differences in color may be slight, and many layers contain subequal mixtures of silt- and clay-sized grains. Contacts between lithofacies may be sharp, particularly at the base of the siltstones, or gradational; and lithologies are commonly interbedded and interlaminated.

Lithofacies were defined and described from cores because weathering had severely oxidized the pyrite and organic matter in outcrop. Outcrops are medium to light shades of gray or brown, whereas cores are black (black shale) or light to dark gray (siltstone). Textures were found to be comparable in outcrop and core, and the mineralogy of the silicate and carbonate fraction was similar. Hence, lithofacies analysis was possible at all localities.

Black Shale

Characteristic Features

Parallel laminae are the most characteristic feature of black shale (fig. 4a, b). Other distinguishing features include abundant pyrite, fine grain size, black color, and high radioactivity. The black color is caused by high concentrations of pyrite (as much as 13 vol %; app. C) and organic carbon (as much as 35 vol % [app. C] or 12 wt % TOC; app. D), and high radioactivity is caused by uranium bound in the organic matter (Swanson, 1960, 1961; Leventhal, 1981).

Bedding and Sedimentary Structures

Continuous parallel laminae predominate (fig. 4a), but other stratification types include discontinuous, wavy, and lenticular laminae and thin beds. Most laminae have no internal structure but can be distinguished by subtle differences in color that result from differences in composition (for example, unequal amounts of detrital quartz, clay, pyrite, dolomite, and organic matter and different numbers of spores and radiolarians). These laminae typically have a varvelike appearance in slabs and thin sections (fig. 4a). Thin graded siltstone-shale couplets were found in some intervals, mostly in shelf regions (app. B; C3, C4, C13). Most graded couplets have sharp bases, and some exhibit primary sedimentary structures such as fading ripple forms.

Burrows are scarce but commonly cause disrupted or distorted layers (fig. 4a through c). Most burrows are confined to, or start in, siltstone laminae (fig. 4a, b), but a few were found exclusively in shale (fig. 4c). Flattened horizontal burrows were the most common type observed, and vertical burrows (fig. 4b, c) were found only locally. Burrows are filled by silt, secondary silica, carbonate, and pyrite in varying proportions, and some contain scattered remnants of anhydrite (fig. 4d).

Syneresis cracks (fig. 4e) were found locally on the Central Basin Platform in organic-rich, pyritic black shale. They are short, wide vertical fractures, linear in plan view and wedge shaped in cross section. Syneresis cracks are found in the middle of the black shale section and not at lithologic or formation contacts (app. B; C2). They are highly compacted and thus are inferred to be syndepositional or very early diagenetic. The cracks are filled mostly by secondary silica (including quartz, chert, and chalcedony) and locally contain carbonate, along with patchy remnants of anhydrite. Filling must have occurred shortly after the cracks formed because cementing phases are deformed, and the surrounding black shale is differentially compacted (fig. 4e). Subaerial exposure is not indicated because pyrite and organic matter in the host shale are unoxidized.

Texture

Black shale consists of more than 50 percent clay-sized material and less than 50 percent silt-sized particles (fig. 4a through c). Silt-sized grains may be randomly scattered (fig. 4c) or concentrated in laminae (fig. 4a, b). Lighter colored laminae will typically contain greater proportions of silt-sized particles than will the darker laminae.

Median grain sizes of the silt fraction are between 0.01 and 0.05 mm. Sand-sized grains are rare. A few large (as much as 5 cm long) greenish shale clasts exhibiting parallel laminae (fig. 4f) were found locally on the Central Basin Platform.

Composition

Clay-sized material consists of organic matter and illite, and the silt-sized fraction consists of mostly dolomite, quartz, pyrite, mica, feldspar, glauconite, biogenic pellets, spores, and radiolarians. Other types of fossils, including conodonts, brachiopods, trilobites, sponge spicules, and vertebrate debris, were found locally, but only rarely.

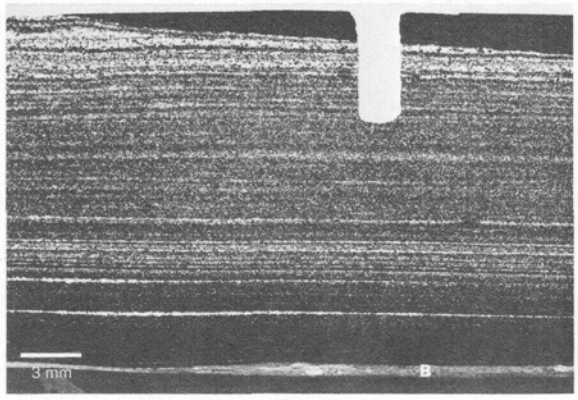
Organic carbon content in core samples ranges from 1.4 to 11.6 weight percent TOC (mean = 4.5 ± 2.6 wt % TOC for 72 samples), or from roughly 4 to 35 volume percent organic matter. Outcrops contain much less organic carbon than do the cores (<0.1 to 2.3 wt % TOC; mean = 0.8 ± 0.6 wt % TOC for 25 samples) primarily because of oxidation during weathering. Average TOC concentration in each core ranges from 2.2 to 9.0 weight percent and in each outcrop from 0.1 to 1.1 weight percent (app. D).

Organic matter most commonly appears as fine-grained, disseminated, amorphous material (app. D), an oil-generating type. Woody particles were rare in thin sections and in separated kerogens. Large plant fragments appeared on a few bedding surfaces in cores from the Northwestern and Eastern Shelves. Recycled vitrinite occurs only in black shale from the Central Basin Platform, Eastern Shelf, and southern Midland Basin (app. D). The mean reflectance values of primary vitrinite in cores and outcrops range from 0.54 to 1.92 percent R_o (app. D) and represent hydrocarbon generation stages between early oil generation and late wet-gas generation (Hunt, 1979).

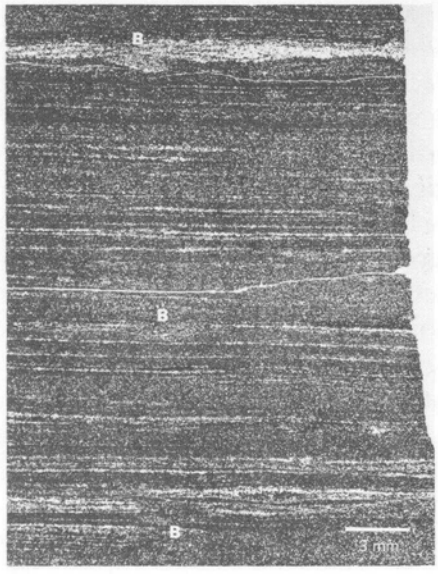
Illite is abundant in the black shale. Volume percentages range between 34 and 79 percent and average 59 ± 3 percent (app. C). The coarse clay mineral fraction (1 to 2 μm) is detrital illite, whereas the fine clay mineral fraction (<0.2 μm) is diagenetic illite (Morton, 1985).

Dolomite and quartz are the most common silt-sized components. They occur randomly mixed in subequal proportions, and they have the same grain-size distribution. Dolomite grains in shale have no overgrowths—most are subhedral to anhedral and appear to be abraded (fig. 4g). Euhedral dolomite grains are abundant only locally in cores from the Central Basin Platform, Midland Basin, and Northwestern Shelf. Scattered silt- to sand-sized poikilotopic dolomite patches cement clay- or fine silt-sized particles in some samples.

Pyrite is ubiquitous in cores and can be found in a variety of forms: (1) large (as much as 8 cm) nodules (some possessing cone-in-cone fabric), (2) irregular elongate patches, (3) thin streaks, (4) smooth elliptical masses having stromatolite-like or oncolitelike fabric, (5) scattered fine grains, (6) framboids, (7) aggregates (silt sized or finer), (8) fillings or replacements of minute organisms (for example, spores and radiolarians), (9) cement or replacement in burrows, and rarely, (10) fracture fillings. Weathering has altered pyrite in outcrop to various oxides and sulfates. Locally, gypsum lines joints and bed-

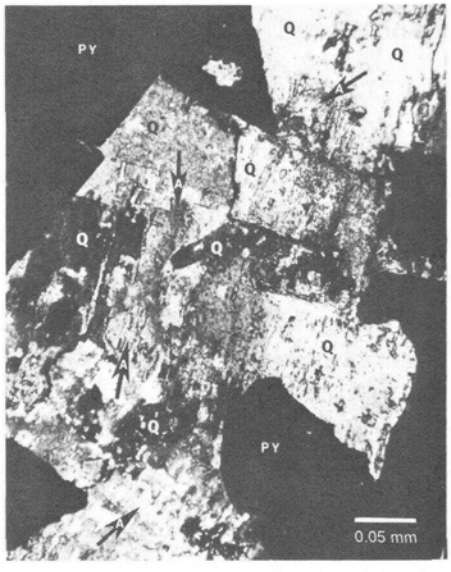


(a)

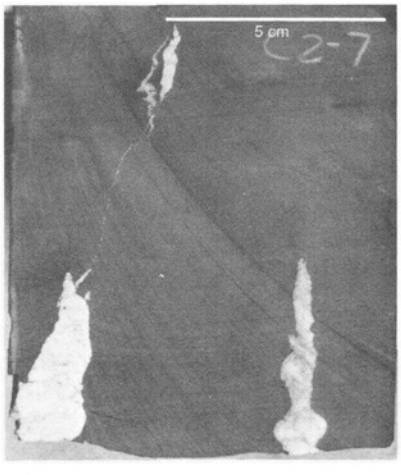


(b)

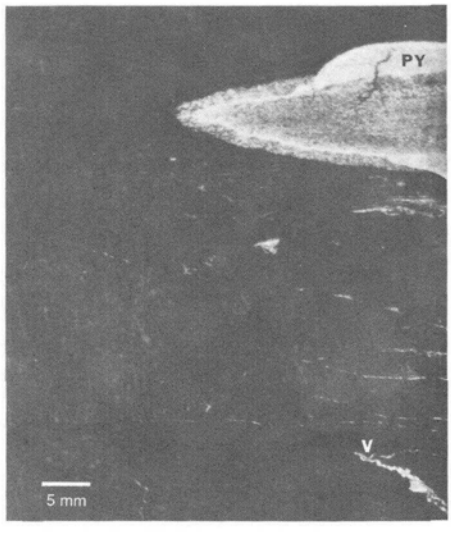
(c)



(d)



(e)



(f)

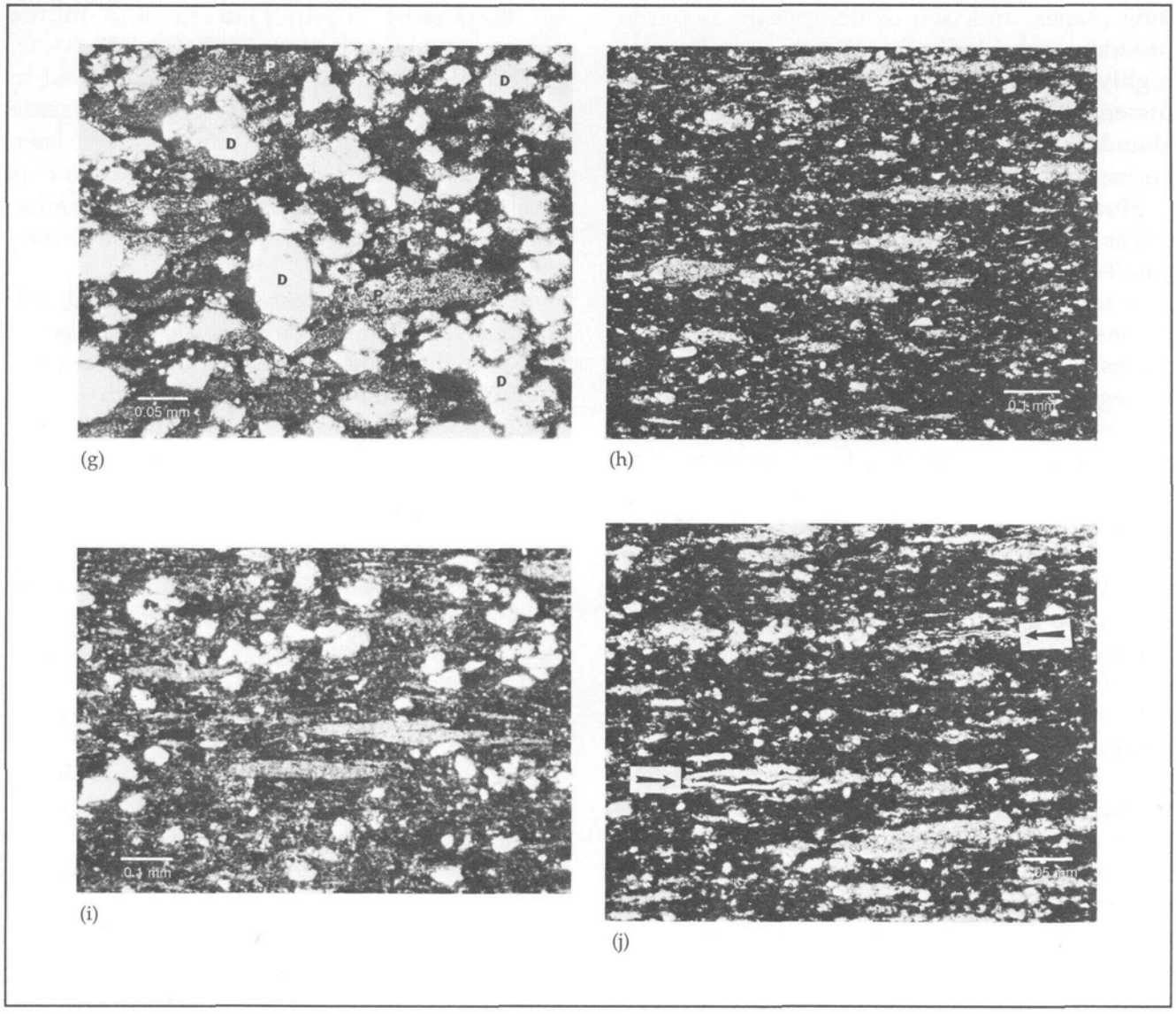


FIGURE 4. Photos of Woodford black shale. (a) Black shale exhibiting continuous parallel laminae at 11,555 ft in the No. 1918 Parks (app. B; Cl, sample C1-10). Note cyclic change from black shale at base, siltstone laminae increasing upward, and abrupt return to black shale at top. Silty lamina at base, B, is burrowed. TOC = 4.2 wt %. (b) Disrupted parallel siltstone laminae in black shale at 10,914 ft in the No. 1 Champeau Federal (app. B; C4, sample C4-4). Disrupted areas, B, are burrows. TOC = 5.0 wt %; R_o = 1.03%. (c) Black shale exhibiting parallel laminae, scattered silt, and burrows at 12,228 ft in the No. 5 Pacific Royalty (app. B; C9, sample C9-2). TOC = 3.2 wt %. (d) Enlarged view of burrow in photo (c) (see arrow in photo [c]). Burrows are filled mostly by quartz, Q; pyrite, PY; and patchy remnants of anhydrite, arrows marked A. Rectangular habit indicates quartz is pseudomorph after anhydrite. Crossed nicols. (e) Syneresis cracks filled mostly by silica and carbonate and locally containing anhydrite at 7,179 ft in No. 43 Yarborough & Alien (app. B; C2, sample C2-7). Note differential compaction of black shale laminae and compactional deformation of syneresis structures. TOC = 8.5 wt % in host shale. (f) Shale clast in black shale at 7,177 ft in No. 43 Yarborough & Alien (app. B; C2, sample C2-6). Clast has parallel laminae, and the outer edge was pyritized, PY. Oblique calcite veins and ptygmatic veinlets, V, reflect shearing. TOC = 11.2 wt % in host shale. (g) Silty shale at 7,172 ft (app. B; C2, sample C2-3). Silt is exclusively dolomite, D, and most grains are angular, broken, or abraded. Pellets, P, are elongate fine-grained aggregates and probably biogenic. Plane-polarized light. TOC = 8.5 wt %. (h) Pellets containing silt particles at 7,404 ft in the No. 1 Sealy Smith (app. B; C12, sample C12-4). Plane-polarized light. Dolomite/quartz ratio = 1.3/1.0; TOC = 10.2 wt % ; R_o = 0.55%. (i) Pellets composed mostly of clay at 11,639 ft in the No. 1 Walker (app. B; C5, sample C5-2). Silt grains are dolomite and quartz. Plane-polarized light. Dolomite/quartz ratio = 1.3/1.0; TOC = 2.8 wt %. (j) Pellets and flattened spores at arrows from same thin section as those in photo (h). Spores are *Tasmanites.* Plane-polarized light.

ding planes, and iron oxide appears as pyrite pseudomorphs, indicating that these rocks were highly pyritic before weathering. Elsewhere, disseminated ferric oxides record the former abundance of pyrite in the Percha and Sly Gap Formations.

Muscovite flakes appear in all samples. Mica flakes and illite typically are well oriented parallel to bedding. In biogenic pellets, however, illite may comprise domains of differing orientations. Locally some mica flakes lie at high angles to bedding, a few flakes being oriented 90 degrees to bedding. Such flakes appear to be part of larger clumps of organic-bound sediment.

Feldspar (microcline) and glauconite are rare in black shale. Feldspar appears mostly in samples from the Northwestern Shelf, Central Basin Platform, and western Midland Basin (app. C; Cl, C2, C4, C13). Glauconite occurs as an isolated grain or two in many thin sections.

Biogenic pellets are common (as much as 11%; app. C) in many black shale samples. They appear as flattened silt sized to fine sand sized aggregates and impart a microlenticular fabric to the rock when viewed in thin section (fig. 4h through j). Pellets are easily distinguished from burrows in plan view because pellets exhibit no trail-like patterns on bedding surfaces or in cross section because pellets show no cross-cutting contacts or internal stratification. Most pellets consist of illite, but some consist of silt-sized grains of quartz and dolomite (fig. 4h). Silty pellets commonly are cemented by carbonate and are flattened slightly less than clay pellets.

Spores are minor components in black shale, but they are widely distributed. Generally spores are flattened as a result of compaction (fig. 4j). However, in some intervals spores have been replaced by pyrite or infilled by pyrite, chert, or carbonate. Locally, early infilling is indicated by spores that are uncompacted or only slightly flattened.

Radiolarians also are a minor but widely distributed component. They are composed mostly of chert or chalcedony, but some have been partly or completely replaced by pyrite or carbonate. Spores and radiolarians may be randomly scattered throughout a laminated sequence or concentrated in laminae or thin beds. Radiolarian chert layers were observed locally on the Central Basin Platform and in the southern Midland Basin (app. B; C2, C6).

Trilobite fragments are sparsely scattered in some intervals and locally occur alongside pellets. Most are carbonate, but a few have been partly replaced by chert. Trilobite fragments locally are common at the top of the formation along the disconformity with the Mississippian limestone (app. B; C10).

Brachiopods are scarce in the Woodford. Inarticulate brachiopods *(Lingula)* were recognized on bedding surfaces in cores from the Central Basin Platform and the Northwestern Shelf (app. B; C2, C4, C9). One silicified articulate brachiopod was found in black shale on the Central Basin Platform (app. B; C2). Elsewhere, articulate brachiopods are abundant only locally at the top of the formation (app. B; C10).

Phosphatic fossil debris is a minor component in black shale. Conodonts are scarce but widely distributed, and bone and teeth fragments and fish scales also are rare. Phosphatic debris sometimes is concentrated in the siltier shales and in interstratified siltstones.

Sponge spicules were found only locally in one core from the Central Basin Platform where monaxons were scattered parallel to stratification (app. B; C2). All of the spicules had altered to chert.

Secondary silica is the major constituent in some layers and sedimentary structures. Secondary silica in the form of chert, chalcedony, and megaquartz fills or replaces fossils and cements or replaces burrows and syneresis cracks (fig. 4c through e). Megaquartz that has pseudomorphic rectangular cleavage after anhydrite was found locally associated with anhydrite (fig. 4d). Also, some of the chalcedony in burrows and syneresis cracks is length-slow, suggesting that it replaced evaporites (Folk and Pittman, 1971).

Siltstone

Characteristic Features

Siltstone in the Woodford Formation is a hybrid siliciclastic-carbonate rock in which dolomite and quartz are the dominant silt-sized framework grains. Compared with black shale, siltstone has coarser grain size, lighter color,

more disrupted or discontinuous strata, and lower radioactivity. Siltstone, unlike the carbonate lithologies of bounding formations, has a more uniform silt-sized texture, abundant quartz grains, no chert, no large body fossils, and higher radioactivity.

Bedding and Sedimentary Structures

Stratification ranges from thin laminae to thin beds. Continuous, discontinuous, and wavy parallel laminae commonly are preserved, but stratification typically is disrupted by burrowing (fig. 5a, b) or, more rarely, contorted by soft-sediment deformation (fig. 5b, c).

Interbedded and interlaminated dark-gray to black shale, fine-grained dolomite grainstone, fine-grained lime grainstone, and lime mudstone locally are common (app. B; C9, C11). The interbedded shales and mudstones typically exhibit continuous, discontinuous, or wavy parallel laminae, and the grainstones, discontinuous and disturbed layers.

Most siltstones and grainstones have sharp lower contacts (fig. 5d through f), and many form graded couplets with shale (fig. 5e, f). Others have gradational upper and lower contacts (fig. 5g). Cores containing well-developed siltstone lithofacies commonly consist of vertically stacked couplets in which siltstone beds as thick as 10 to 15 cm grade upward into shale layers as thick as 5 cm (fig. 5a, b, e). Primary sedimentary structures include normal grading (fig. 5a, b, e, f), fading ripple forms (fig. 5e), climbing ripple cross-stratification (fig. 5d), horizontal stratification, soft-sediment deformation (fig. 5b), and flow-sheared laminae (fig. 5c). The vertical succession of structures typically comprises a partial or complete Bouma sequence (fig. 5e). Siltstone sequences such as these constitute a basal facies of the Woodford in the Northwestern Shelf and northern Midland Basin (app. B; C5, C9, C11).

Texture

Median grain sizes of siltstone are between 0.01 and 0.05 mm. Typically, little or no sand-sized material is present, although sand grains as. large as the medium-sized grade were encountered locally. Clay-sized material ranges from 0 to almost 50 percent by volume. Siltstone is moderately to poorly sorted and rarely well sorted.

Composition

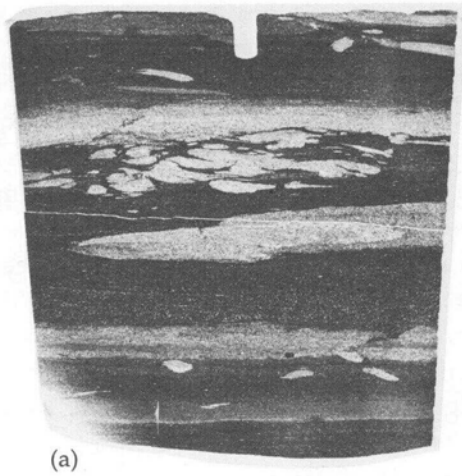
Quartz and dolomite are the most abundant framework grains in siltstone, and they typically have the same grain-size distribution (fig. 5h). They are commonly present in subequal proportions and are mixed with a variety of other components so that neither constitutes more than 50 percent of the rock. Dolomite is mostly subhedral or anhedral, and such grains commonly have an abraded appearance (fig. 5h). Euhedral grains were found locally, but many have anhedral or subhedral cores rimmed by euhedral overgrowths. In most siltstones, dolomite forms an interlocking mosaic with quartz, yet dolomite is rarely poikilotopic, even in dolomite grainstones. Locally, poikilotopic patches of dolomite cement a few angular silt-sized grains.

Other silt-sized constituents are pyrite, mica, feldspar, glauconite, phosphatic debris, and rare zircon and tourmaline. Pyrite is common and appears as nodules, euhedral crystals, irregular grains, aggregates, and framboids. In some beds, pyrite has subhedral and anhedral shapes similar to those of quartz and dolomite (fig. 5f, h) and may be reworked.

Mica (muscovite) was observed in all quartz-dominated siltstones and most dolomite-dominated siltstones; however, it is rare in carbonate mudstones and grainstones. Feldspar (microcline) is a minor component mostly in quartz-dominated siltstone. Both mica and feldspar are more abundant in the Northwestern Shelf and northern Midland Basin (app. B and C; C5, C11) where they occur along with minor amounts of the ultrastable silicates zircon and tourmaline.

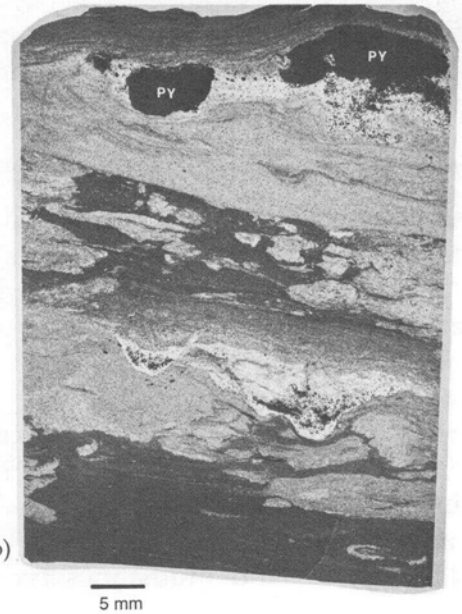
One or two grains of glauconite were seen in many samples, but glauconite is concentrated only locally at the top of the formation (app. B; C10, C13). Many core samples contained minor amounts of phosphatic debris, mostly conodonts and fish debris.

Illite and organic matter compose the fine fraction of siltstones, and in some samples the clay constitutes almost 50 percent of the rock. Illite is abundant in wispy laminae, in the upper part of graded layers, and in gradational shaly



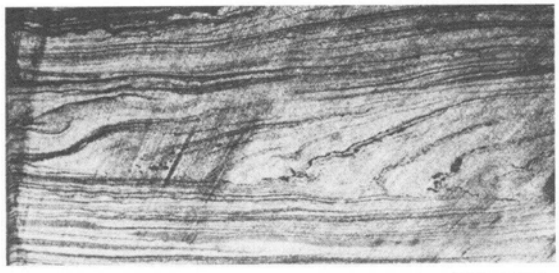
(a)

5 mm



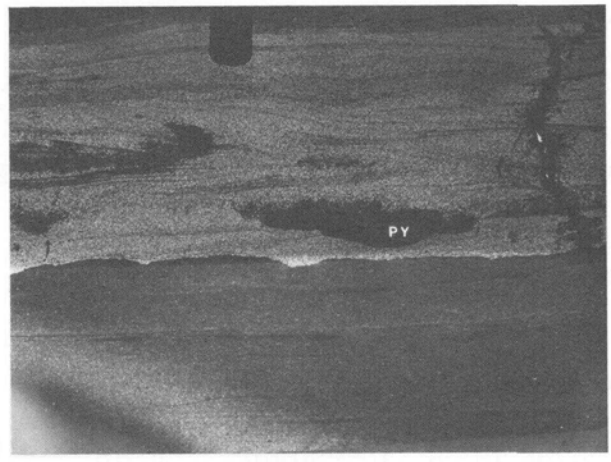
(b)

5 mm



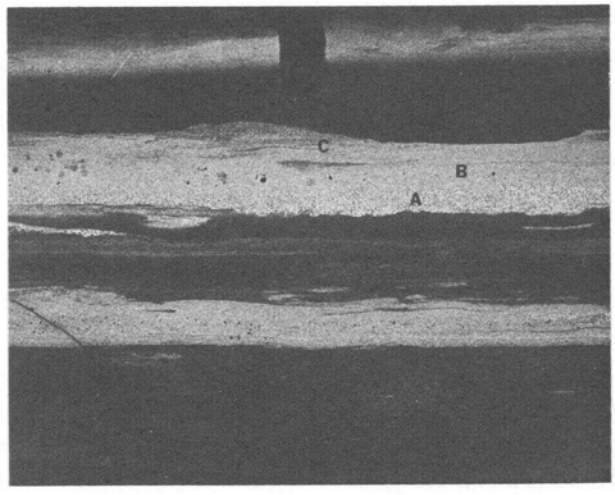
(c)

1 cm



(d)

3 mm



(e)

3 mm

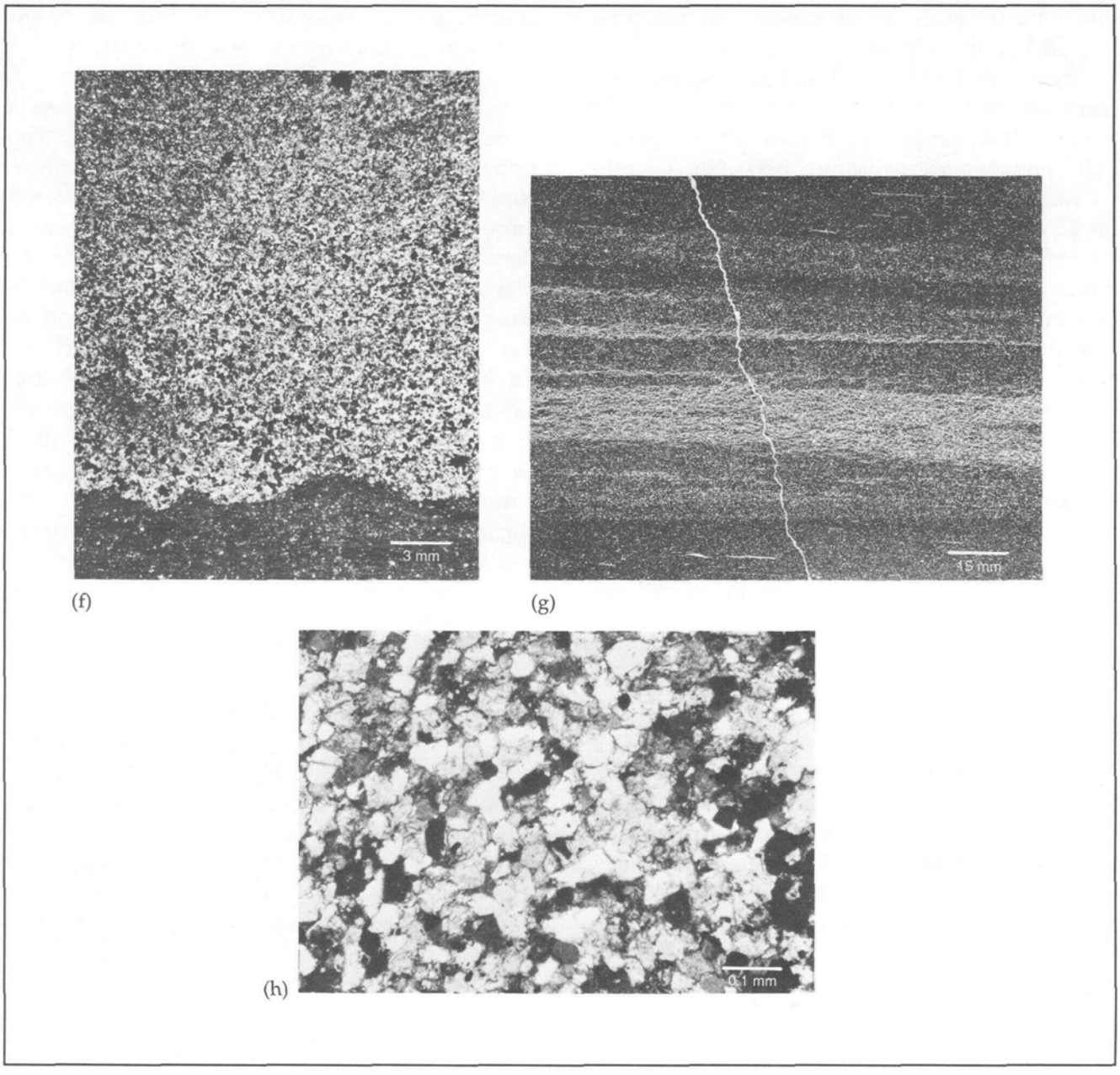


FIGURE 5. Photos of Woodford siltstone. (a) Burrowed quartz-dominated siltstones and interlaminated shale in No. 1 Walker at 11,681 ft (app. B; C5, sample C5-12). Mean TOC of interlaminated interval = 0.2 wt %. (b) Quartz-dominated siltstone in No. 1 Williamson at 13,064 ft (app. B; C11, sample C11-10). Note soft-sediment deformation fabric just below pyrite, PY, nodules. Mean TOC of interlaminated interval = 0.7 wt %. (c) Core chip showing fine-grained dolomite grainstone in No. 1 Federal Elliott at 14,638 ft (app. B; C13, sample C13-6). Contorted laminae record flow shear during rapid deposition in a bottom flow. Dolomite/quartz ratio = 40/1. (d) Very thin dolomite-dominated siltstone bed in No. 1 A. E. State at 13,771 ft (app. B; C3, sample C3-6). Bed contains small-scale climbing ripple cross-laminae and grades into silty shale at top. Dark patches, PY, are pyrite. TOC in underlying shale bed = 2.3 wt %. (e) Dolomite-dominated siltstone laminae in No. 1 A. E. State at 13,768 ft (app. B; C3, sample C3-5). Middle lamina shows Bouma sequence that has graded, A; flat, B; and rippled, C, intervals. Ripple crests are spaced roughly 1.5 cm apart. Mean TOC in shale laminae = 1.6 wt %. (f) Enlarged view of graded interval, A, in photo (e). Silt is a subequal mixture of dolomite, quartz, and pyrite. (g) Dolomite-dominated siltstone laminae in No. 43 Yarborough and Alien at 7,172 ft (app. B; C2, sample C2-3) having indistinct contacts and lacking internal structure. (h) Magnified view of quartz-dominated siltstone shown in photo (b). White and dark-gray grains are quartz, pale-gray grains are dolomite, black grains are pyrite. Note angular and abraded appearance of some dolomite grains. Dolomite/quartz ratio = 0.95/1.0. Crossed nicols.

intervals between black shale and siltstone (fig. 5a, b, d through g).

Organic matter is not abundant, and siltstone cores and outcrops average less than 1 weight percent TOC (app. D). In individual samples TOC concentrations range between 0.1 and 1.1 weight percent (mean = 0.5 ± 0.3 wt % TOC for 20 samples), which roughly corresponds to 0.3 to 3 percent organic matter by volume. The types of organic matter include amorphous particulate material, spores, and wood, but amorphous organic matter greatly predominates in all samples. Spores are rare, and only a few wood fragments were found on bedding planes. Siltstones contain only small amounts of primary vitrinite and no recycled vitrinite (app. D), suggesting that terrigenous source areas had minimal plant cover and few carbonaceous rock exposures. Reflectance values range from 0.8 percent to 1.3 percent and are directly related to present-day burial depth (app. D).

Formation-Boundary Lithologies

Lower Contact

In the Permian Basin, contact between Silurian-Devonian carbonate rocks and the overlying Woodford Formation was preserved in two cores, the No. 1 A. E. State and the No. 1 Walker (app. B; C3, C5). In the No. 1 Walker core, the Woodford disconformably overlies Silurian-Devonian limestone that consists of mottled fine-grained grainstones and brachiopod grainstones (fig. 6a, b) that contain scattered chert lenses and nodules. The upper surface of the limestone is irregular, and locally it is bored. The basal Woodford layer is conglomeratic chert arenite that contains glauconite and phosphatic debris (fig. 6a, b) and is texturally and compositionally similar to the basal chert breccia in the Arbuckle Mountains described by Amsden (1975, 1980). Phosphatic debris includes conodonts, assorted fragments (bone, teeth, fish scales, *Lingula),* aggregates (fecal material), and ooids that exhibit both radial-fibrous and concentric fabric. Basal Woodford chert arenite is unsorted and has no current-induced primary sedimentary structures; thus it appears to be a residual lag produced by dissolution of the underlying cherty limestone. The fossils, glauconite, and phosphatic ooids indicate open-marine conditions and slow sedimentation.

In the No. 1 A. E. State core (from Lea County, New Mexico) brecciated, cavernous limestone is overlain disconformably by black shale. The uppermost 1 ft of limestone contains black shale clasts, and the basal Woodford contains scattered angular fragments of black shale and limestone (app. B; C3). The transition from limestone to black shale is abrupt; however, the contact is irregular and penetrative, and infiltration of mud tens of feet downward into the underlying limestone has occurred. Some of the solution cavities and fissures in the limestone are partly or completely filled by black shale that either has no structure or contains deformed, contorted laminae indicative of soft-sediment deformation (fig. 6c). The shale-filled cavities and fissures at Lea County, New Mexico, are similar to those in Andrews and Terry Counties, Texas, described by Peirce (1962).

Upper Contact

Contact between the Woodford and the overlying Mississippian limestone was preserved in two cores, the No. 1 Brennand and Price and the No. 1 Federal Elliott (app. B; C10, C13). In the No. 1 Brennand and Price, the uppermost Woodford contains articulate brachiopods, trilobite fragments, black shale clasts, dolomite grains, glauconite, and phosphatic debris (fig. 6d). The overlying Mississippian limestones are mostly laminated fine-grained grainstones along with some lime mudstones, sparsely fossiliferous grainstones, wackestones, and packstones. Locally these carbonate lithologies compose thin, graded beds. Chert beds, lenses, and nodules, locally spiculitic, are scattered throughout the Mississippian limestone section. Contact between the black shale and the overlying carbonate rocks is sharp and disconformable (fig. 6d), marking an abrupt change in lithology and fauna.

In the No. 1 Federal Elliott, Mississippian limestone rests conformably on the Woodford. Woodford black shale grades upward through 10 ft of interbedded dark-gray lime mudstone, black siltstone, and black glauconitic sandstone into medium to dark-gray fine-grained Mississippian grainstones and lime mudstones (app. B;

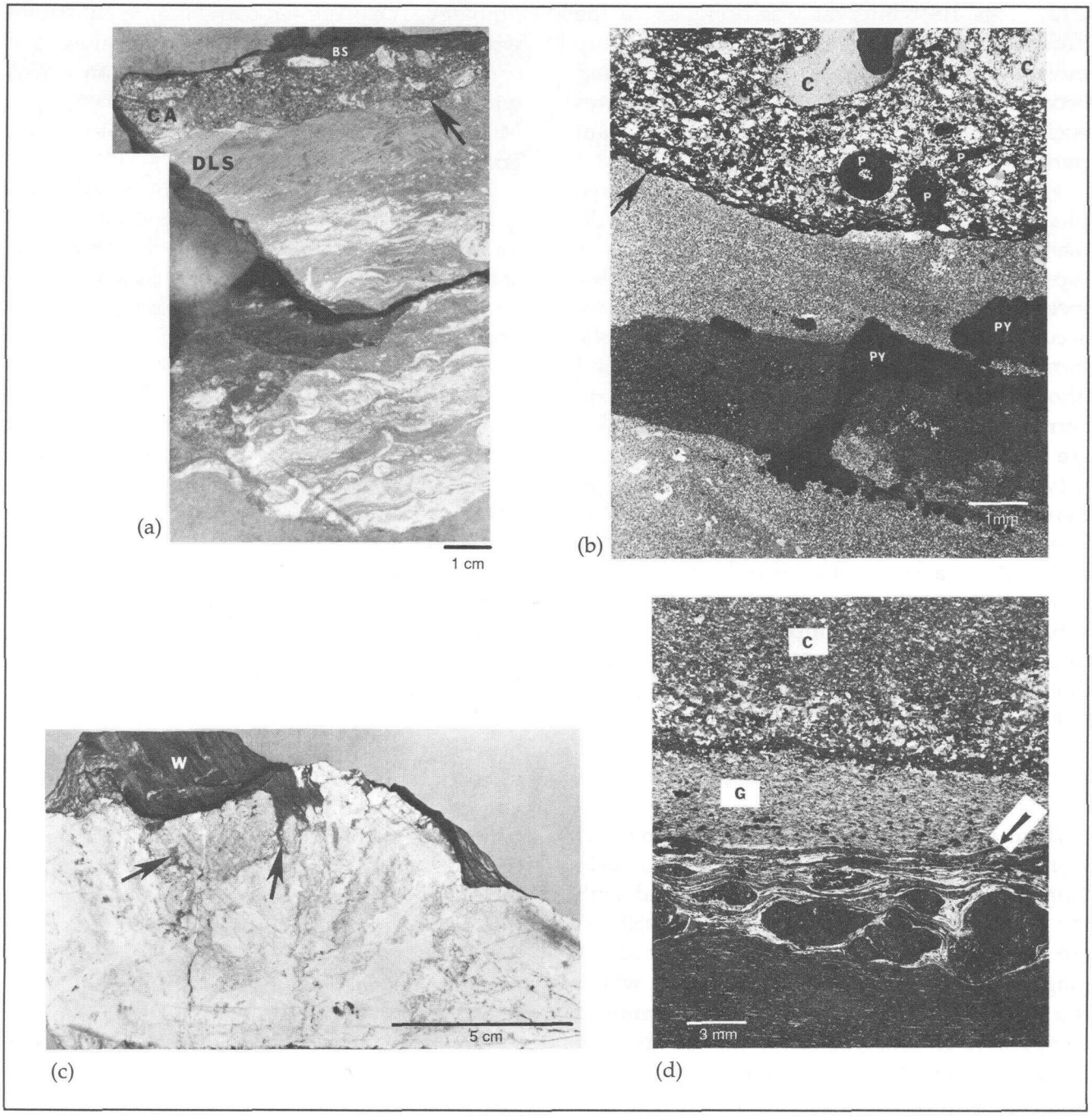


FIGURE 6. Photos of Woodford contacts, (a) Core slab showing lower contact, arrow, in No. 1 Walker at 11,689 ft (app. B; C5, sample C5-14). Silurian-Devonian limestone, DLS, overlain by basal Woodford chert arenite, CA, and black shale, BS, at top of core, (b) Thin-section photomicrograph of area at arrow in (a). Chert, C; pyrite, PY; phosphate, P. Three phosphatic grains from left to right are ooid containing a chert nucleus, aggregate of probable fecal origin, and skeletal fragment. Finer grains are chert (light) and phosphate (black). Below contact is fine-grained grainstone. Crossed nicols. (c) Core chip from 13,850 ft in No. 1 A. E. State (app. B; C3). Woodford black shale, W, in solution cavities in Silurian-Devonian limestone. Contorted laminae in shale and shale penetrating limestone crevices at arrows indicate soft-sediment infiltration of mud into the underlying limestone, (d) Thin-section photomicrograph of Woodford-Mississippian contact, arrow, at 8,459 ft in No. 1 Brennand and Price (app. B; C10, sample C10-1). Upper Woodford consists of brachiopod shells and trilobite carapaces (white ribbonlike material), black shale clasts, and silt-sized grains (white specks) that are mostly dolomite. Fine white streaks in black shale at base are brachiopod and trilobite fragments. Mississippian above contact is fine-grained grainstone, G, and chert bed containing scattered, unreplaced remnants of carbonate, C. Crossed nicols.

C13). This 10-ft interval was assigned to the Woodford Formation because it is markedly more radioactive than the overlying rocks and because it contains diagnostic Woodford features such as varvelike parallel laminae and abundant pyrite.

High concentrations of glauconite and phosphate in sedimentary rocks indicate low sedimentation rates (Odin and Letolle, 1980). The top stratum of the Woodford at these two localities is consequently inferred to have accumulated more slowly than the rest of the formation. Commonly, glauconitic grains and phosphatic ooids and pellets are unbroken, current-induced primary sedimentary structures are absent, and brachiopods possess articulated valves, indicating little or no active sediment transport at the close of Woodford deposition. The abundance of reduced iron, sulfur, and carbon and the absence of oxidized phases document absence of oxidation and imply absence of subaerial exposure. The upper boundary at these two localities thus suggests a submarine hiatus during which sedimentation slowed or ceased but the sea floor did not emerge.

Lithofacies Correlation

Basal siltstone in Woodford cores from the Northwestern Shelf and northern Midland Basin (app. B; C5, C9, C11) is herein correlated with the lower Woodford unit of Ellison (1950) on the basis of lithology, radioactivity, and stratigraphic position (fig. 7). Basal siltstone, which is a hybrid of silt-sized quartz and dolomite, is comparable to Ellison's lower unit in its high carbonate content and low radioactivity. Unfortunately, Ellison's cores were discarded, and direct comparison of lithologies was impossible. In the subsurface, both the lower unit and the basal siltstone immediately overlie the regional unconformity.

Stratigraphic position and lithology also suggest correlation of basal Woodford siltstone with the upper Middle to lower Upper Devonian Onate Formation in southeastern New Mexico. Both units rest on the regional unconformity surface and comprise a stratigraphic succession of interbedded siltstone, carbonate, and shale in which dolomitic siltstone is the dominant lithology. The proposed correlation is consistent with that by Wright (1979), who suggested a correlation of the lower unit of Ellison (1950) with the Ives Breccia Member of the upper Middle Devonian to Lower Mississippian Houy Formation in Central Texas.

Basal siltstone also occupies the same stratigraphic position above the regional unconformity as the Canutillo Formation in West Texas and the Misener and Sylamore Sandstones in Oklahoma and Arkansas. These formally named units are mostly late Middle to early Late Devonian in age and are locally as young as Early Mississippian. Although the units are diachronous across the southern Midcontinent (Amsden and others, 1967; Freeman and Schumacher, 1969; Rosado, 1970; Amsden and Klapper, 1972; Amsden, 1975), they are at least partly correlative.

The black shale lithofacies is correlated with the middle and upper Woodford units of Ellison (1950) also on the basis of lithology, radioactivity, and stratigraphic position (fig. 7). Ellison's middle and upper units are not described as separate lithofacies in this report because striking, lithologic differences between them are absent in cores (app. B; C1, C6). Although both units are pyritic black shale exhibiting parallel laminae, the middle unit is more radioactive (Ellison, 1950); hence, the middle and upper units can be mapped using gamma-ray logs (fig. 7; pls. 3 through 7). Wright (1979) correlated the middle unit with the Doublehorn Shale Member and the upper unit with the unnamed phosphatic member of the Houy Formation in Central Texas, thereby implying that the upper unit is partly Kinderhookian. Wright's correlation seems reasonable because the middle unit in both formations has higher radioactivity and more spores than does the upper unit (Ellison, 1950; Cloud and others, 1957).

Well log correlations (pls. 3 through 7) show that complete Woodford intervals containing all three units of Ellison (1950) are common only in the Midland, Delaware, and Val Verde Basins (pl. 3, A–A´, wells 4, 9; pl. 4, B–B´, well 5; pl. 5, C–C´, wells 2 through 6, 9, 10; pl. 6, D–D´, wells 9 through 12; pls. 7, E–E´, wells 10, 11, 16, 17). Elsewhere Woodford sections are incomplete mostly because of the absence of the lower or

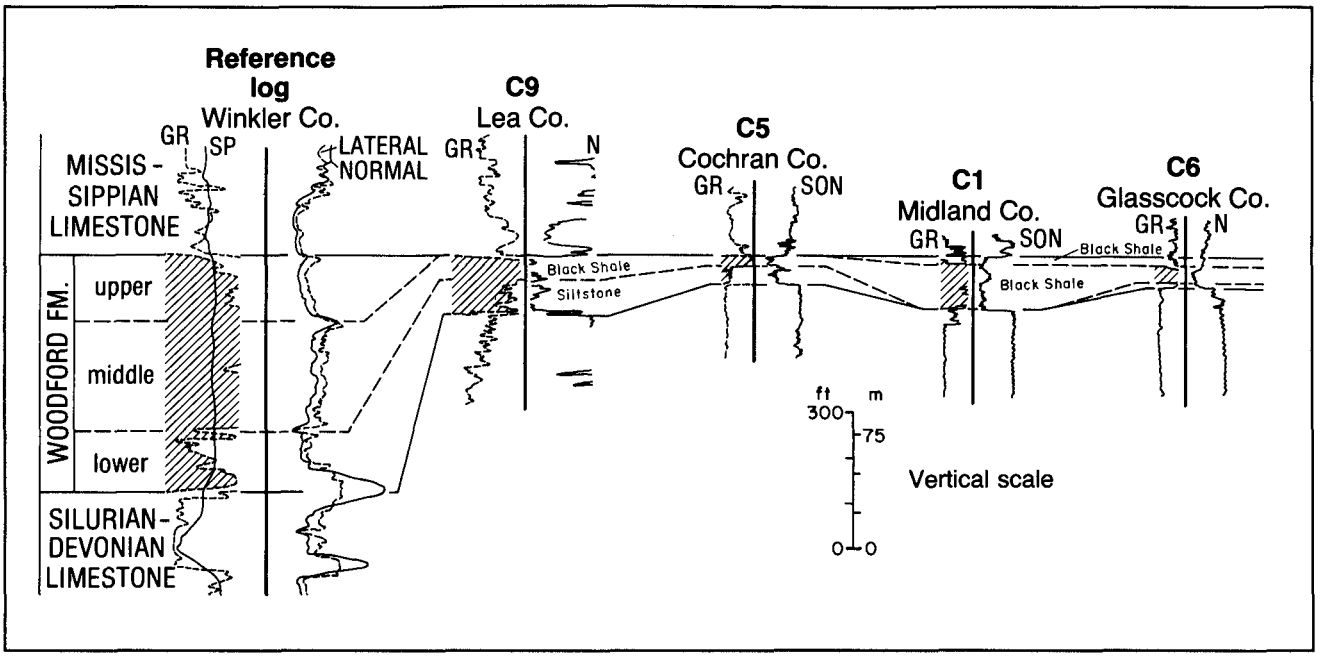


FIGURE 7. Log correlation of Woodford lithofacies. Reference log from Ellison (1950). Datum is top of Woodford. For detailed core descriptions see appendix B (Cl, C5, C6, C9).

upper units. The lower unit gradually pinches out and is overstepped by the middle unit along the basin flanks (pls. 3 through 7), indicating depositional onlap. Lines of section showing onlap include (1) from the Midland Basin toward the Eastern Shelf (pl. 3, A–A´, wells 9 through 13; pl. 4, B–B´, wells 11 through 15; pl. 5, C–C´, wells 9 through 12), (2) from the Midland Basin onto the Pecos Arch (pl. 7, E–E´, wells 11 through 14), (3) westward from the Delaware Basin toward the Diablo Platform (pl. 4, B–B´, wells 1 through 3; pl. 5, C–C´, wells 1, 2), and (4) in the western Midland Basin (pl. 4, B–B´, well 10). Many sections in which the upper unit is absent are overlain by Mississippian limestone, indicating nondeposition or erosional truncation that occurred after Woodford deposition but before Mississippian limestone deposition. Sections showing truncation include (1) along the eastern margin of the Central Basin Platform (pl. 3, A–A´, well 8; pl. 4, B–B´, well 9), (2) in the northern and central Midland Basin (pl. 7, E–E´, wells 7, 8, 11), and (3) on the Northwestern Shelf (app. B; C5, C9). Most of the lines of section that show onlap also show evidence of increased truncation of the Woodford in the direction of onlap, suggesting that these were the last flooded and first exposed areas during the Late Devonian transgression and latest Devonian regression. The patterns of onlap and truncation (pls. 3 through 7) indicate that all of the structural provinces shown in figure la had topographic expression in the Late Devonian. Onlap in the western Midland Basin supports the observation of Galley (1958) that a middle Paleozoic precursor of the Central Basin Platform lay slightly to the east of the present-day structure.

Lithofacies Distribution

Correlations shown in the cross sections (pls. 3 through 7) and the Woodford lithofacies distribution shown in a fence diagram (fig. 8) reveal that black shale is nearly ubiquitous and the most widely distributed lithofacies. Siltstone is more common in the northern part of the study area and in basinal depocenters. Silt-sized quartz is more abundant in northern and eastern areas, and silt-sized dolomite is more abundant in the far western outcrop belt and along the Central Basin Platform. Log correlations indicate that basal siltstone is areally restricted to deep parts of the Delaware, Midland, and Val Verde Basins, proximal areas on the Northwestern Shelf, and a few localities on the Central Basin Platform (pl. 3, A–A´, wells 3 through 10; pl. 4, B–B´, wells

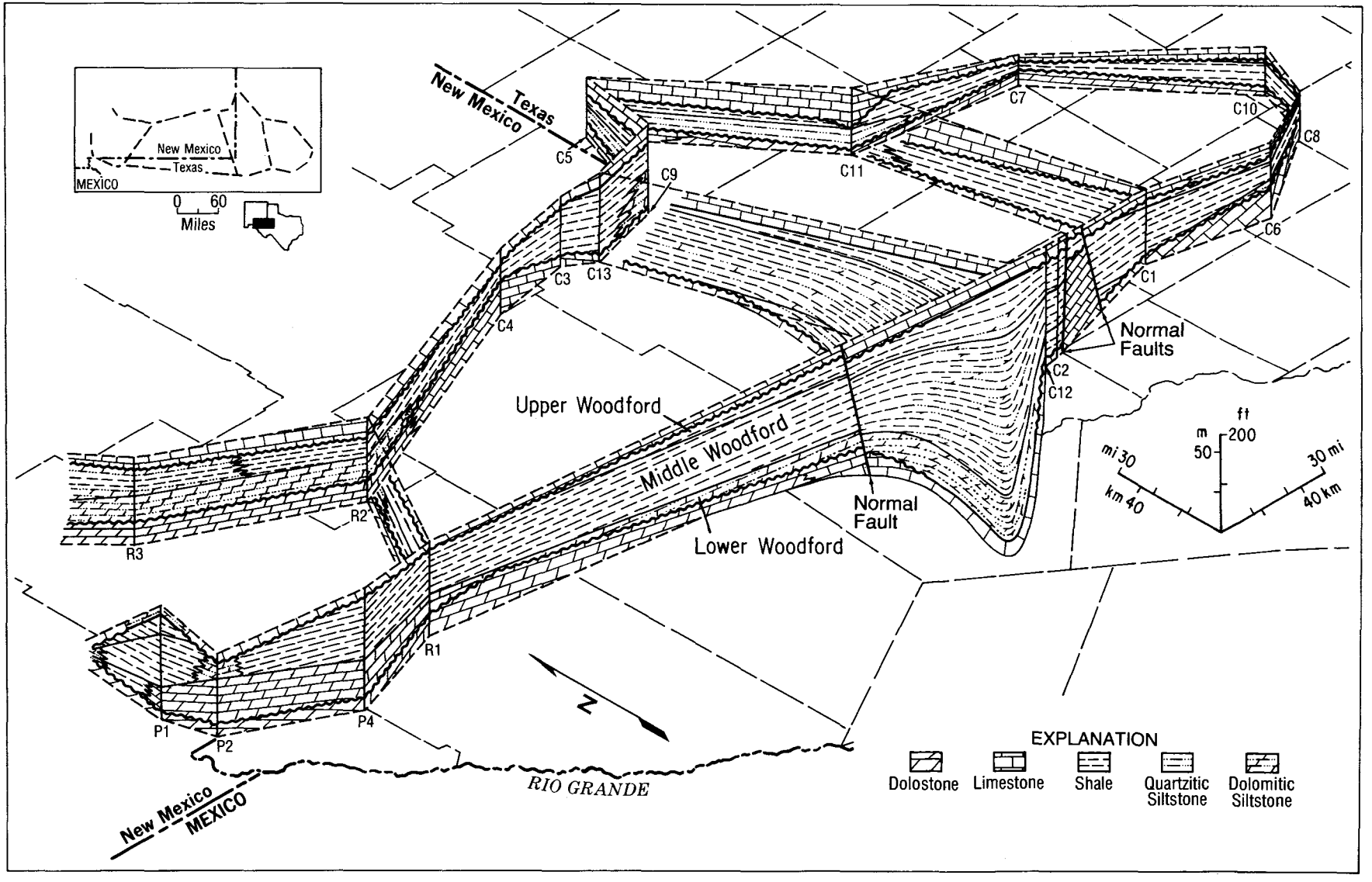


FIGURE 8. Fence diagram of Upper Devonian units. Correlation from outcrop to subsurface from Rosado (1970). Datum is top of Woodford. Locality numbers refer to map symbols in appendix A.

2 through 5, 7, 9, 11, 12; pl. 5, C–C′, wells 2 through 6, 9, 10; pl. 6, D–D′, wells 6 through 12; pl. 7, E–E′, wells 7, 8, 10, 11, 16, 17).

Facies changes between black shale and siltstone appear in many parts of the study area (fig. 8; pls. 3 through 7). Siltstone beds common throughout the Sly Gap Formation in southeastern New Mexico correlate with black shale in the Percha and Woodford Formations to the south and east (Laudon and Bowsher, 1949; Ellison, 1950; Rosado, 1970). Dolomitic siltstones of the Onate Formation in New Mexico also correlate with dolostone and cherty dolostone beds of the Canutillo Formation in West Texas and with black shales in the Percha and Woodford Formations (King and others, 1945; Rosado, 1970). On the Northwestern Shelf, siltstone is the basal unit of the Woodford at some localities (app. B; C5, C9), but it is higher in the section at others (app. B; C3, C13). In the Delaware and Val Verde Basins, siltstone beds appear to be common throughout the formation, as indicated by the generally reduced radioactivity and the highly erratic nature of the gamma-ray log patterns shown in plates 5 through 7 (pl. 5, C–C′, logs 4, 6; pl. 6, D–D′, logs 9 through 13; pl. 7, E–E′, logs 16, 17).

Depositional Processes

Siltstone

Many of the siltstone strata and siltstone-shale couplets in the Woodford Formation (fig. 5a through f) closely resemble the silt and mud turbidites described by Piper (1978) and Stow and Piper (1984) and the distal storm deposits described by Aigner (1982, 1984). In the Woodford, these strata range from laminae less than 2 mm thick to beds rarely more than 10 to 15 cm thick. They commonly contain graded layers (fig. 5a, d through f), climbing ripple cross-stratification (fig. 5d), horizontal stratification, fading (incipient) ripple forms (fig. 5e), flow-sheared laminae (fig. 5c), and laminae contorted by soft-sediment failure (fig. 5b). Many of these strata are partial or complete Bouma sequences that have scoured bases, normally graded sequences, and a vertical succession of primary sedimentary structures that indicate rapid deposition from a waning current during a single event.

Both fine-grained turbidites and distal storm deposits described in the literature have similar thicknesses and sedimentary structures (Piper, 1978; Aigner, 1982, 1984; Stanley, 1983; Stow and Piper, 1984; Schieber, 1987; Davis and others, 1989). Mud turbidites in the deep ocean consist of the division E mud of Bouma (1962), which Piper (1978) subdivided into laminated, graded, and ungraded units. The vertical pattern and the contained sedimentary structures, such as grading and low-amplitude climbing ripples, are diagnostic of turbidite origin (Stow and Piper, 1984). Silt turbidites are silt-dominated sequences that exhibit the same suite of sedimentary structures and the same divisions (Bouma A through F) as classical sandy turbidites (Stow and Piper, 1984). The siltstone and shale layers in the Woodford Formation (fig. 5a through f) differ from silt and mud turbidites described in the literature (for example, Piper, 1978; Stanley, 1983; Stow and Piper, 1984) only in the scarcity of bioturbation in the shale that is common at the top of the turbidite sequence (Bouma division E mud and division F pelagite). This difference indicates that anoxic bottom conditions toxic to benthic organisms prevailed throughout the basin during deposition of the shale laminae.

Sedimentary processes related to storms, such as wind-forced currents (Morton, 1981), ebb currents produced by storm surge setup (Nelson, 1982), and seaward-flowing currents caused by coastal downwelling (Swift and others, 1983), deposit sediment that has textures and structures virtually identical to those of turbidites. Distal storm deposits characteristically are fine grained, thinly stratified, and normally graded, having scoured bases and Bouma sequences (Aigner, 1982). They differ from proximal equivalents in grain size and layer thickness and in their having no hummocky stratification or oscillatory ripples, both of which, when present, indicate deposition under combined flow conditions above wave base (Aigner, 1982). Whether storms produce turbidity currents is debatable, but it is clear that storms generate bottom currents that transport large quantities of sediment (Hayes, 1967; Morton, 1981, 1988; Nelson, 1982; Walker, 1984, 1985). Storm-generated bottom flows and turbidity currents may represent end members of a single process if, as suggested by

Walker (1984, 1985), distal storm currents passing below wave base become turbidity currents. Such a subtle change in the transport mechanism may explain the present difficulty in distinguishing fine-grained turbidites from storm deposits in the stratigraphic record. Whether the siltstones and siltstone-shale couplets in the Woodford Formation are turbidites or storm deposits is likewise problematic, but the presence of grading and partial or complete Bouma sequences indicates deposition from bottom flows.

Black Shale

Most layers in the black shale lithofacies (fig. 4a through h) do not have grading or Bouma divisions as do beds in the siltstone. Black shale that displays undisturbed parallel laminae typically contains higher concentrations of marine organic matter, less clastic material, and more planktonic microfossils (for example, radiolarians, spores, conodonts) than do the Bouma E and F shales of the siltstone-shale couplets (fig. 5a through f). Shale displaying parallel laminae constitutes the bulk of the Woodford black shale lithofacies and is mostly pelagic in origin.

Origin of the thin varvelike siltstone and shale laminae in pelagic black shale (fig. 4a, b, e) is less certain. These laminae may represent mud turbidites or storm layers too small or far from the source to produce grading and recognizable Bouma divisions, or they may represent episodic fallout from the pycnocline. Pierce (1976), Maldonado and Stanley (1978), and Stanley (1983) described detachment of low-concentration turbidity plumes and entrainment of the muddy water along the isopycnals in strongly density stratified water columns. Episodic fallout of material (for example, terrigenous silt and planktonic tests) occurs as particle concentration builds up and exceeds the density of the pycnocline, producing a relatively clean, well-sorted, structureless lamina of widespread areal extent. Similar laminae are common in muddy marine sediments, such as those found in the eastern Mediterranean Sea near the Nile delta (Maldonado and Stanley, 1978; Stanley, 1983). Sediment deposition by this process seems likely during Woodford accumulation because of the exclusively fine grained texture of the rocks and because of the strong density stratification that existed within the basin. Water-density stratification is an inherent property of the sea and, judging from the scarcity of bioturbation and its implicit link with bottom stagnation and anoxia (Byers, 1977; Arthur and Natland, 1979; Demaison and Moore, 1980; Leggett, 1980; Ettenshon and Barron, 1981; Stanley, 1983; Pratt, 1984; Ettensohn and Elam, 1985; Stein, 1986; Davis and others, 1989) strong density stratification probably occurred during Woodford black shale deposition. (See also Paleoceanography, p. 33.) In this context, the relative abundances of benthic fossils, trace fossils, and undisturbed parallel laminae in the Woodford (figs. 4a through h, 5a through h) indicate that the black shale and siltstone lithofacies represent anaerobic and dysaerobic biofacies, respectively (Rhoads and Morse, 1971; Byers, 1977).

Lithologic Patterns and Origin of Sediments

The Woodford Formation consists of varying proportions of terrigenous, pelagic, and authigenic constituents (app. C), and textural and compositional evidence indicates much resedimentation within the basin. Terrigenous material includes fine-grained quartz, muscovite, microcline feldspar, illite, wood and leaf fragments, vitrinite, and the trace heavy minerals (zircon and tourmaline). The silt-sized silicate minerals are most common in the northern basin. Locally, in rocks from the Northwestern Shelf, coarse-grained mica flakes glitter on fresh bedding surfaces (app. B; C4, C5), and the silt-sized fraction is subarkosic (app. C). The distribution and texture of these minerals indicate that the principal source was the land north of the basin, the Pedernal Massif and northern Concho Arch (fig. 1b).

Siltstone depocenters lie in the northern, central, southern, and westernmost parts of the basin (fig. 9a) in areas coincident with the modern-day Northwestern Shelf, the deepest parts of the Delaware, Val Verde, and Midland Basins, and the Sacramento Mountains. The patchy distribution of these depocenters suggests that sediment

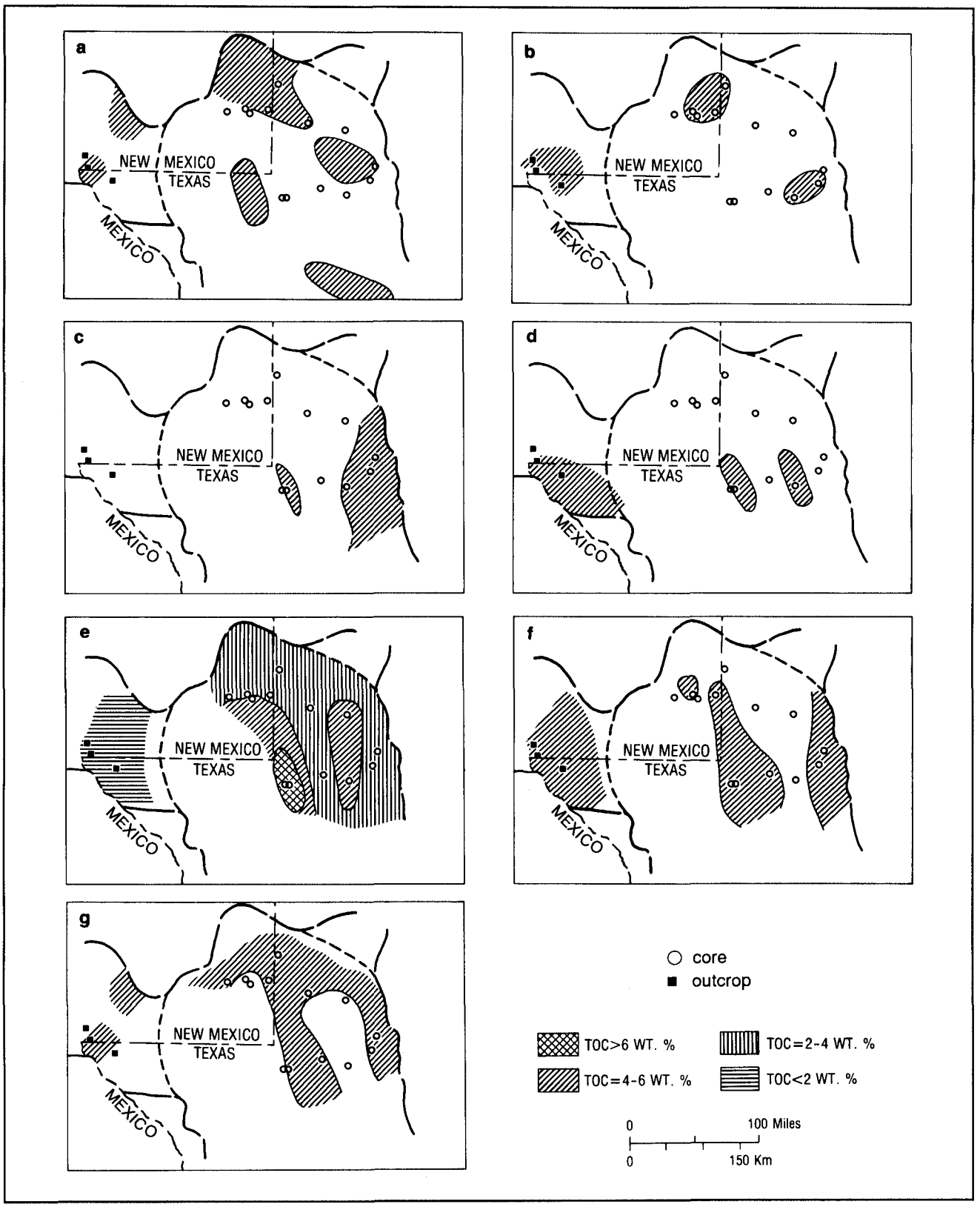


FIGURE 9. Regional lithologic variations in Upper Devonian rocks in West Texas and southeastern New Mexico. Maps show Late Devonian shoreline and limit of Tobosa Basin depocenter (fig. Ib). (a) Siltstone depocenters, (b) Illite depocenters, (c) Recycled vitrinite depocenters, (d) Radiolarian chert depocenters, (e) TOC concentration in black shale, (f) Depocenters of silt-sized dolomite where dolomite/quartz ratio is greater than 1. (g) Depocenters of dysaerobic, shallow-water sedimentary structures.

bypassing was common as silt and mud moved from siliciclastic source areas downslope into the basin. This inference is consistent with the interpretation that most silt was deposited from bottom flows, a mechanism sensitive to bottom irregularities and channelization.

The most abundant terrigenous component in the Woodford is illite (app. C). Detrital illite has an apparent Rb-Sr source age of 540 m.y., an age uncommon in North American basement rocks but common in regionally metamorphosed rocks found in large areas of Africa and South America (Morton, 1985). The source age and the good fit to the isochron for data from widely different localities in West and Central Texas are cited as evidence that illite came from a southern (Gondwana) source or was thoroughly mixed during transport from multiple sources (Morton, 1985). In the present study, the highest concentrations of illite (>60%) were found in northern, southeastern, and westernmost regions (fig. 9b) in the present-day Northwestern and Eastern Shelves, Midland Basin, and western outcrop belt. The wide distribution of illite depocenters and their proximity to northern siltstone depocenters and siliciclastic source areas suggest that illite came from multiple sources on the Pedernal Massif and Concho Arch (fig. 9b). The broad extent of the exposed land implies that it derived from diverse stratigraphic levels. Although contribution from a Gondwana source cannot be ruled out because of the absence of control in the southern part of the basin, a mixed provenance for illite seems most likely.

Trace amounts of vitrinite are ubiquitous, documenting a small contribution of land plant debris to all parts of the basin. Recycled vitrinite was found only in the eastern and central parts of the basin (fig. 9c) in black shale from the Central Basin Platform, southern Midland Basin, and Eastern Shelf (app. D), indicating that these areas were close to emergent land that displayed eroding bedrock. A few wood and leaf impressions were found mostly in northern and eastern parts of the basin in rocks from the Northwestern and Eastern Shelves (app. B; C4, C7, C13). Their distribution implies that land areas on the Pedernal Massif and Concho Arch supported most of the terrestrial plant life in the study area during the Late Devonian. Abundances of vitrinite and land plant remains are low, however, even in the siltstones, indicating that terrestrial source areas were only sparsely vegetated.

Pelagic constituents include radiolarians, amorphous particulate organic matter, algal spores, conodonts, fish fragments, and associated fecal material. Radiolarian chert is most common in the central and eastern parts of the basin (fig. 9d) at localities on the present-day Central Basin Platform and in the southeastern Midland Basin (app. B; C2, C6). Chert is also abundant in the Canutillo Formation in West Texas (King and others, 1945; Rosado, 1970). Anomalously high biogenic silica is perhaps the best indication of nutrient-rich water upwelling in ancient seas (Parrish and Barron, 1986; Hein and Parrish, 1987) and suggests that upwelling occurred in the basin and was most pronounced in central and western areas. Intrabasinal upwelling is a likely consequence of the major oceanic upwelling that occurred adjacent to the study area along the margin of the North American craton during the Late Devonian. This upwelling episode is recorded as extensive Upper Devonian novaculite beds of biogenic origin in the Ouachita allochthon (Park and Croneis, 1969; Lowe, 1975; Parrish, 1982).

Volumetrically, amorphous organic matter (AOM), which accounts for nearly all of the TOC, is the most abundant pelagic constituent in the Woodford (app. C). The highest TOC concentrations (>6 wt %) are found in the center of the basin on the modern-day Central Basin Platform (fig. 9e). Somewhat lower TOC values (4 to 6 wt %) are found to the east and north in areas coincident with parts of the western and eastern Midland Basin, southern Northwestern Shelf, and western margin of the Eastern Shelf (fig. 9e). Localities that have the highest TOC concentrations also have the most radiolarian chert, suggesting that high TOC values record increased biologic productivity at sites of intrabasinal upwelling. The area that has the highest TOC's (fig. 9e) is surrounded by siltstone depocenters (fig. 9a), supporting the inference that it was bypassed by siliciclastic sediment.

Authigenic material includes dolomite, pyrite, secondary silica, glauconite, anhydrite, calcite, and phosphatic ooids. Some cored intervals on the Central Basin Platform and Northwestern Shelf (app. B; C2, C3) contain abundant pristine, euhedral dolomite rhombs floating in organic-rich black shale. The texture and association are similar to those observed in Deep Sea Drilling Project (DSDP) cores and in very young sediments in the Gulf of California (Baker and Kastner, 1981), suggesting that the rhombs are authigenic and formed in situ. Most of the dolomite in the Woodford, however, appears to be resedimented because it contains abraded anhedral and subhedral silt-sized grains and commonly appears randomly mixed with quartz in graded layers and Bouma sequences (fig. 5e, f, h). Derivation from ancient dolomitic rocks is not indicated. The poor durability of dolomite precludes long-distance subaerial transportation. Moreover, dolomite in the Woodford is typically monocrystalline and monotonously uniform in texture, whereas in older Paleozoic rocks, dolomite texture is quite variable. One would expect to see dolomitic rock fragments and a greater variety of textures if Woodford dolomite were terrigenous detritus.

If most of the dolomite in the Woodford is resedimented but not terrigenous in origin, then it must be penecontemporaneous. Early formation of dolomite in marine sediment is promoted by hypersaline brine (Zenger, 1972) and by low concentrations of dissolved sulfate that develop in organic-rich sediments as the result of microbial sulfate reduction (Baker and Kastner, 1981). Given the abundance of organic matter and the presence of anhydrite in the Woodford, both are plausible mechanisms for contemporaneous dolomitization in the Permian Basin during the Late Devonian.

Areas that have a high ratio of dolomite to quartz (fig. 9f) are found in the central, northern, eastern, and westernmost parts of the basin, suggesting that these were the areas of highest carbonate production. The highest dolomite/quartz ratio is in the center of the basin (app. C; C2) where very little detrital quartz is found, and the quartz typically is much finer grained than dolomite. This observation is further evidence that the basin center, which coincides with the modern-day Central Basin Platform, was bypassed by siliciclastic detritus.

Secondary silica is a common cement in primary sedimentary structures, such as burrows and syneresis cracks, where it is associated locally with calcite and anhydrite. Burrows and syneresis cracks are abundant in the northern, central, and eastern basin (fig. 9g) in areas that were onlapped by Woodford sediments (for example, the Northwestern and Eastern Shelves, Central Basin Platform, and western Midland Basin). They are less abundant or absent in cores farther east in the Midland Basin. The distribution and association with anhydrite suggest that these structures are shallow-water indicators formed under dysaerobic conditions above the anoxic zone.

Benthic components are scarce and include trilobite fragments, brachiopods, and biogenic pellets. Some of the pellets in siltstone and others associated with scattered trilobite fragments in shale may be fecal material from a sparse benthos. However, many are found in black shale that has parallel laminae and has no burrows or benthic fossils, suggesting that they originated in the upper water column amid a thriving, normal marine biota. Most benthic fossils are found in the shelf regions, but biogenic pellets are also common in rocks from the Central Basin Platform (app. C; C2, C12).

Depositional Setting

Paleogeography

Late Devonian paleogeography of the study area (fig. 10) was inferred from the patterns of onlap (pls. 3 through 7) and lithology (fig. 9) described earlier. The widespread, blanketlike distribution and nearly uniform lithology of the Woodford indicate that the entire region was one of low relief during the Late Devonian. Major topographic features in the model include (1) the land in the north and northwest representing the Pedernal Massif and Concho Arch, (2) the ancestral Delaware and Val Verde Basins, (3) the shallow Midland Basin, (4) an intrabasinal archipelago representing the ancestral Central Basin Platform and Pecos Arch, (5) shallow shelf regions to the north and east representing the ancestral Northwestern and Eastern Shelves, (6) a western shelf that had irregular channels and shoals representing parts of the Northwestern Shelf and Diablo Platform, and (7) a land mass to the southwest representing the southern part of the Diablo Platform (fig. 10).

The Pedernal Massif and northern Concho Arch represent the southern end of the Transcontinental Arch, which was the dominant topographic high in the western North American craton during the Late Devonian (Poole and others, 1967; Poole, 1974; Heckel and Witzke, 1979). Grain size and composition of Woodford siltstones indicate that this arch supplied most of the terrigenous sediment to the basin and consequently must have had the highest elevations in the study area. The absence of deltas and coarse clastic wedges, however, indicates that elevations were not high enough to create an orographic barrier to winds or to introduce major rainfall, runoff, and clastic influx into the basin.

The Northwestern and Eastern Shelves and the Diablo Platform are onlapped by Woodford

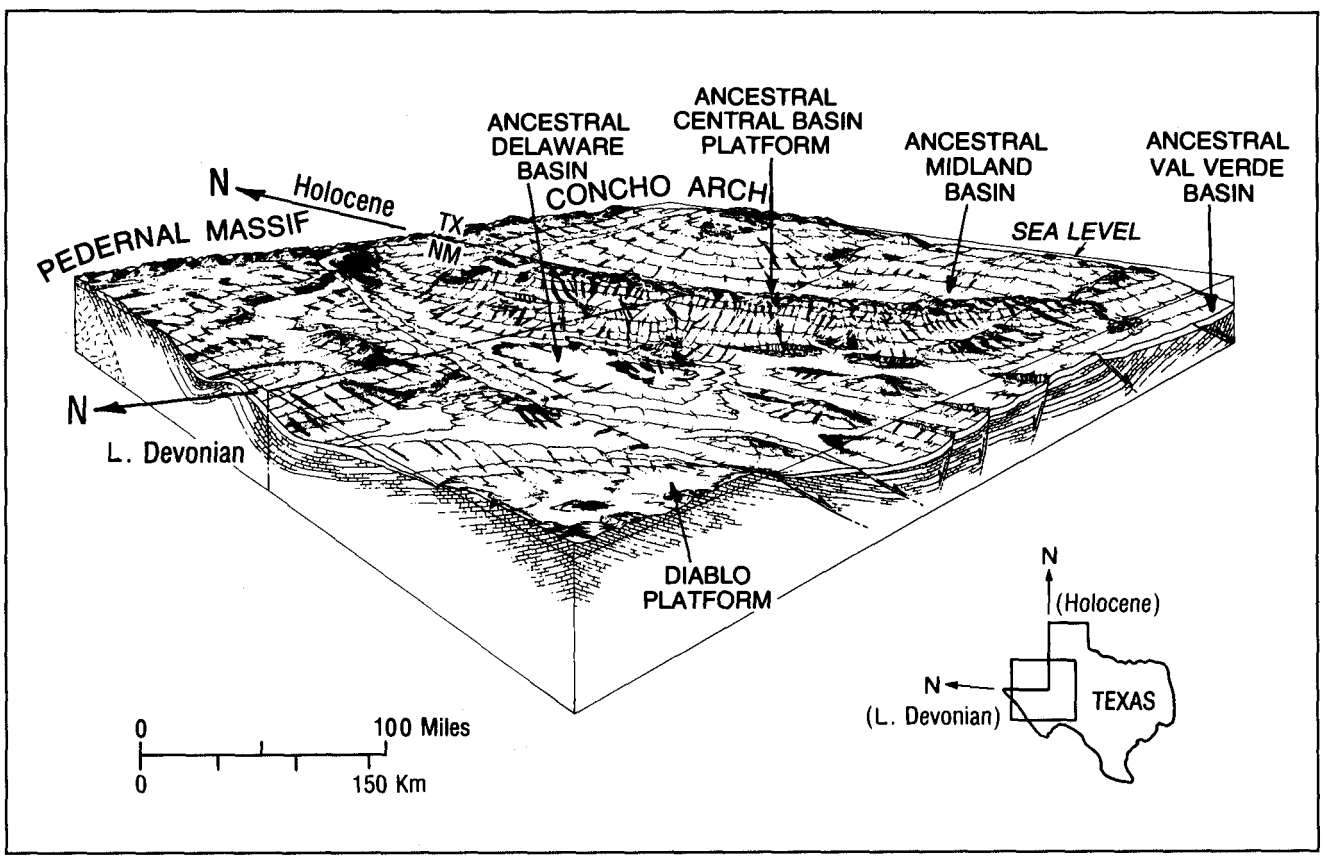


FIGURE 10. Late Devonian paleogeography of West Texas and southeastern New Mexico.

sediment (pls. 3 through *7),* indicating that they were low-relief expanses of intermediate elevation, and that during the Late Devonian transgression they became shallow-water shelf environments that had local channels, scattered islands, and protected shoals. The westernmost outcrop belt is characterized by complex facies changes (Stevenson, 1945; Laudon and Bowsher, 1949; Rosado, 1970), indicating that it comprised an extensive, low-relief cratonic shelf that had prominent shoals and channels (Rosado, 1970). The southern Diablo Platform may have remained emergent, but it was not a major source of terrigenous sediment (Wright, 1979).

The deepest parts of the Late Devonian epeiric sea coincided with the deepest parts of the present-day Delaware and Val Verde Basins (fig. 10), where the thickest and most complete Woodford sections are found (pls. 3 through 7). Gradual changes in well log signatures at formation boundaries in these depocenters suggest that the Woodford may be conformable with the bounding formations (pl. 5, C–C´, wells 4, 6; pl. 6, D–D´, wells 10, 11, 13; pl. 7, E–E´, wells 16, 17). That the Midland Basin was a topographic depression (fig. 10) is supported by the following evidence: (1) the Woodford thickens and contains all three units toward the basin axis and (2) the Woodford generally has no bottom features (such as anhydrite-bearing burrows and syneresis cracks), that would indicate elevations above the anoxic and sulfate-reducing zones.

The ancestral Central Basin Platform and Pecos Arch are shown as a continuous intrabasinal archipelago (fig. 10). Whether the two actually connected is unknown, but the onlap of both structures by the Woodford indicates that both were topographically high during the Late Devonian. Lithologic patterns (fig. 9) indicate that the Central Basin Platform was bypassed by terrigenous sediment, and stratigraphic onlap indicates that bypassing occurred because the platform was elevated above the surrounding provinces. The abundance of dysaerobic primary sedimentary structures on the platform (fig. 9g) suggests a shallow-water setting and supports this conclusion. Folk (1959) inferred the presence of an island chain along the platform during the Early Ordovician on the basis of the abundance of feldspar in the Ellenburger Formation. Similarly, the presence of recycled vitrinite in the black shale lithofacies (fig. 9c) indicates that eroding bedrock existed nearby and that scattered islands lay along the platform during Late Devonian eustatic highstand.

Paleotectonics

Ellison (1950) recognized anomalously thin but complete Woodford intervals on structural highs along the Central Basin Platform and interpreted them as evidence of contemporaneous uplift during Woodford deposition. Pre-Mississippian truncation of the Woodford along the ancestral Central Basin Platform (for example, pl. 4, well 9) and on the Northwestern Shelf (app. B; C5, C9), where the lower unit is well developed and the upper unit is absent, is further evidence of contemporaneous uplift in these areas. Vertical tectonic adjustments in the Late Devonian most likely reflect reactivation of basement structures because truncated sections are found along zones of weakness in the basement and near the major Paleozoic fault systems (pls. 1, 2) that formed along reactivated basement faults (Walper, 1977; Muehlberger, 1980; Hills, 1984). In figure 10, contemporaneous vertical movements are illustrated by the schematic representations of normal faults in the Delaware and Val Verde Basins. These faults represent the dominant Paleozoic faults shown in plates 1 and 2.

Epeirogeny in the southern Midcontinent probably was linked to renewed tectonism along the continental margins. The Acadian orogeny produced highlands (fig. 11) that shed coarse terrigenous elastics toward the craton to form the Catskill delta (Ettensohn and Barron, 1981; Faill, 1985; Ettensohn, 1987). The Antler orogeny also produced a rising highland (fig. 11) that shed coarse elastics into a subsiding foreland basin (Poole and others, 1967; Poole, 1974). Forces transmitted from the Antler erogenic belt have been correlated with minor faulting, uplift, and subsidence in New Mexico (Poole and others, 1967) and are inferred to account for Late Devonian epeirogeny in the study area.

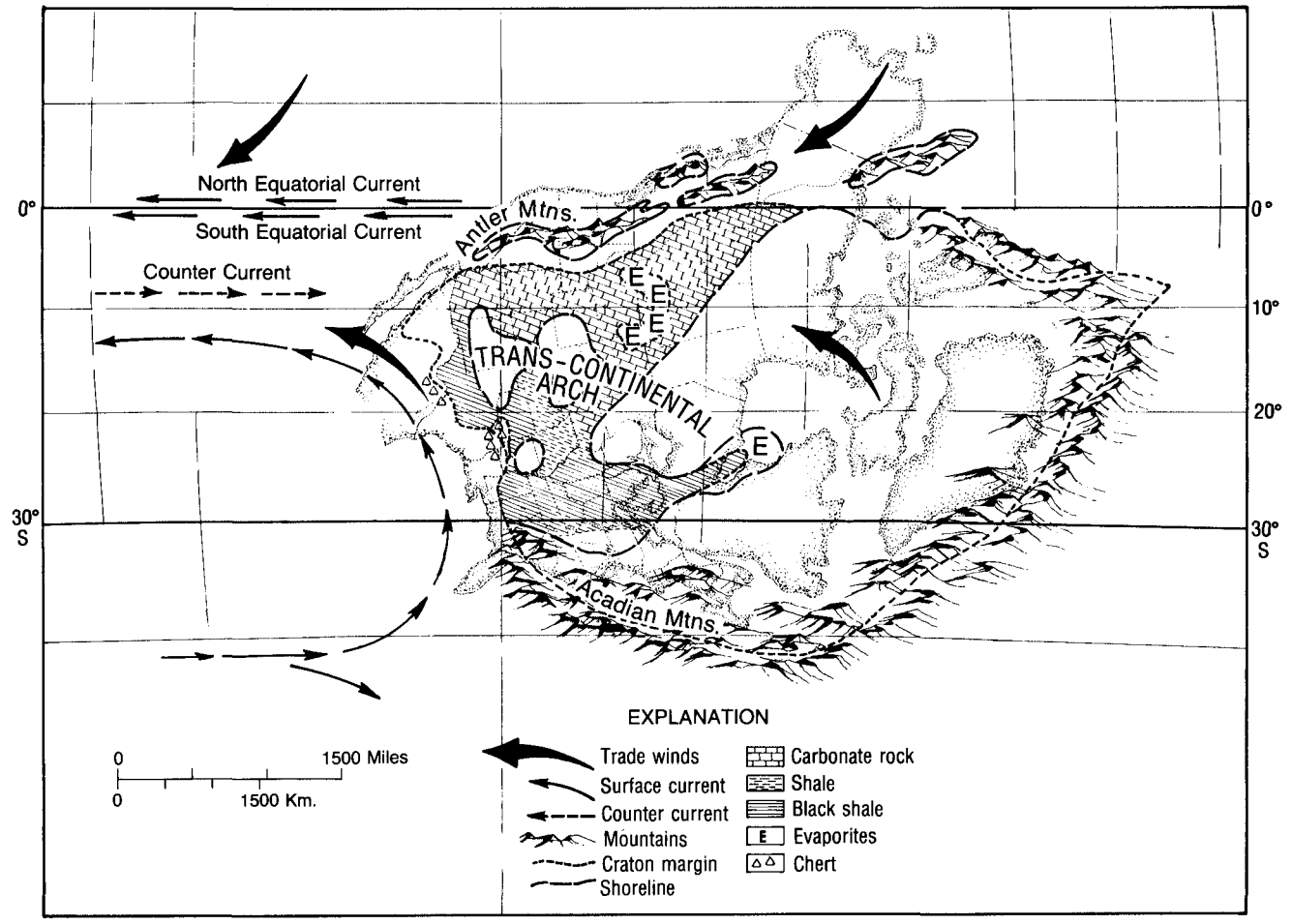


FIGURE 11. Late Devonian paleogeography of North America. After Heckel and Witzke (1979).

Paleoclimate

The paucity of terrestrial organic matter in the Woodford Formation, including the siltstone lithofacies, suggests that land in the region was mostly barren, and the absence of coarse-grained sediments and thick deltaic or fan deposits indicates that the land was low lying and not drained by large rivers. Furthermore, the presence of anhydrite in primary sedimentary structures documents hypersalinity within the basin. Together these observations indicate that the Permian Basin was arid during the Late Devonian. An arid paleoclimate and hypersalinity suggest that some of the dolomite in the Woodford formed in shallow-water evaporitic settings. Episodic resedimentation by bottom flows would account for the hybrid mixture of dolomite and quartz grains composing graded layers and Bouma divisions.

Arid-climate indicators support a Paleogeographic reconstruction in which the study area lies along the western margin of North America at approximately 15 degrees south latitude in the warm, arid southern trade-wind belt between the wet equatorial doldrums and the wet southern temperate zone (Heckel and Witzke, 1979; fig. 11). In this reconstruction the Late Devonian paleoequator lies along the Antler orogenic belt and the Canadian Rockies from California to Alberta. Other plate tectonic reconstructions of the Late Devonian also place the study area at low southern latitudes in the warm tropics or on the paleoequator (Lowe, 1975; Ettensohn and Barron, 1981; Parrish, 1982).

Paleoceanography

Features characteristic of black shale in the Woodford, including high organic content, abundant pyrite, and parallel laminae, indicate that bottom waters were stagnant and anoxic during deposition. The abundance of pelagic marine fossils and marine types of organic matter indicates that surface waters supported a luxuriant, normal marine biota. Coexistence of a putrid bottom and fertile surface waters requires a strongly stratified water column and implies the presence of a pycnocline (Byers, 1977; Arthur and Natland, 1979; Demaison and Moore, 1980; Ettensohn and Barron, 1981; Stanley, 1983; Ettensohn and Elam, 1985; Stein, 1986). The arid climate and hypersaline indicators imply that a pycnocline formed as a result of the strong density contrast between warm, normal-salinity surface water and cold, somewhat hypersaline bottom water. Anaerobic conditions developed below the pycnocline because no vertical mixing was occurring and because oxygen had been depleted owing to the high demand created by decay of the large volume of organic matter.

The abundance of marine organic matter and pelagic fossils indicates that efficient circulation of surface water and continuous resupply of nutrients characterized the upper part of the water column. Upwelling off the west and southwest coasts of North America during the Late Devonian (Lowe, 1975; Heckel and Witzke, 1979; Parrish, 1982) was the most likely source of the nutrients. No record exists of large rivers discharging into the basin (that is, deltas or fans) that would indicate a significant, continuous terrestrial source. Published circulation models suggest that oceanic surface currents flowing along the continental margin were diverted northward and northeastward, carrying upwelled water onto the North American craton (Lowe, 1975; Heckel and Witzke, 1979; Ettensohn and Barron, 1981). The model shown in figure 12 suggests that upwelled water moved eastward into the basin primarily as counter currents. In the southeast trade-wind belt, net flow of surface water would have been directed westward out of the basin by the Coriolis force and the Ekman spiral. The arid climate that produced hypersalinity caused net evaporation of surface water, particularly over shallow-water shelves, platforms, and shoals. The loss of surface water via wind-driven currents and evaporation would have amplified the negative water balance required by eustatic rise, causing inflowing counter currents to be stronger than outflowing surface currents.

The model in figure 12 differs from other published models (Lowe, 1975; Heckel, 1977; Demaison and Moore, 1980; Witzke, 1987) in that the floor of the basin in this model remained stagnant and anoxic, receiving sulfide-rich mud that had parallel laminae, even though net evaporation, local brine production, and negative water balance was occurring. This happened because the circulation pattern developed during a major marine transgression; therefore, much of the increased volume of water flowing onto the craton can be accounted for by the addition of hypersaline brine to stagnant bottom waters. Consequently, dense water gradually filled depressions in the epeiric sea without deep circulation being necessary to maintain water balance.

The existence of only dysaerobic (siltstone) and anaerobic (black shale) biofacies in the Woodford Formation indicates that bottom water became depleted in oxygen soon after the Late Devonian transgression began. Early oxygen depletion most likely was related to the early development of hypersalinity and strong density stratification. Dense water accumulated at the bottom of the water column in topographic lows and probably caused many local pycnoclines to develop during the initial stages of transgression. Later, at transgressive highstand, a single pycnocline (fig. 12) apparently developed, allowing anaerobic mud, represented by the black shales of the middle Woodford unit, to accumulate uniformly across the entire region. Dysaerobic bottom indicators found locally in the black shale on topographic highs (burrows, syneresis cracks, and anhydrite) may record some of the small-scale eustatic regressions documented by Johnson and others (1985) and reflect short-term fall of the pycnocline caused by falling sea level.

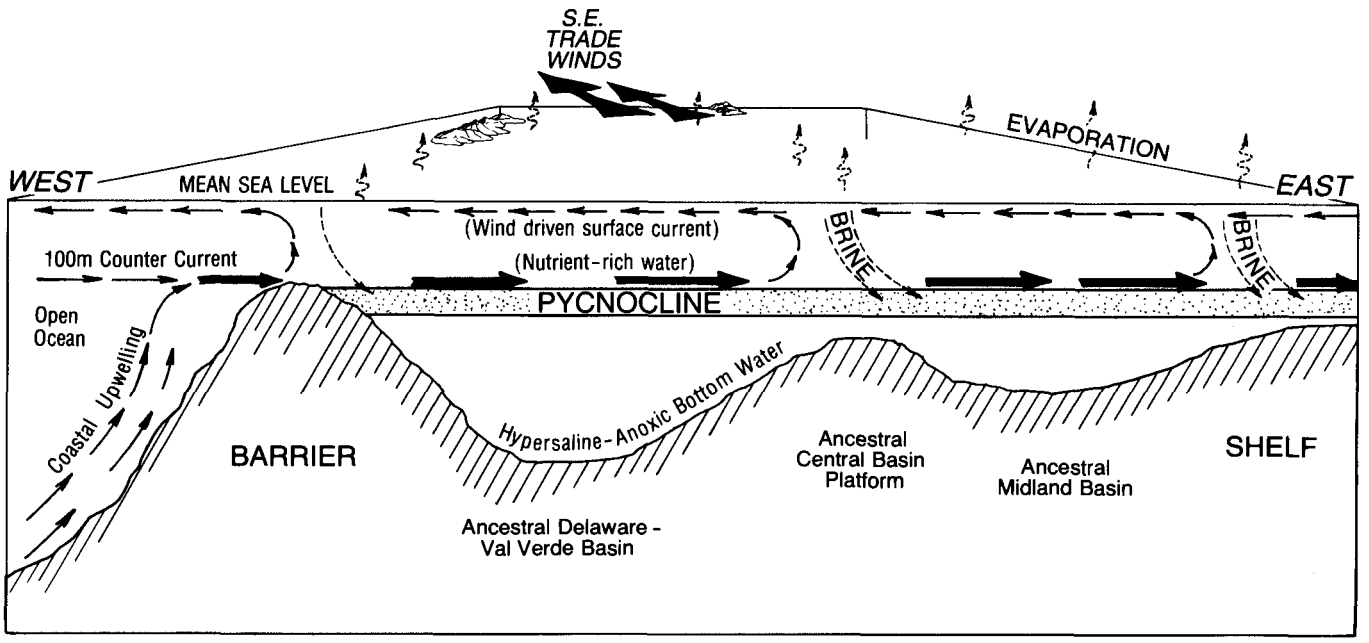


FIGURE 12. Model of Late Devonian circulation during eustatic highstand.

Depositional Mechanisms

Because the study area was once located in the tropics (fig. 11), and particularly because the Late Devonian was an epoch of worldwide transgression and global warming (Johnson and others, 1985), storms were most likely frequent and geologically significant events (Marsaglia and Klein, 1983; Morton, 1988; Barron, 1989). Frequent storms are therefore the most plausible mechanism for explaining the generation of bottom flows. Triggering mechanisms for bottom flows include (1) turbid, dense discharge from deltas, submarine fans, and rivers in flood, (2) spontaneous slumping of rapidly deposited, unconsolidated sediment, (3) slope failure resulting from earthquakes, and (4) sediment liquefaction and autosuspension during storms (Walker, 1984).

The absence of deltas and submarine fans in the Woodford precludes the first two mechanisms. What little turbid flood discharge entered the basin would not have been dense enough to sink beneath marine or hypersaline basin water (Drake, 1976; Pierce, 1976). Most likely, flood discharge was hypopycnal, or it produced detached turbidity layers by processes similar to those that had occurred in modern submarine canyons off southern California (Pierce, 1976) and in the Nile cone and Hellenic trench regions of the Mediterranean Sea (Maldonado and Stanley, 1978; Stanley and Maldonado, 1981). Deposition from turbid, muddy plumes would not produce graded layers or Bouma sequences but could yield the varvelike laminae (Pierce, 1976; Stanley, 1983) characteristic of the black shale lithofacies in the Woodford.

Earthquakes associated with epeirogenic movements probably triggered some bottom flows, but the subtlety of structural displacement during the Late Devonian indicates that these movements probably were weak and infrequent. Furthermore, bottom flows starting in shallow water would be diverted along the pycnocline in strongly stratified seas (Pierce, 1976; Stanley, 1983), unless they entrained brine from restricted hypersaline basins, shelves, or shoals (Arthur and Natland, 1979).

Storms, rather than earthquakes, probably were the most frequent and powerful agents of sediment transport in the warm Late Devonian tropics. They can account for both the indiscriminate mixing of siliciclastic and dolomite grains and the generation of bottom flows that persisted into basinal depocenters. In modern seas, storms can disrupt density stratification

(Mooers, 1976a, b), a condition that could minimize flow detachment and promote sustained bottom flows. It is probable that such a process happened in Late Devonian times as well. Storm winds and surge would flush shallow-water, hypersaline environments and give rise to very dense bottom flows consisting of sediment-laden brine. Briny bottom flows would maintain their integrity below the pycnocline even in strongly stratified basins.

Evidence indicates that bottom flows periodically disturbed anoxia that existed beneath the pycnocline. In black shales, burrows are commonly confined to graded layers and Bouma divisions, indicating that the bottom was briefly inhabited by organisms after sediment deposition. Bottom flows originating in shallow, aerobic or dysaerobic environments apparently entrained enough oxygen to sustain a temporary benthic population. However, oxygen was quickly depleted by the meager fauna, decay of organic matter, and absence of oxygen resupply. And because bottom oxygenation was short-lived, anaerobic conditions quickly returned, killing the few allochthonous organisms. Burrowed layers in the Cretaceous Mowry Shale (Davis and others, 1989) and the Devonian Chattanooga Shale (Potter and others, 1982) have been similarly explained, and entrainment of oxygen and benthic organisms in turbidity currents apparently occurred in modern sediments in the Santa Barbara Basin (Sholkovitz and Soutar, 1975).

Basal siltstones in proximal shelf and basin environments (app. B; C5, C9, C11) consist of vertically stacked siltstone-shale couplets, documenting episodic deposition from bottom flows. The greater numbers and thicknesses of siltstones in the deepest parts of the Delaware, Midland, and Val Verde Basins indicate that these depocenters were locations where bottom flows, initiated in various parts of the basin, finally converged. The high frequency of bottom flows in basinal depocenters implies that basin axes were dysaerobic more often than were distal shelves, slopes, and platforms. Thus, the lower concentrations of organic matter in the basins (fig. 9e) can be attributed to the combined effects of dilution by clastic sediment and destruction by oxidation, aerobic microbes, and the temporary benthos.

Synopsis of Depositional History

Woodford deposition began when the sea drowned marine embayments in what are now the deepest parts of the Delaware and Val Verde Basins and advanced over a subaerially eroded and dissected terrane composed mostly of carbonate rocks of Ordovician to Middle Devonian age. A broad epeiric sea formed that had irregular bottom topography and scattered, low-relief land masses. The basin lay in the arid midtropics surrounded by lands that supported little vegetation and few rivers. Oceanic water from an area of coastal upwelling flowed into the expanding epeiric sea and maintained a thriving, normal marine biota in the upper levels of the water column. Net evaporation locally produced hypersaline brines, and strong density stratification developed that restricted vertical circulation. The basin quickly became dysaerobic and then anaerobic as sea level continued to rise. Once oxygen was eliminated from the bottom, sulfide-rich mud began to accumulate. Rising sea level and persistent oceanographic and climatic patterns allowed anaerobic mud deposition to continue slowly during the rest of the Late Devonian Epoch. Frequent storms and occasional earthquakes triggered bottom flows that supplied silty mud to proximal shelves and deep basin troughs and caused much resedimentation throughout the basin. Tectonic stress arising from the Antler orogeny initiated epeirogenic movements throughout the region and caused contemporaneous movements along reactivated basement faults.

Woodford deposition probably ended because sea level stabilized or dropped and oceanographic patterns changed, thus halting the strong net flow of ocean water onto the craton and forcing deep circulation through most of the basin. Glauconite and calcified benthic epifauna accumulated on the floor of the epeiric sea, marking a change in bottom conditions from anaerobic to dysaerobic and locally aerobic and recording the improved vertical circulation through most of the basin.

Petroleum Potential

The Woodford Formation is currently generating oil in the Midland Basin, Central Basin Platform, and Eastern and Northwestern Shelves and is currently generating gas in the Delaware and Val Verde Basins. Thermal maturity of the Woodford Formation was deduced from the depth and R_o data in appendix D and the depth versus R_o log-normal relationship derived for the Woodford in the Anadarko Basin (Cardott, 1989). Oil generation in the Woodford occurs between R_0 values of 0.5 and 1.3 percent (Cardott, 1989) at depths between 6,000 and 13,000 ft in the Permian Basin. These depths correspond to depths below sea level of approximately 4,000 to 10,000 ft in the region east of the Central Basin Platform and 2,000 to 9,000 ft in the Delaware Basin and regions to the west (fig. la; pl. 1). Condensate and wet-gas generation occurs between R_0 values of 1.3 and 2.0 percent (Cardott, 1989) at depths between 13,000 and 18,000 ft common only in the Delaware and Val Verde Basins. These depths correspond to depths below sea level of approximately 9,000 to 14,000 ft in the region west of the Central Basin Platform and south of the Pecos Arch (fig. la; pl. 1). Dry gas is generated between R_0 values of 2.0 and 5.0 percent at depths between 18,000 and 26,000 ft (Cardott, 1989), or at depths below sea level of 14,000 to 22,000 ft in the Delaware and Val Verde Basins (fig. 1a; pl. 1).

Commercial production of hydrocarbons from the Woodford is possible in areas where the formation is highly fractured. The fractured Upper Devonian shales (Ohio, Chattanooga, Antrim, Bakken, and Woodford) that produce gas in the Appalachian and Michigan Basins and oil in the Williston and Ardmore Basins illustrate the commercial potential and provide appropriate geological models for exploration in the Permian Basin. In West Texas and southeastern New Mexico, optimum drilling targets are the siltstones and radiolarian cherts because they are competent lithologies that are the most likely to maintain open fracture systems. Areas that have the greatest density of major faults are the most prospective: these include the Central Basin Platform, southernmost Midland Basin, and parts of the Northwestern Shelf (fig. la; pls. 1, 2). Production may be possible from the well-developed basal siltstone in the northern part of the Midland Basin and adjacent Northwestern Shelf (for example, app. B; C5, C11 in Cochran and Gaines Counties, Texas). Although faults are uncommon there, commercial production could be established in zones where porosity has been enhanced or permeability can be artificially stimulated. Gas undoubtedly is present in siltstones and fractured shales in the Delaware and Val Verde Basins; however, drilling depths would make costs prohibitive in most places.

Summary

The Woodford Formation is an organic-rich petroleum source rock that has long been recognized as an important marker unit because of its black shales, anomalously high radioactivity, widespread distribution, and stratigraphic position between carbonates. The Woodford is mostly Late Devonian in age and is stratigraphically equivalent to the Devonian black shales (for example, Chattanooga, Ohio, Antrim, New Albany, Bakken, Exshaw, and Percha) that are present in many North American basins. At most localities, the Woodford overlies a major regional unconformity and is diachronous.

In the Permian Basin, the Woodford is thickest (661 ft) in the Delaware Basin depocenter and locally is absent from structural highs on the Central Basin Platform and Pecos Arch. Structural relief in the subsurface is 20,000 ft; it developed primarily during the late Paleozoic as a response to erogenic activity in the Ouachita Fold Belt.

Two lithofacies, black shale and siltstone, compose the Woodford. The black shale exhibits

varvelike parallel laminae, abundant pyrite, very high radioactivity, and high concentrations of marine organic matter (mean = 4.5 ± 2.6 wt % TOC). It is the most widely distributed and distinctive rock type in the formation. Siltstone is a hybrid of silt-sized quartz and dolomite grains and exhibits discontinuous or disrupted stratification, graded layers, fine-grained Bouma sequences, and moderately high radioactivity. It is restricted to deep basin and proximal shelf settings and is commonly the basal unit. On the basis of lithology and stratigraphic position, basal siltstone is correlated with the Onate and Canutillo Formations in New Mexico and West Texas, the Misener and Sylamore Sandstones in Oklahoma and Arkansas, and the Ives Breccia Member of the Houy Formation in Central Texas. The black shale lithofacies is correlated with the Sly Gap and Percha Formations in the west and the Doublehorn Shale and phosphatic members of the Houy Formation in Central Texas. Black shale is mostly pelagic and represents an anaerobic biofacies, whereas siltstone was deposited by bottom flows and comprises a dysaerobic biofacies. Upward transition from basal siltstone to black shale locally records the worldwide marine transgression that occurred during the Late Devonian.

The Woodford onlaps Paleozoic structures flanking the Midland, Delaware, and Val Verde Basins, indicating that all of the major structural provinces in the modern-day Permian Basin had topographic expression in the Late Devonian. The blanketlike geometry and nearly uniform lithology, however, indicate that the region was one of low relief. The increased size and abundance of siliciclastic grains (quartz, muscovite, feldspar) and wood fragments in the northern part of the basin show that the Pedernal Massif and northern Concho Arch were the principal source areas of terrigenous sediment. In contrast, most dolomite formed contemporaneously on distal platforms and shelves in highly reduced, low-sulfate mud or restricted marine environments. Resedimentation of dolomite grains and mixing with siliciclastics were accomplished by bottom flows.

Woodford black shale records widespread bottom stagnation and anoxia during deposition and a strongly density-stratified water column. High concentrations of marine organic matter and siliceous pelagic micro-organisms in the shale indicate high biological productivity in surface waters supported mainly by dynamic upwelling. Episodes of hypersalinity, documented by the presence of anhydrite in burrows and syneresis cracks, suggest an arid paleoclimate and indicate that density stratification was caused, at least partly, by accumulation of hypersaline bottom water.

The plate tectonic reconstruction most consistent with an arid paleoclimate and dynamic upwelling places the study area on the western margin of North America in the dry tropics near 15 degrees south latitude. In this setting, southeasterly trade winds and the Ekman spiral would push surface waters westward toward the open ocean and upwelled oceanic water eastward onto the craton as counter currents. The negative water balance required for marine transgression would be amplified by flow into the basin replacing water lost by evaporation.

This circulation model accounts for the large supply of nutrients needed to support high biological productivity in the upper part of the water column of the epeiric sea. Furthermore, the low-latitude paleogeography and Late Devonian global warming imply frequent tropical storms and suggest that the bottom flows that caused the deposition of hybrid quartz/dolomite siltstones were storm generated.

The end of Woodford deposition coincided with the end of the Late Devonian eustatic rise. Bottom oxygenation, recorded as accumulations of glauconite and calcitic benthic fossils, indicates that new oceanographic conditions included deep circulation in most of the basin. The stabilization or fall of sea level would have ended the strong net flow of ocean water containing upwelled nutrients onto the craton and forced deep circulation to maintain water balance.

The Woodford Formation is now in the oil window in the Midland Basin, Central Basin Platform, and Eastern and Northwestern Shelves, and it is in the gas window in the Delaware and Val Verde Basins. Commercial production of hydrocarbons is possible from intervals that are highly fractured, but optimum drilling targets are siltstone and radiolarian chert

beds in densely faulted regions, such as the Central Basin Platform, southernmost Midland Basin, and parts of the Northwestern Shelf.

Development of reserves in unusual geological settings such as the Woodford Formation in the Permian Basin undoubtedly will be required to meet future demands for petroleum. These reserves can be discovered through comprehensive studies, similar to the present report, that integrate stratigraphic, petrologic, and geochemical data. Such studies can help predict the location and lithology of unconventional oil and gas reservoirs that are inherently difficult to find.

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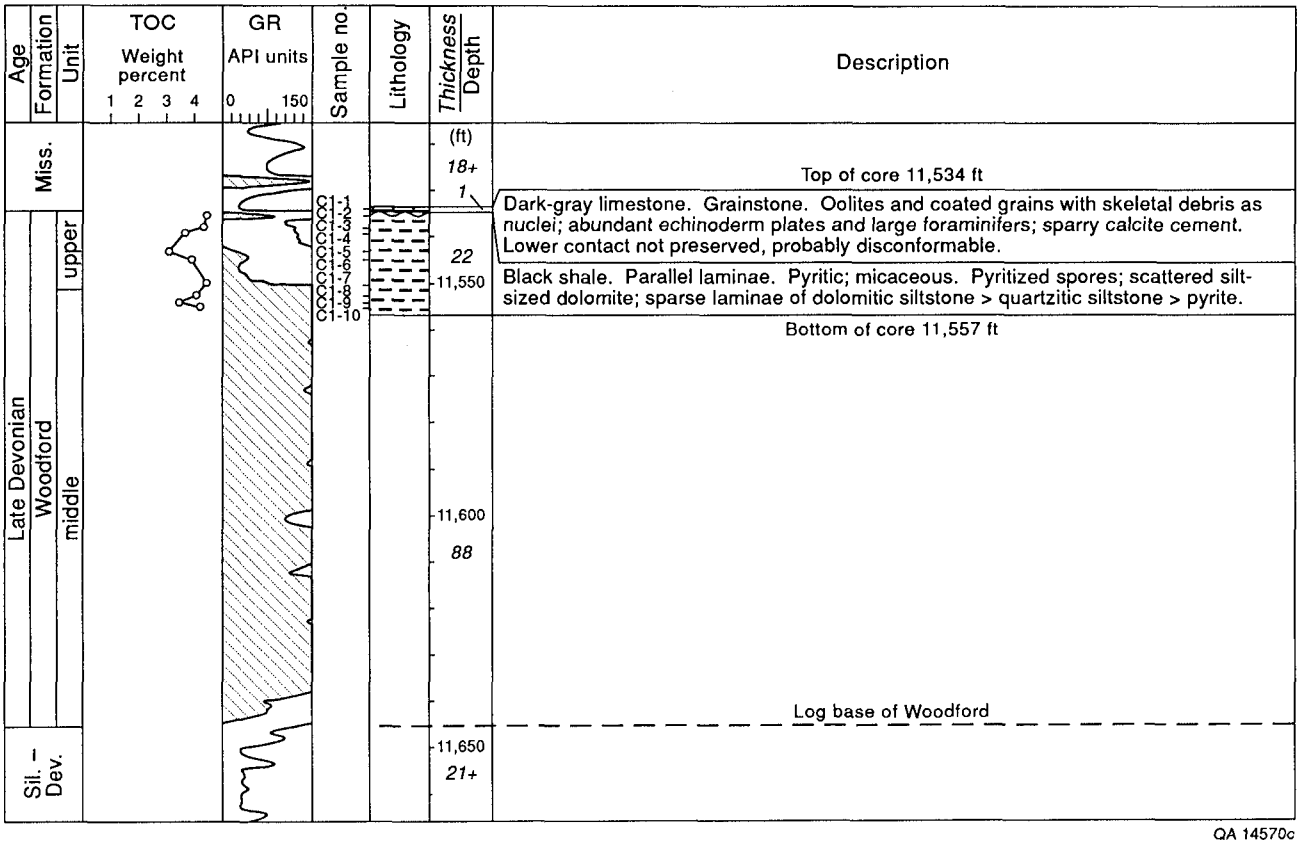
APPENDICES

Appendix A. Location of cores and measured sections.

Map symbol	Operator	Well	County	State	Location
			Cores		
C1	Mobil	#1918 Parks Unit 2	Midland	Texas	Sec. 14, Block 40, C.F. O'Neal Survey
C2	Humble	#43 Yarborough & Allen	Ward	Texas	Sec. 66, E.J. Brady Survey
C3	Humble	#1 A. E. State	Lea	New Mexico	Sec. 16, T.15S., R.33E.
C4	Shell	#1 Champeau Federal	Chaves	New Mexico	Sec. 31, T.15S., R.30E.
C5	Pan American	#1 Walker	Cochran	Texas	Sec. 8, Block Z, PSL Survey
C6	Shell	#1 Chrieseman	Glasscock	Texas	Sec. 12, Block 36, T.5S., T&P Survey
C7	Standard of Texas	#1-28 Canon	Dawson	Texas	Sec. 28, Block 33, T.5N., T&P Survey
C8	Roden & Cosden	#1 Reed	Sterling	Texas	Sec. 9, Block 30, W&NW Survey
C9	Shell	#5 Pacific Royalty	Lea	New Mexico	Sec. 10, T.15S., R.37E.
C10	McGrath & Smith	#1 Brennand & Price	Mitchell	Texas	Sec. 7, Block 17, SPRR Survey
C11	Shell	A#1 Williamson	Gaines	Texas	Sec. 110, Block H, D&WRR Survey
C12	Shell	#1 Sealy Smith	Ward	Texas	Sec. 38, Block A, G&MMB&A Survey
C13	Humble	#1 Federal Elliott	Lea	New Mexico	Sec. 1, T.16S., R.34E.
			Measured Sections		
P1	Bishop Cap		Doña Ana	New Mexico	Sec. 25, T.24S., R.3E.
P2	Anthony Gap, Northern Franklin Mountains		Doña Ana	New Mexico	Sec. 34, T.26S., R.4E.
P4	Martin Canyon, Hueco Mountains		El Paso	Texas	106°00'30" W. Longitude, 31°48'30" N. Latitude
			Sections from Rosado (1970)		
R1	Magnolia	#1 University 39881	Hudspeth	Texas	Sec. 19, Block C, University Lands Survey
R2	Gulf	#1 Munson Federal	Chaves	New Mexico	Sec. 28, T.19S., R.18E.
R3	Alamo Canyon, Sacramento Mountains		Otero	New Mexico	Sec. 2, T.17S., R.10E.

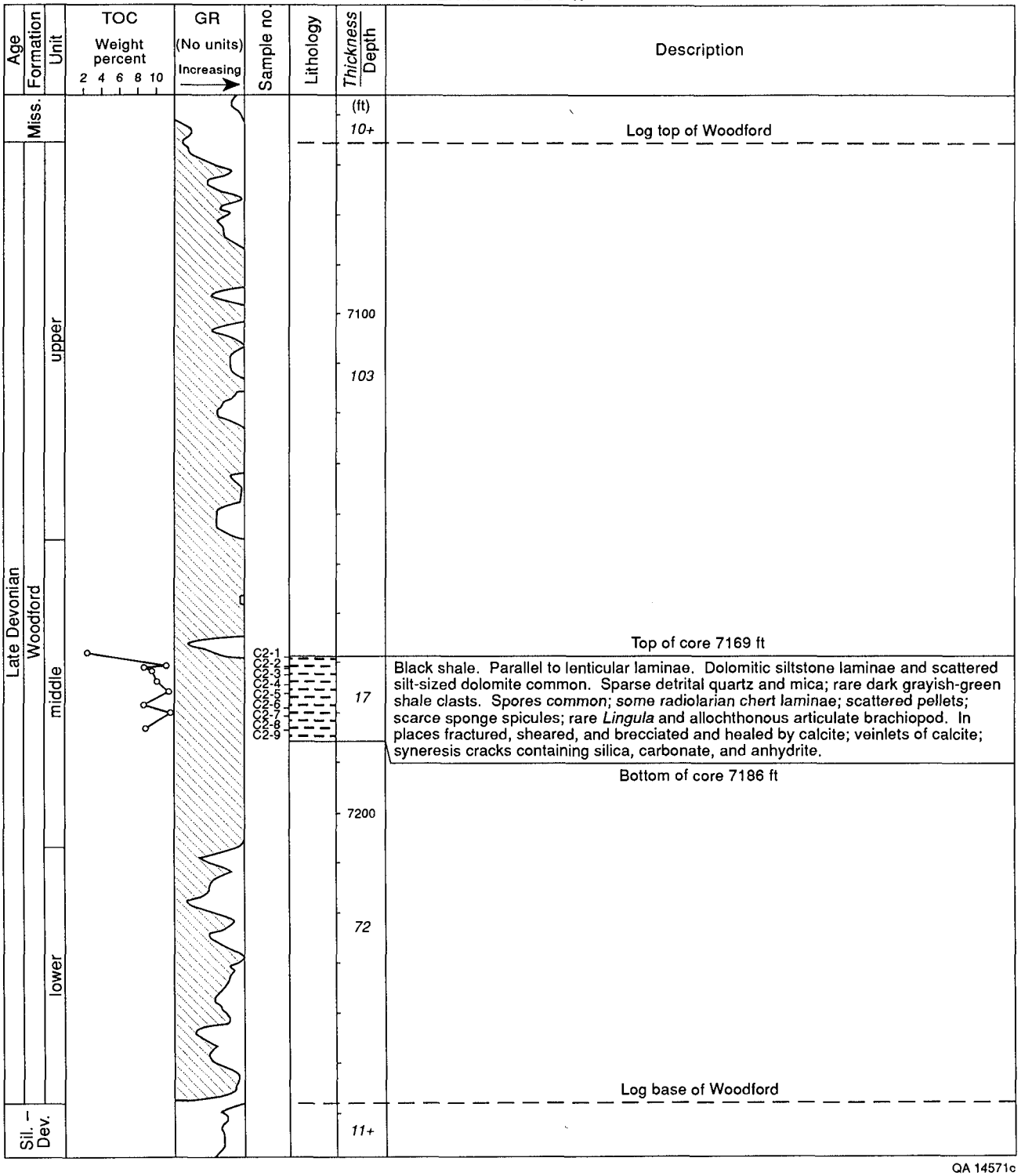
Appendix B. Description of cores and measured sections. For map locations, see figure 2 and plates 1 and 2.

C1
Mobil No. 1918, Parks Unit 2
Midland County, Texas
Section 14, Block 40, C. F. O'Neal Survey
Elevation 2825 ft



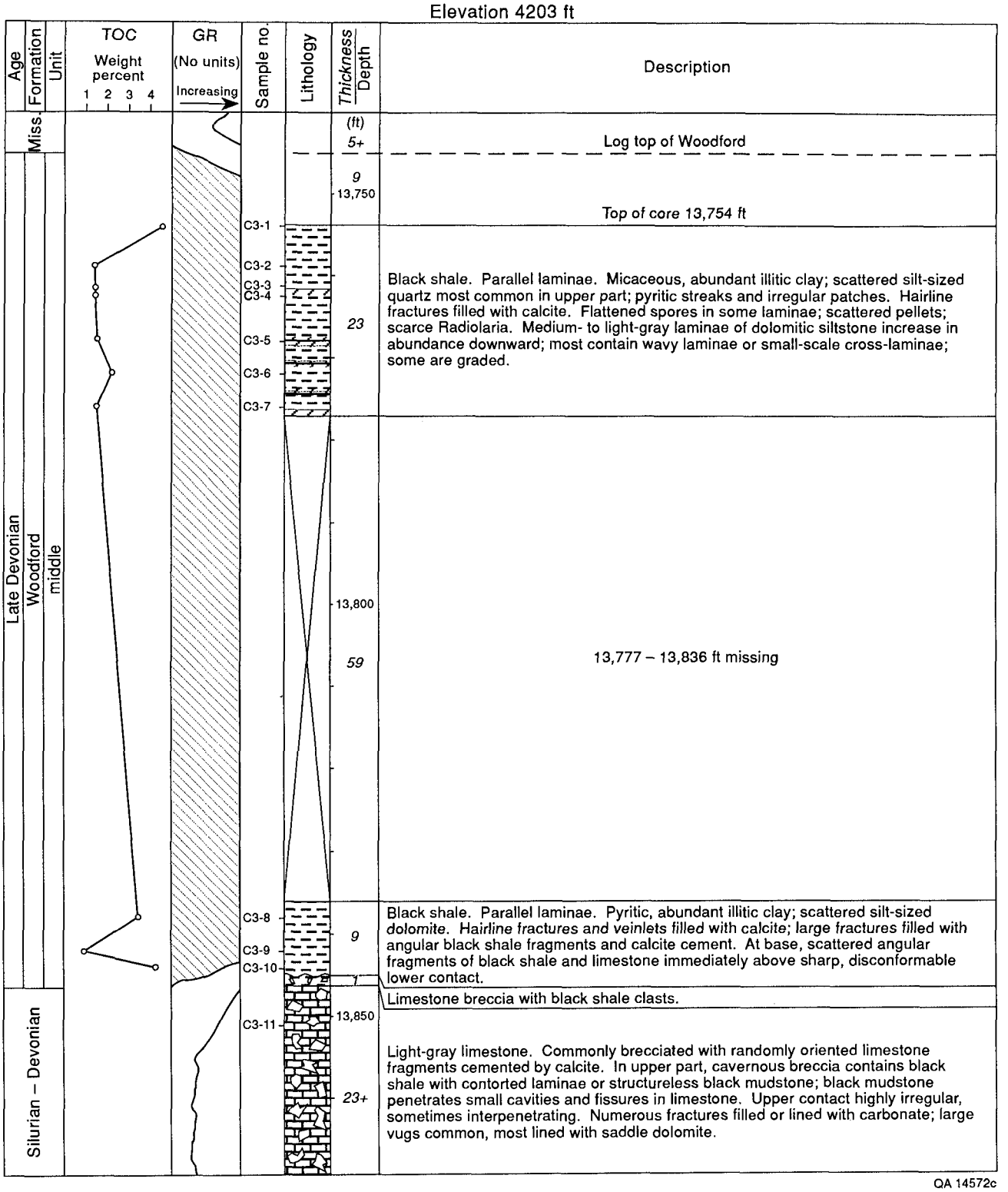
QA 14570c

C2
Humble No. 43 Yarborough and Allen
Ward County, Texas
Section 66, E. J. Brady Survey
Elevation 2756 ft



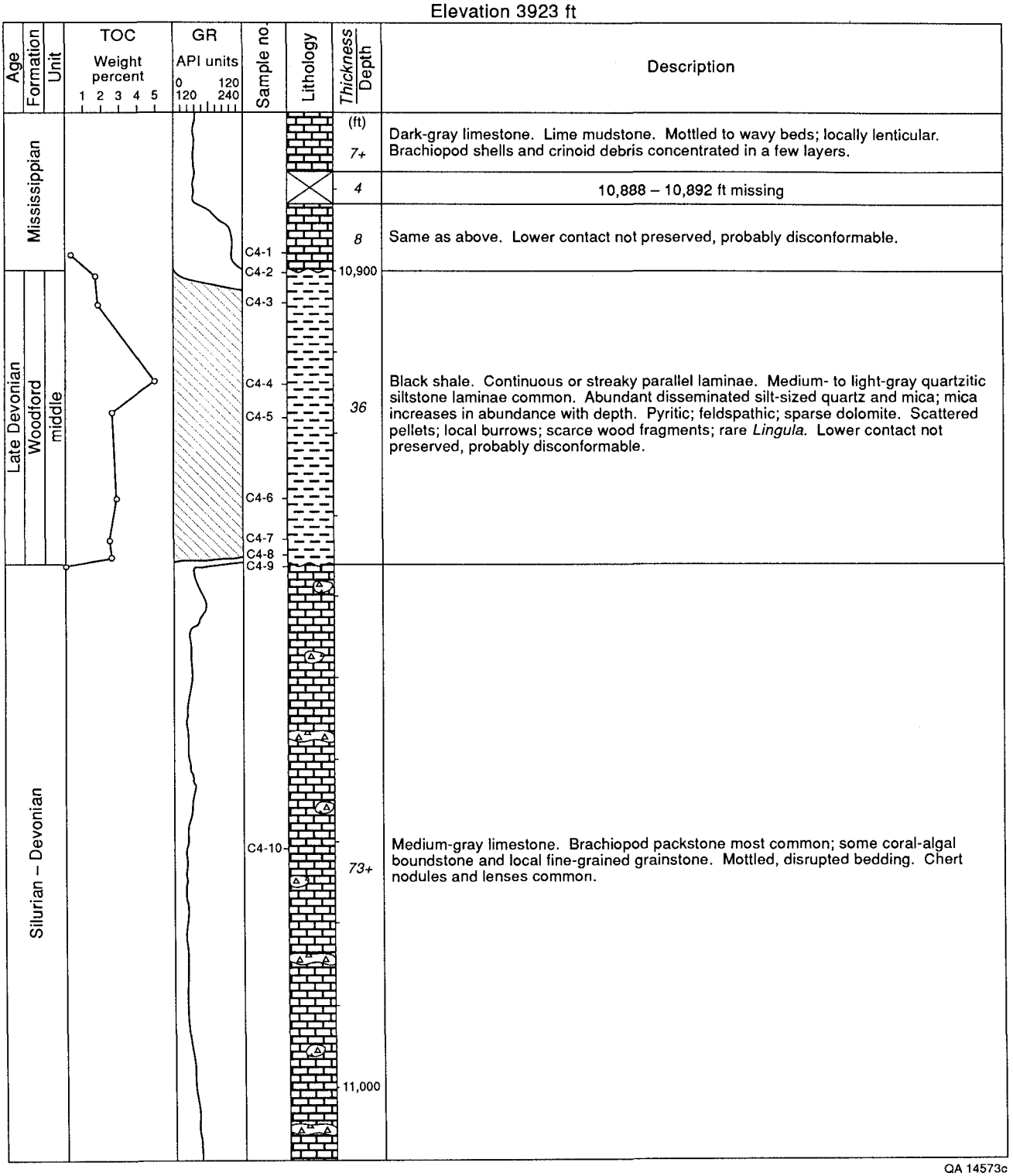
QA 14571c

C3
Humble No. 1 A. E. State
Lea County, New Mexico
Section 16, T 15 S – R 33 E
Elevation 4203 ft



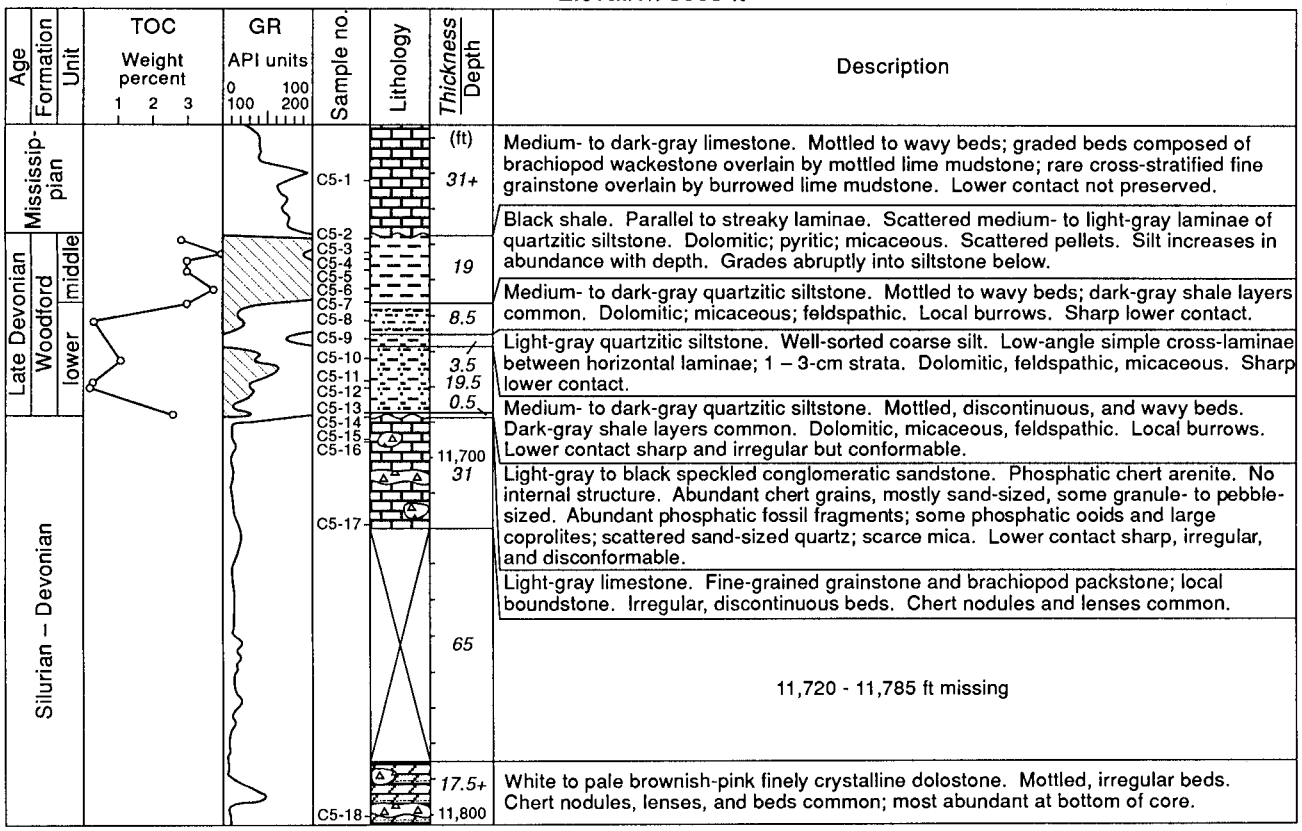
QA 14572c

C4
Shell No. 1 Champeau Federal
Chaves County, New Mexico
Section 31, T 15 S – R 30 E
Elevation 3923 ft



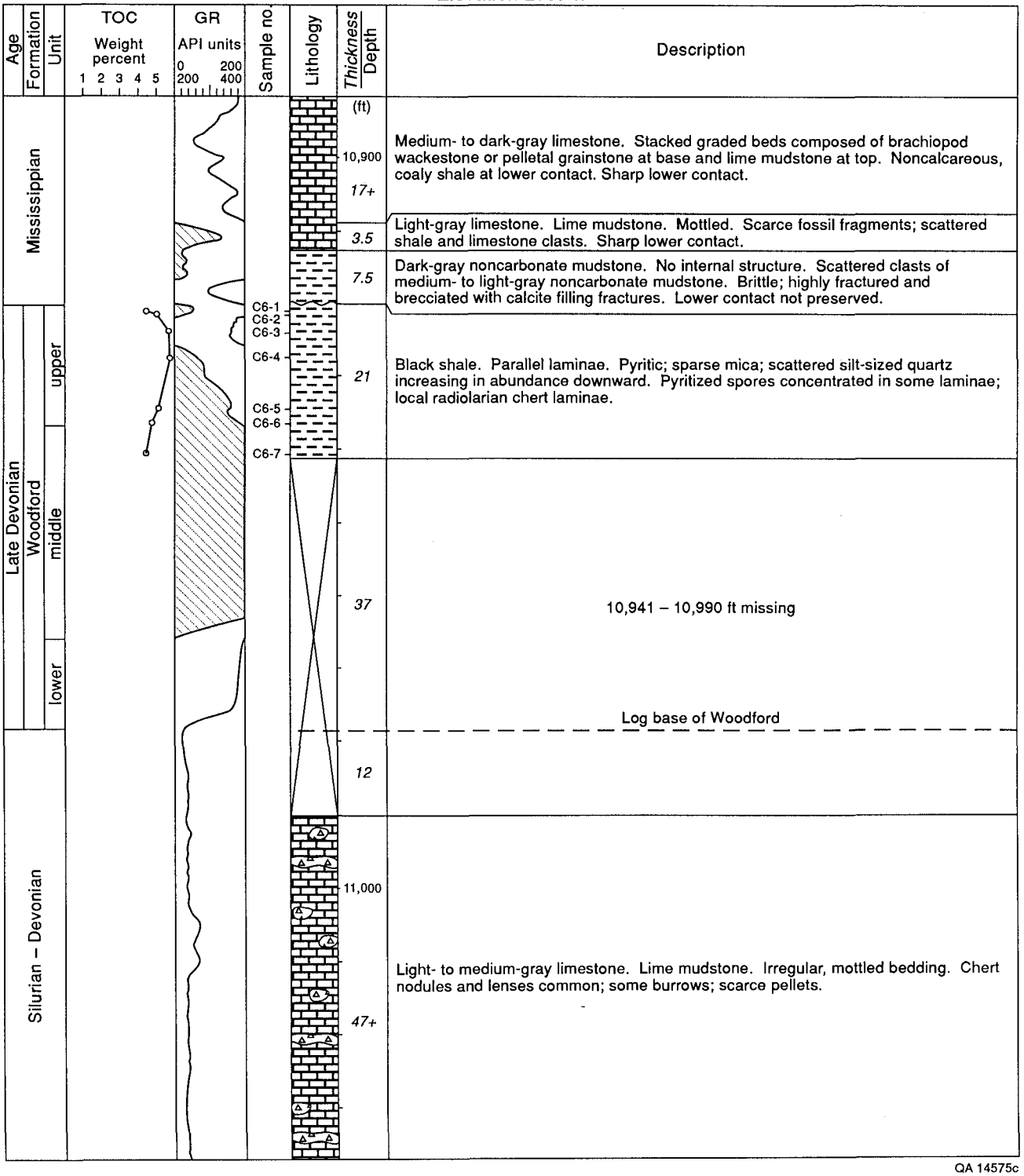
QA 14573c

C5
Pan American No. 1 Walker
Cochran County, Texas
Section 8, Block Z, PSL Survey
Elevation 3883 ft



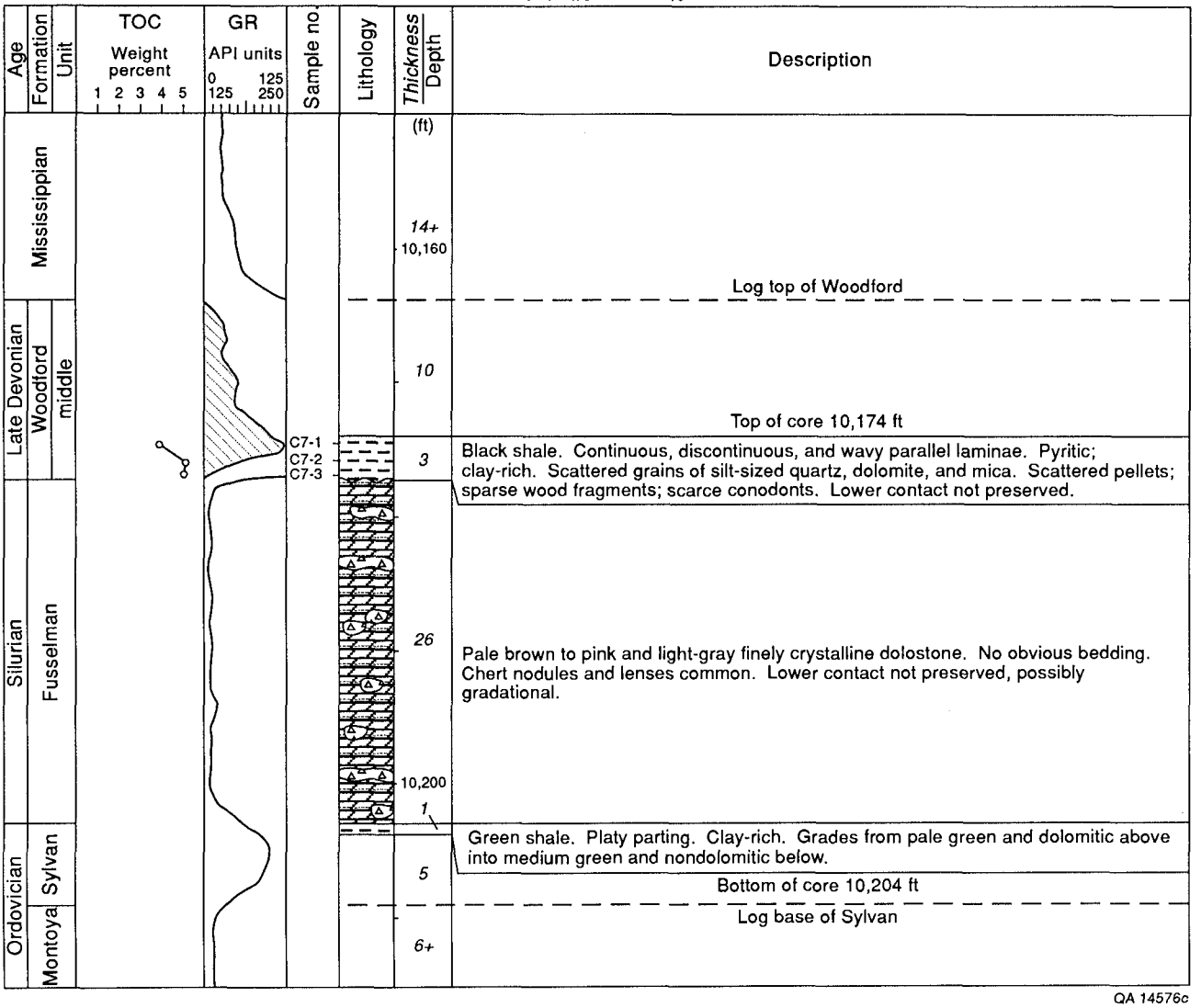
QA 14574c

C6
Shell No. 1 Chriesman
Glasscock County, Texas
Section 12, Block 36, T 5 S, T and P Survey
Elevation 2697 ft



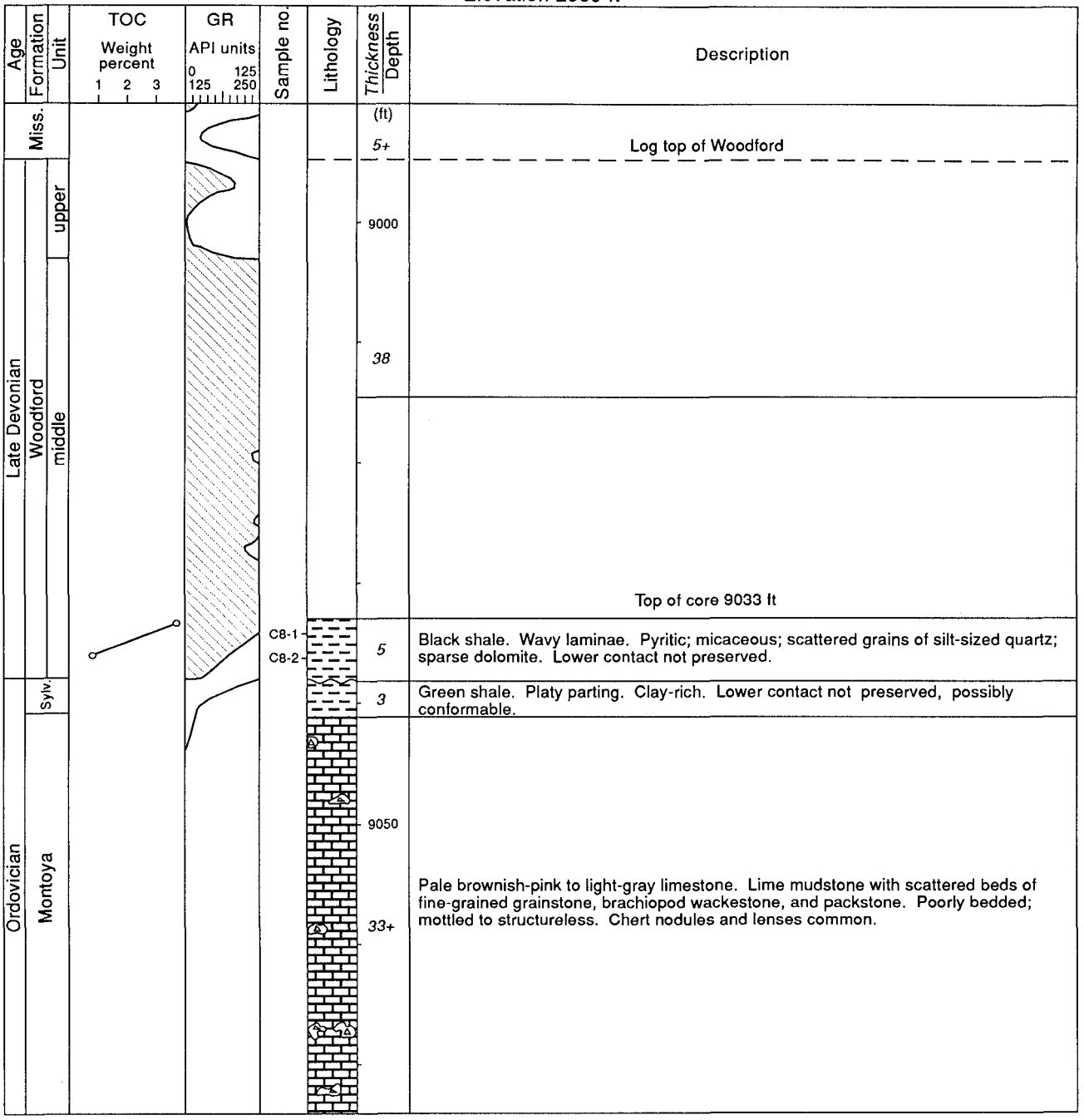
QA 14575c

C7
Standard of Texas No. 1-28 Canon
Dawson County, Texas
Section 28, Block 33, T 5 N, T and P Survey
Elevation 2711 ft



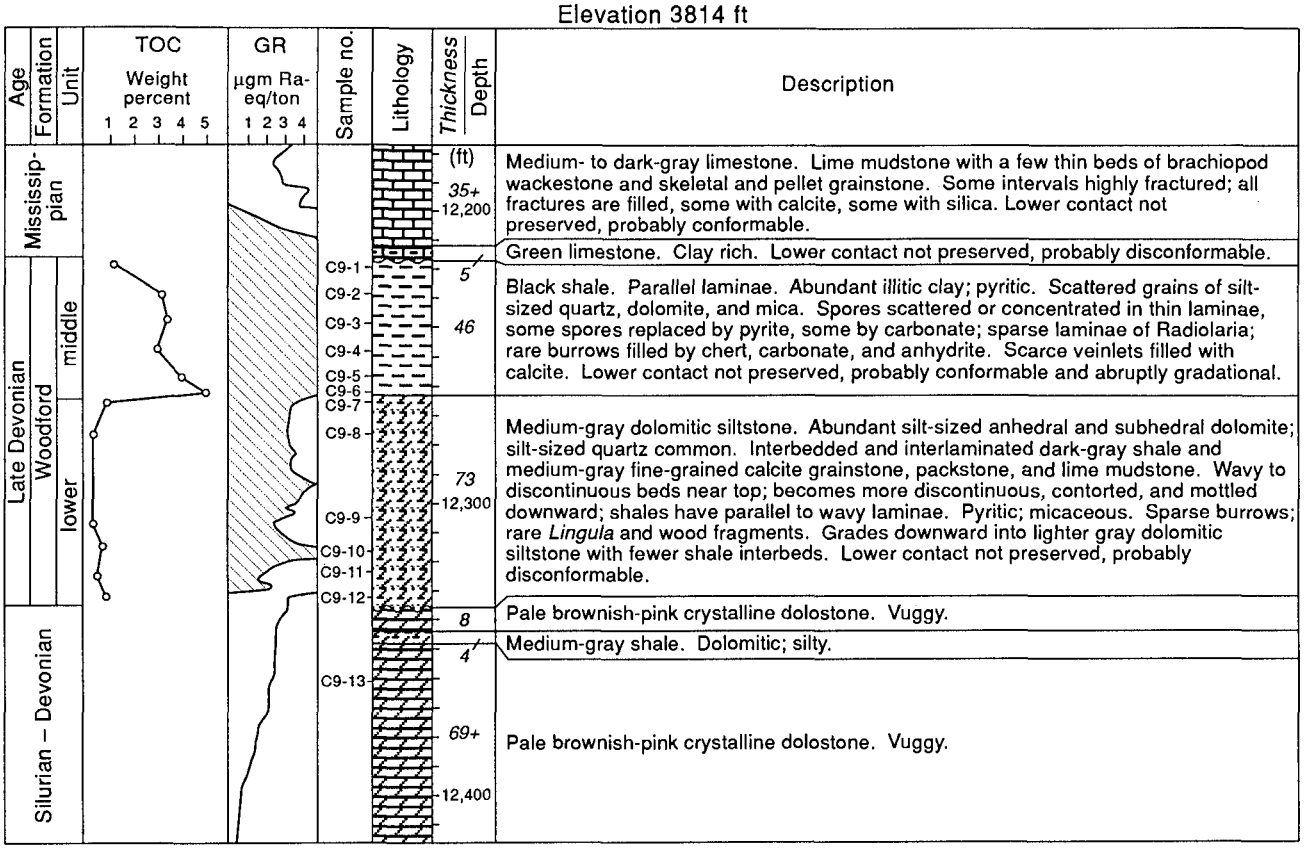
QA 14576c

C8
Roden and Cosden No. 1 Reed
Sterling County, Texas
Section 9, Block 30, W and NW Survey
Elevation 2569 ft



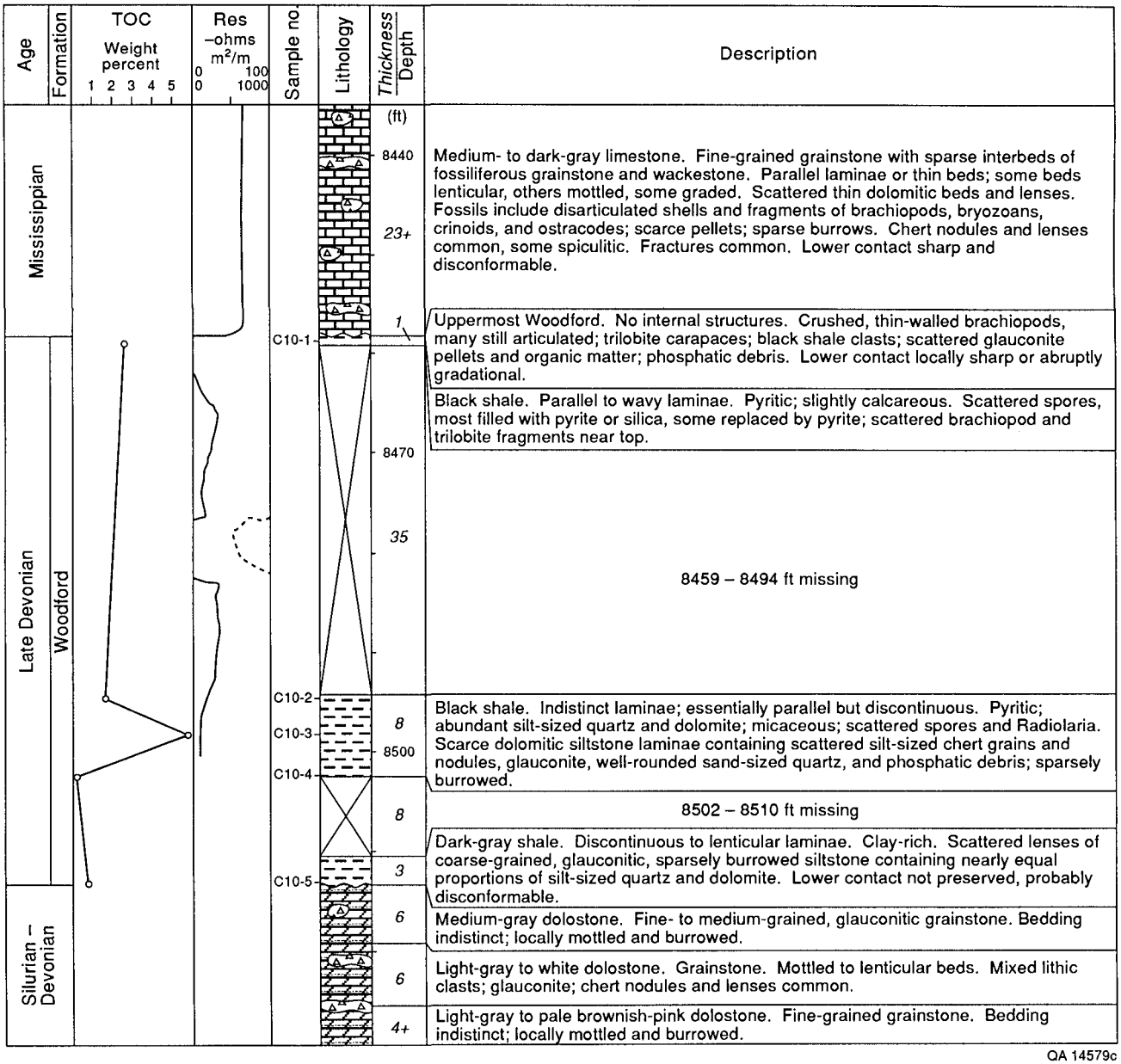
QA 14577c

C9
Shell No. 5 Pacific Royalty
Lea County, New Mexico
Section 10, T 15 S – R 37 E
Elevation 3814 ft



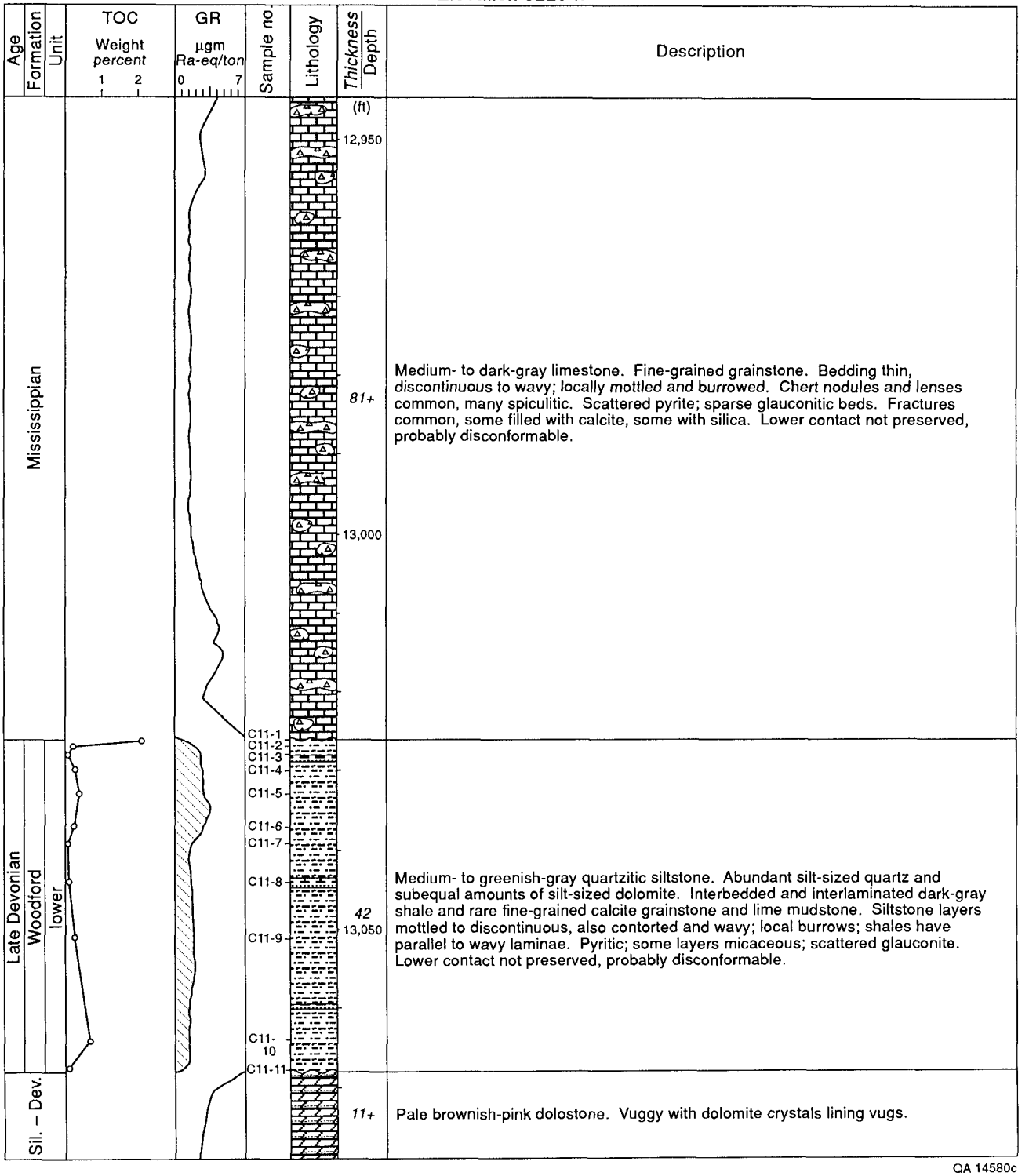
QA 14578c

C10
McGrath and Smith No. 1 Brennand and Price
Mitchell County, Texas
Section 7, Block 17, SPRR Survey
Elevation 2332 ft



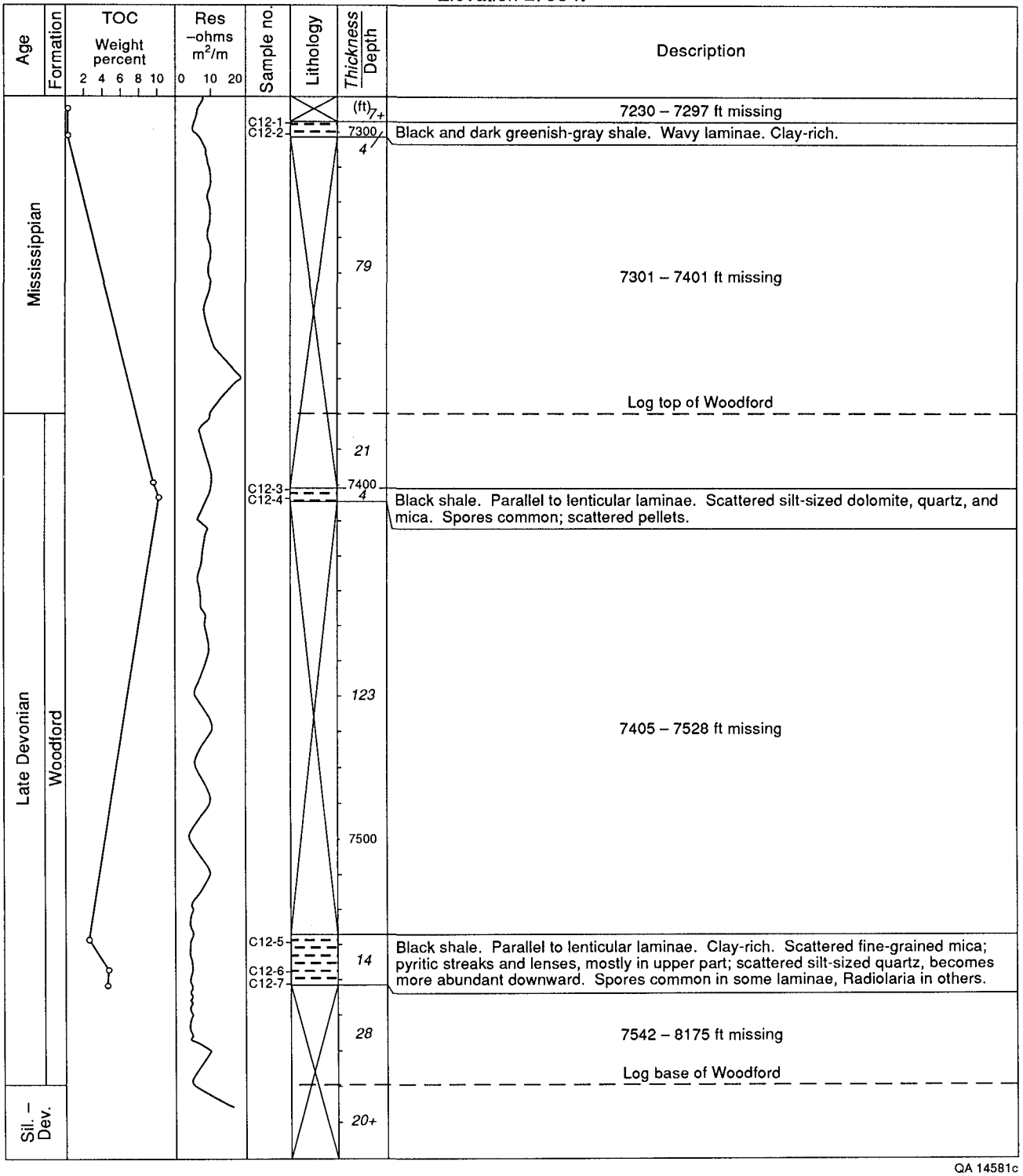
QA 14579c

C11
Shell A No. 1 Williamson
Gaines County, Texas
Section 110, Block H, D and W RR Survey
Elevation 3229 ft



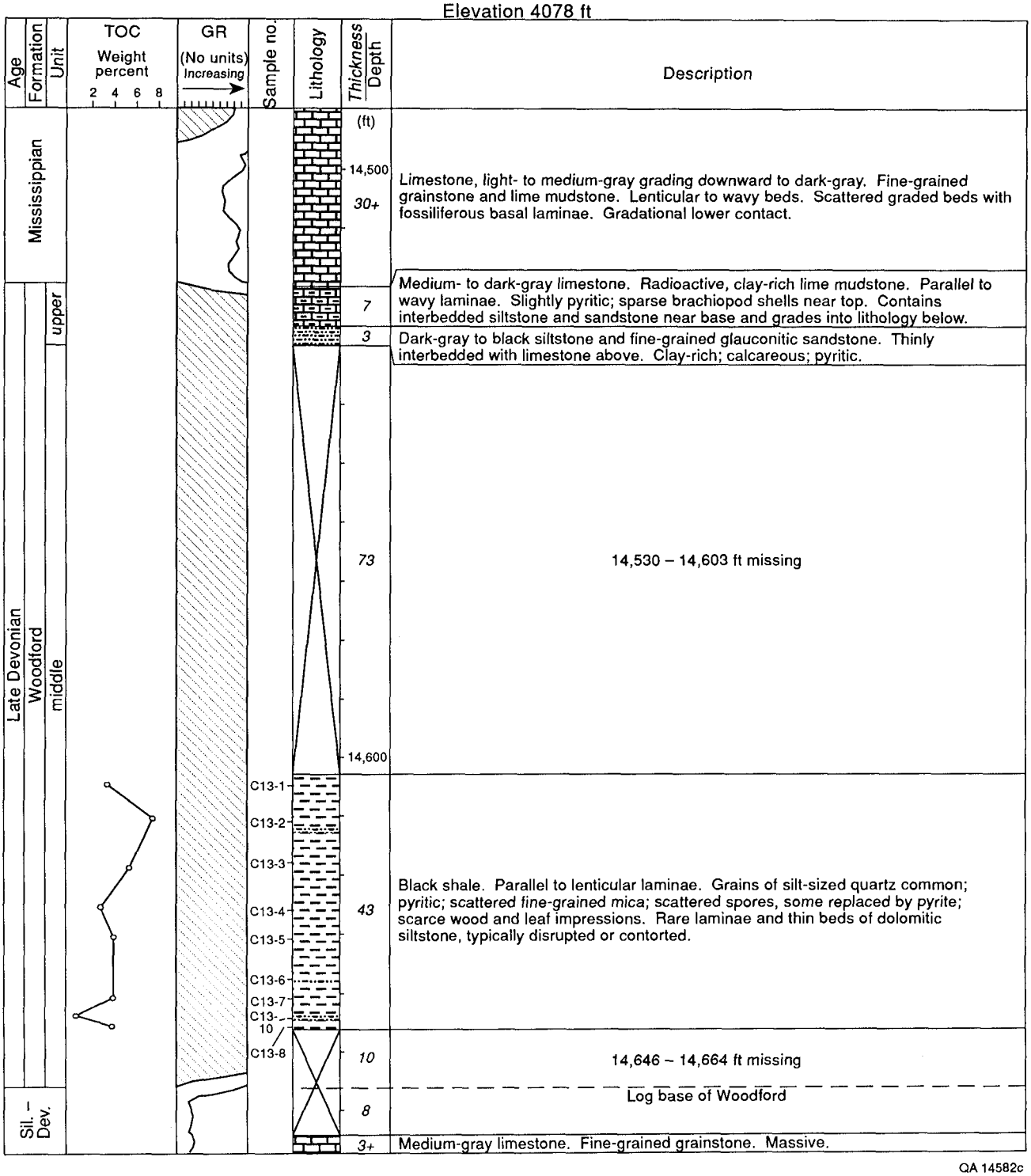
QA 14580c

C12
Shell No. 1 Sealy Smith
Ward County, Texas
Section 38, Block A, G and MMB and A Survey
Elevation 2736 ft



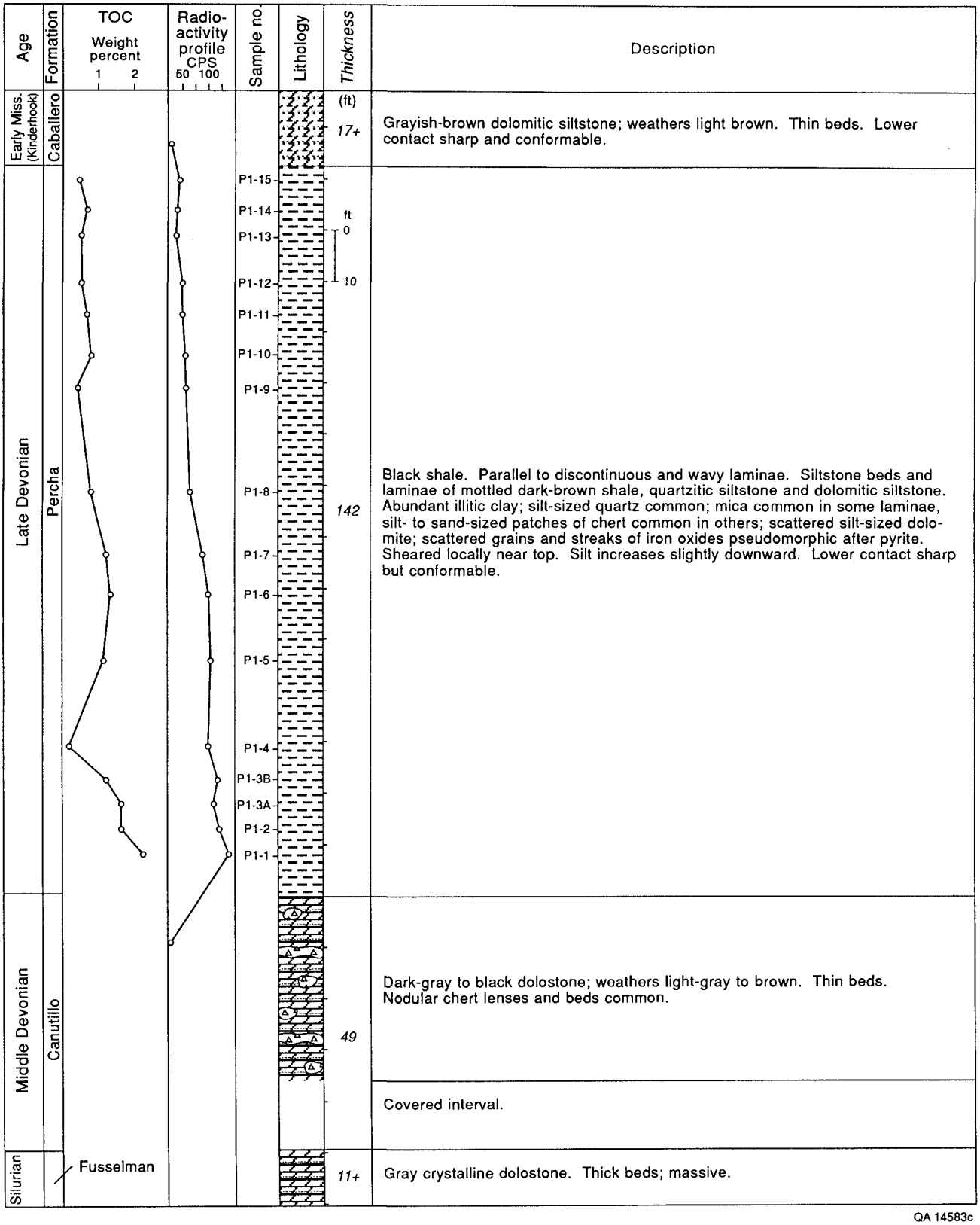
QA 14581c

C13
Humble No. 1 Federal Elliott
Lea County, New Mexico
Section 1, T 16 S – R 34 E
Elevation 4078 ft



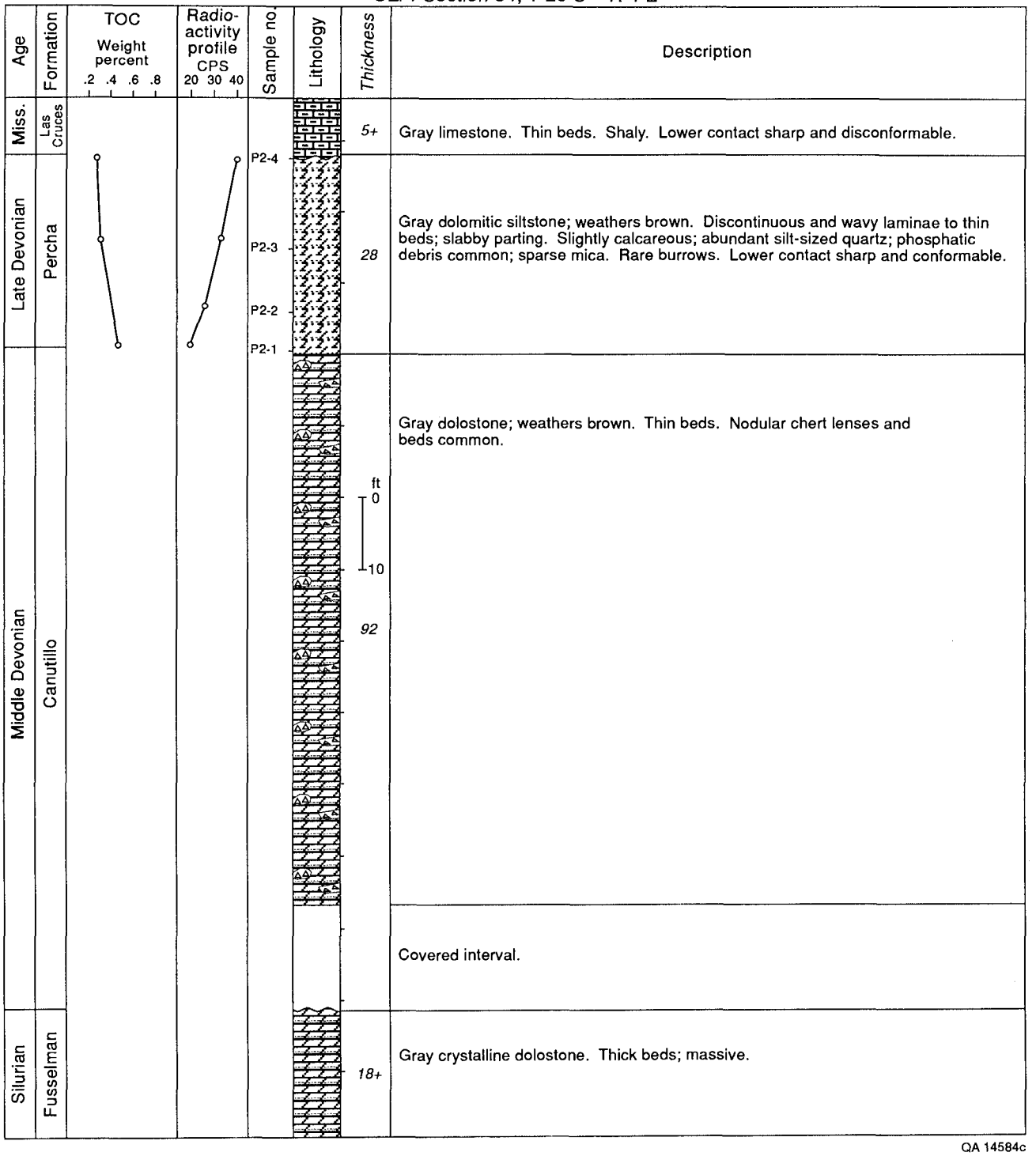
QA 14582c

P1
Bishop Cap
Doña Ana County, New Mexico
NE/4 Section 25, T 24 S – R 3 E



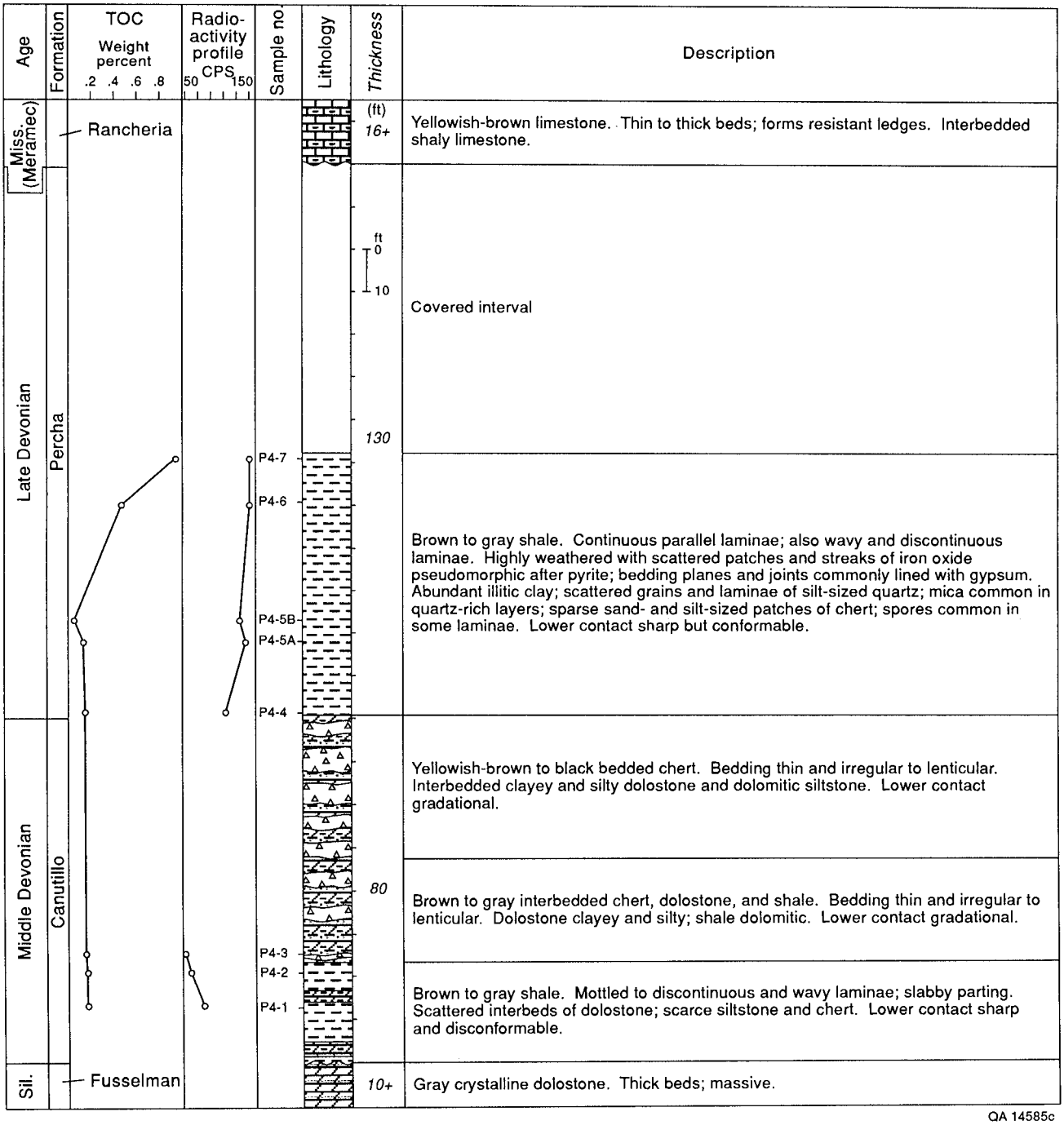
QA 14583c

P2
Anthony Gap
North Franklin Mountains
Doña Ana County, New Mexico
SE/4 Section 34, T 26 S – R 4 E



QA 14584c

P4
Martin Canyon
Hueco Mountains
El Paso County, Texas
106° 00' 30" W. Longitude – 31° 48' 30" N. Latitude



QA 14585c

Appendix C. Point-count data for the Woodford Formation.

Core and sample no.	Depth (ft)	Terrigenous				Pelagic		Authigenic		
		Quartz (%)	Mica (%)	Feldspar (%)	Illite (%)	AOM* (%)	Pellets (%)	Dolomite (%)	Pyrite (%)	Other (%)
BLACK SHALE										
C1–4	11,540	6	3	— **	68	11	—	1	—	—
C1–9	11,555	14	2	1	45	10	—	22	6	—
C2–3	7,172	3	—	—	43	25	4	23	1	1
C2–8	7,181	—	—	1	34	35	5	19	2	4
C3–1	13,754	1	—	—	76	14	5	1	2	1
C3–10	13,884	2	—	—	53	13	—	20	—	12
C4–2	10,899	15	1	1	52	5	8	3	13	2
C4–7	10,933	17	2	2	56	8	—	6	8	1
C5–2	11,639	5	—	—	67	8	11	—	7	2
C5–5	11,648	6	—	—	64	9	2	15	2	2
C6–3	10,924	2	1	—	77	17	—	1	—	2
C7–2	10,176	16	—	—	53	15	3	7	5	1
C8–1	9,033	2	—	—	79	12	—	5	2	—
C9–2	12,228	9	—	—	69	10	—	2	3	7
C10–4	8,502	9	—	—	57	6	—	25	3	—
C12–4	7,404	3	2	—	50	31	7	4	2	1
C13–4	14,626	10	3	1	61	9	—	9	6	1
SILTSTONE										
C3–6	13,772	6	—	—	—	—	—	68	24	2
C5–8	11,662	36	4	2	28	—	—	30	—	—
C10–4	8,502	32	—	—	—	—	—	39	—	29 ***
C11–5	13,033	43	—	1	14	—	—	41	—	2

* Volume percent of amorphous organic matter (AOM) = wt % TOC × 3. The conversion factor, 3, represents the density difference between organic matter and minerals, ~2.5, and a generalized value of carbon in kerogen, 80 wt %, or 2.5/0.8 ≈ 3.

** Less than 1.

*** Fossils, calcite cement, and phosphate.

Appendix D. Organic content of the Woodford Formation.

Core no.	Depth (ft)	TOC* (wt %)	Kerogen morphology	Primary (%)	Recycled (%)
			BLACK SHALE		
C1	11,536–11,555	3.9	Amorphous**	1.14	ND
C2	7,169–7,184	9.0	Amorphous	0.55	0.87
C3	13,745–13,776	2.3	Amorphous	1.44	ND
C3	13,838–13,844	2.9	Amorphous	1.66	ND
C4	10,898–10,936	2.7	Amorphous	1.05	ND
C5	11,639–11,657	3.2	Amorphous	0.79	ND
C6	10,921–10,941	5.1	Amorphous	1.52	2.21
C7	10,174–10,177	4.6	Amorphous	0.68	ND
C8	9,033–9,036	2.4	Amorphous	0.78	1.15
C9	12,219–12,263	3.3	Amorphous	0.92	ND
C10	8,459–8,513	2.2	Amorphous	0.61	0.99
C12	7,401–7,542	6.3	Amorphous	0.54	ND
C13	14,605–14,644	4.2	Amorphous	1.64	ND
P1	Outcrop	1.1	Amorphous	1.92	ND
P3	Outcrop	0.1	Amorphous	NA	NA
P4	Outcrop	0.4	Amorphous	NA	NA
			SILTSTONE		
C5***	11,662–11,688	0.9	Amorphous	0.85	ND
C9****	12,266–12,333	0.7	Amorphous	0.99	ND
C11***	13,026–13,068	0.4	Amorphous	1.32	ND
P2****	Outcrop	0.4	Amorphous	NA	ND

* Data represent mean values of samples in designated depth interval.

** Amorphous kerogen is aquatic, nonterrestrial organic matter that yields oil during thermal maturation (Hunt, 1979; Tissot and Welte, 1984).

*** Quartz-dominated siltstone.

**** Dolomite-dominated siltstone.

ND not detected.

NA not analyzed.

OCC Hearing Exhibit 44 e

Radium in drinking water and the risk of death from bone cancer among Ontario youths

Murray M. Finkelstein, PhD, MD, CM

Objective: To determine whether residents of Ontario who are exposed to radium 226 naturally occurring in drinking water are at increased risk of bone cancer.
Design: A population-based case–control study of records from death and birth registries. Water samples were obtained from residences at the time of birth and of death.
Setting: Ontario.
Participants: All Ontario-born people under the age of 26 years who died of bone cancer between 1950 and 1983. Control subjects were those who died of any other disease matched by age, sex and year of death.
Outcome measures: Radium exposure distributions and estimation of risk.
Results: An association was found between death from bone cancer and exposure to radium at the birthplace residence in concentrations of 7.0 mBq/L or more (odds ratio 1.58, 90% confidence interval [CI] 1.01 to 2.50; $p = 0.047$). There was a statistically significant exposure–response relation ($p = 0.045$). The increase in risk was similar for the main types of childhood bone cancer: osteosarcoma, Ewing's sarcoma and chondrosarcoma.
Conclusions: The estimated risk at these exposure levels is much higher than would be predicted. The association may be spurious, the point estimates of risk may be too high, or risk factors derived from other exposure circumstances may not be valid for exposure to radium beginning in the prenatal period. Should the findings be confirmed, consideration might be given to removing radium from drinking-water sources.

Objectif : Déterminer si les résidents de l'Ontario exposés au radium 226 naturel présent dans l'eau potable risquent davantage d'être victimes de cancer des os.
Conception : Étude cas–témoin, en fonction de la population, d'enregistrements tirés des registres des décès et des naissances. On a obtenu des spécimens d'eau des résidences au moment de la naissance et du décès.
Contexte : Ontario.
Participants : Tous les Ontariens de moins de 26 ans décédés des suites d'un cancer des os entre 1950 et 1983. Les sujets témoins sont ceux du même âge, du même sexe et décédés la même année des suites de toute autre maladie.
Mesures des résultats : Répartitions de l'exposition au radium et estimation du risque.
Résultats : On a constaté un lien entre les décès des suites d'un cancer des os et l'exposition, au lieu de résidence à la naissance, à des concentrations de radium de 7,0 mBq/L ou plus (risque relatif de 1,58, intervalle de confiance (IC) à 90 % de 1,01 à 2,50; $p = 0,047$). Il y avait un rapport important sur le plan statistique entre l'exposition et les réactions ($p = 0,045$). L'augmentation du risque était semblable pour les principaux types de cancer des os chez l'enfant : ostéosarcome, sarcome d'Ewing et chondrosarcome.
Conclusions : Le risque estimé à ces niveaux d'exposition est beaucoup plus élevé qu'on ne l'aurait prédit. Le lien peut être attribuable au hasard, les estimations ponctuelles du risque peuvent être trop élevées, ou les facteurs de risque tirés d'autres circonstances liées à l'exposition peuvent ne pas être valables dans le cas de l'exposition au radium qui commence au cours de la période prénatale. Si les constatations sont confirmées, on pourrait envisager d'éliminer le radium des sources d'eau potable.

Reprint requests to: Dr. Murray M. Finkelstein, Health and Safety Studies Unit, Ontario Ministry of Labour, 7th floor, 400 University Ave., Toronto, ON M7A 1T7

← For prescribing information see page 700

People are exposed to environmental radiation from many sources. With the possible exception of the association between lung cancer and exposure to radon,[1] it has not been possible to demonstrate an increased risk of cancer in populations exposed to elevated levels of environmental radioactivity. Radium is present in soil, foods and groundwater. Isotopes of radium occur naturally, arising as decay products of heavier elements present in soil and rock. The main isotopes are radium 224 (half-life 3.6 days), radium 226 (half-life 1620 years) and radium 228 (half-life 5.8 years). In communities where wells are used, drinking water can be an important source of ingested radium.

Radium is absorbed from food and water in the gastrointestinal tract. Although most is excreted, bone becomes the principal repository for retained radium because of the chemical similarity between radium and calcium. Radium can cross the placenta, and the ratio of radium to calcium in the newborn reflects the ratio in the mother's blood. The limited evidence shows that under conditions of long-term intake the concentration of radium in the body is nearly invariant throughout life.[2]

Information on the health effects of radium comes from extensive studies of ^{224}Ra, ^{226}Ra and ^{228}Ra in humans and in laboratory animals. The most important effects are bone and sinus cancers. A recent estimate of the risk of these two types of cancer from the lifelong ingestion of 200 mBq of ^{226}Ra per day was 9 and 12 cases respectively per million population during a lifespan of 75 years on average.[3] (The becquerel [Bq] is a measure of the activity of a radioactive nuclide. It is equal to 1 disintegration per second. A millibecquerel thus corresponds to one disintegration per 1000 seconds. The older system of units measured activity in picocuries [pCi]; 1 pCi = 37 mBq.)

There have been three attempts in the United States to determine whether populations that drink water containing elevated levels of radium have an increased risk of cancer. In the first study the US Public Health Service and the Argonne National Laboratory[4] studied rates of death from bone cancer in communities in Iowa and Illinois in which public water supplies contained at least 3 pCi/L (110 mBq/L) of radium. In control cities the radium content was less than 1 pCi/L (37 mBq/L). Among residents under the age of 30, there were 25 deaths from bone cancer in the exposed towns and 15 in the unexposed towns (one-tailed test, $p = 0.08$). There was no information about individual exposures, and an association was uncertain because of population mobility.

In the second study, of Iowa towns, no cases of bone cancer were reported.[5] The incidence rates of lung and bladder cancers among men and of breast and lung cancers among women were higher in towns with a ^{226}Ra level of more than 5 pCi/L (185 mBq/L) in the drinking water.

A significant association between leukemia and groundwater contamination with radium was found in Florida.[6] All exposure inferences were based on area assessments, and interpretation of the results was confounded by substantial population mobility.

In 1981 the Ontario Ministry of the Environment conducted a survey of municipal wells to assess the natural levels of radioactivity in deep groundwaters in parts of southwestern Ontario. Radium concentrations in several towns exceeded the Canadian target concentration of 100 mBq/L. A subsequent ecologic analysis indicated that rates of death from bone cancer might be elevated in those counties overlying an aquifer known to contain radium. This article describes an epidemiologic study undertaken to determine whether there was an association between measured levels of radium in home drinking water supplies and an increased risk of death from bone cancer.

Methods

A case–control study was conducted. A computer tape of Ontario death registrations was used to identify people 25 years of age or less who died of bone cancer between 1950 and 1983. This period was chosen because bone cancer is sufficiently rare that a wide time span was needed to increase the sample size. The start point was 1950 because identification data were available in machine-readable form from that point; 1983 was the last year for which such data were available at the time subjects were being identified for the study.

Birth and death certificates of Ontario-born people were abstracted. Each subject was matched, with the use of random numbers, with a control subject who had died of any disease other than bone cancer. Matching variables were birth in Ontario, sex, age and year of death.

A total of 335 matched pairs were identified. Because of the 34-year span over which the deaths occurred, no attempt was made to collect and review pathologic records. Data from the Ontario Cancer Treatment and Research Foundation (OCTRF) concerning people with bone cancer since 1964 indicated that seven of the case subjects did not have primary bone tumours; they and the matched control subjects were excluded from the study. Of the remaining 328 case subjects 270 (82.3%) had an OCTRF file or an indication of surgery or autopsy on the death certificate. This was taken as confirmatory evidence for the diagnosis listed on the death certificate.

Because of confidentiality restrictions pertaining to the use of death certificates, families could not be contacted for exposure information, and drinking water sources had to be determined from documents. The patient's address at the time of death and the mother's address at the time of birth were obtained from the death and birth certificates. For 24 case and 23 control subjects it was not possible to obtain information detailed enough to identify a birthplace sampling site. An additional 21 case and 20 control subjects were born in remote north-

ern locations, which were not sampled for financial reasons. The study population thus consisted of 283 case subjects and 285 control subjects for whom a measurement of the concentration of radium in birthplace water supplies was obtained. Table 1 provides demographic information about the study population.

Water was sampled by the Ontario Ministry of the Environment from 1987 to 1992. The people collecting the samples indicated that they were from the ministry and were performing a survey of water quality; they did not ask about the health status of current or former residents. Individual water samples were collected from residences supplied by wells. Samples from municipal supplies were obtained for residences served by communal sources. When a water softener was present an attempt was made to bypass the softener if it had been installed since the birth of the subject. It was sometimes not possible to obtain samples from the source used by the subject because the well could not be accessed. Frequently a sample was available from a newer well on the property or a neighbour's well, and information was obtained on the depth and location of the target and substitute wells. If the substitute source drew water from the same geologic stratum it was taken to be representative of the target well. If a substitute source was not representative, the sampling result was not used in the analysis and the subject was excluded. The sampling distribution among the study subjects was as follows: target well (263 cases, 263 controls), substitute well sampled on the property (4 cases, 2 controls) and substitute well sampled off site (16 cases, 20 controls).

Water was collected in acidified jugs and analysed by the Radiation Protection Laboratory of the Ontario Ministry of Labour. Neither the people collecting the samples nor the laboratory staff knew the case–control status of the subjects. The samples were filtered, and the radon emanation method was used to measure the ^{226}Ra concentration. The radium isotopes were coprecipitated with barium sulfate, and the barium–radium sulfate was taken up into solution with a complexing agent, basic diethylenetriamine penta-acetic acid. The solution was transferred to a bubbler and aerated to remove all radon 222. After aging for about 3 weeks, the radon was deemanated and transferred to a counting chamber, in which ^{222}Rn and its daughters were counted using scintillation counting techniques. In addition to its internal quality-control procedures and its participation in international laboratory standardization programs, the Radiation Protection Laboratory analysed duplicate samples collected in the field, distilled water samples ("blanks") and samples spiked with a known concentration of radium.

Table 1: Demographic characteristics of people in Ontario less than 26 years of age who died of bone cancer (case subjects) or other types of disease (control subjects) from 1950 to 1983

Characteristic	Group; no. of subjects: Case (n = 283)	Control (n = 285)
Sex		
Male	179	171
Female	104	114
Age, yr		
< 12	59	60
12–18	138	142
19–25	86	83
Year of death		
1950–1964	86	87
1965–1974	94	97
1975–1983	103	101

A radium-exposure value was assigned to each subject based on the sampling result at the birthplace residence. Subjects were assigned to the "reference" category if the radium concentration was less than 7.0 mBq/L; others were classified as "exposed." (Information on how the cutpoint between the reference level and the exposure level was selected is available from the author upon request.) Exposed subjects were further classified into two categories: those whose birthplace water sample had a radium level of 7.0 to 29.9 mBq/L and those whose sample had a radium level of 30.0 mBq/L (approximately 1 pCi/L) or more.

Odds ratios and confidence intervals were calculated and tests for trends and common odds ratios performed from exact analysis of unstratified and stratified $2 \times k$ tables with the use of the EGRET computer program (EGRET Statistical Software, Statistics and Epidemiology Research Corp., Seattle, 1988).

Logistic regression analysis, performed with the EGRET program as well, was used to determine the exposure–response relation with the use of the actual exposure value for each subject. In the first model, only the logarithm of radium concentration was considered as an explanatory variable. Subsequent models allowed for the possibility that the odds ratios would be affected by the matching variables sex, age and year of death.

The null hypothesis was that there is no association between bone cancer and exposure to radium-containing drinking water. Since radium causes bone cancer the alternative hypothesis was that exposure increases the risk of bone cancer. One-tailed p values and 90% confidence intervals (CIs) are thus presented.

Results

Grouped analysis

Overall, 87% of the subjects fell into the reference category. In the exposed category radium concentrations ranged from 7.0 to 160.0 mBq/L (Table 2). The exposed category was subdivided into radium levels ranging from 7.0 to 29.9 mBq/L and those of 30.0 mBq/L or greater.

The mean (and geometric mean) radium levels for the two subcategories were 12.2 (11.4) and 75.5 (66.3) mBq/L respectively.

Radium was present at a level of 7.0 mBq/L or more in the birthplace drinking water of 15.2% of the case subjects, as compared with 10.2% of the control subjects (odds ratio [OR] 1.58, 90% CI 1.01 to 2.50; $p = 0.047$). There was a significant trend in the odds ratio with increasing level of exposure ($p = 0.045$) (Table 2). When the results were adjusted individually for sex, age and year of diagnosis of bone cancer, there was essentially no effect on the odds ratio.

Logistic regression analysis

The risk of death from bone cancer was significantly associated with the level of radium exposure ($p = 0.04$). The functional form of the exposure–response relation was markedly sublinear, with an estimated exponent of 0.28. Sex, age and year of death were not significant factors. A sensitivity analysis, in which subjects (both case and control) in the exposed category were sequentially excluded from the data set, indicated that the results were insensitive to individual exposure values.

Risk by type of bone cancer

Table 3 presents an analysis of risk by type of bone cancer. The odds ratio was elevated for each type. Within the limitations imposed by the small number of cases of each type (particularly of chondrosarcoma) and the correspondingly wide CIs, the increase in risk could be said to be the same for each of the subtypes of bone cancer. There was no increased risk of osteosarcoma for females in the exposed category, but the number of subjects was so small that the difference in risk between the males and the females was compatible with chance fluctuation.

Table 4 shows the association between radium exposure and risk of death from bone cancer when only the control subjects who died of other types of cancer were used as the comparison group. In this case only 5.3% of

Table 2: Exposure status of subjects, by radium level in drinking-water samples from birthplace residence

Exposure status; radium level, mBq/L	Group; no. (and %) of subjects		Odds ratio (and 90% CI*)
	Case	Control	
Reference category			
< 7.0	240 (84.8)	256 (89.8)	1.00
Exposed category			
7.0–29.9	35 (12.4)	26 (9.1)	1.44 (0.88–2.35)†
≥ 30.0	8 (2.8)	3 (1.1)	2.84 (0.81–12.60)†
Total	43 (15.2)	29 (10.2)	1.58 (1.01–2.50)

*CI = confidence interval.
†$p = 0.045$, test for trend.

Table 3: Estimated risk of bone cancer, by type of cancer

Type of bone cancer	Exposure category; no. of case subjects		Odds ratio* (and 90% CI)	Common odds
	Exposed	Reference		
Osteosarcoma				
Males	15	72	1.88 (0.93–3.78)	
Females	5	53	0.80 (0.26–2.22)	
Total	20	125	1.41 (0.80–2.45)	$p = 0.33$
Ewing's sarcoma				
Males	9	64	1.27 (0.55–2.81)	
Females	6	29	1.75 (0.60–4.76)	
Total	15	93	1.44 (0.77–2.64)	$p = 0.73$
Chondrosarcoma				
Males	3	7	3.84 (0.79–15.30)	
Females	0	2	0.00 (0.00–30.90)	
Total	3	9	2.90 (0.64–10.50)	$p = 1.00$
Other (both sexes)	5	13	3.40 (1.15–9.58)	
All	43	240	1.58 (1.01–2.50)	

*For calculating the odds ratios the number of control subjects in the exposed category was 29 (17 males, 12 females), and the number in the reference category was 256 (154 males, 102 females).

the control subjects were in the exposed category, as compared with 15.2% of the case subjects.

Relation between radium exposure at place of birth and at place of death

The focus in this analysis was on exposure to radium at the birthplace residence, because this is deemed to reflect prenatal and early childhood exposure. The address at death was available from the death certificate, but there was no information about the length of time spent at any residence. A water sample from the place of death was available for 550 (96.8%) of the subjects. For 252 (89.0%) of the case subjects and 255 (89.5%) of the control subjects the exposure status (exposed or not exposed to water containing 7.0 mBq/L or more of radium) was the same at both addresses. Eleven case and five control subjects had been exposed at the birthplace residence but not at the deathplace residence. Conversely, 13 case and 14 control subjects were not exposed at the birthplace residence but were exposed at the deathplace residence. These findings suggest that the subjects in the two groups were similar in their mobility patterns.

Risk of cancer other than bone cancer

Since 95 (33.3%) of the control subjects died of cancer other than bone cancer it was possible to examine whether the risk of cancer other than bone cancer was associated with radium exposure. According to the data in Table 4, there was no evidence of an association except between radium exposure and bone cancer.

Discussion

The aim of this study was to determine whether residents of Ontario who are exposed to naturally occurring ^{226}Ra in their drinking water are at increased risk of bone cancer. The case–control design permitted a sampling program of manageable size. The study population was restricted to subjects 25 years of age or less in order to lessen the problem of population mobility. Particular attention was paid to the radium content of the water supply at the birthplace residence, on the presumption that this measurement reflects prenatal and early childhood exposures. If consumption of the radium-containing water continues after birth, the level of radium in the child's bones will remain in equilibrium with that in the water. If the child consumes water with a lower level of radium, irradiation of bone will continue while deposited radium is gradually removed by remodelling. If, in contrast, a child moves from a supply with a low radium level to one with a higher level it may take years for the radium level in the bones to come into equilibrium with the new water source.

The risk of death from bone cancer was elevated among the children whose residences at birth were supplied with water containing a radium level of 7.0 mBq/L or more. There was a trend of increasing risk with increasing exposure. There was no statistical evidence in this study that radium-associated risk was modified by age, sex or year of death.

Osteogenic sarcoma is a well-accepted result of exposure to radium. It has been observed among dial painters[7] exposed to ^{226}Ra and ^{228}Ra and among medical subjects injected with ^{224}Ra.[8] Ewing's sarcoma has not previously been associated with exposure to radium, al-

Table 4: Estimated risk of bone cancer versus other types of cancer and estimated risk of other types of cancer versus nonmalignant diseases

	Exposure category; no. of subjects					
	Case subjects*		Control subjects†		Odds ratio	Common
Variable	Exposed	Reference	Exposed	Reference	(and 90% CI)	odds
Bone cancer v. other types of cancer*						
Males	30	149	4	52	2.61 (0.99–8.45)	
Females	13	91	1	38	5.39 (0.93–117)	
Total	43	240	5	90	3.17 (1.36–8.66)	$p = 1.00$
Leukemia v. nonmalignant disease†	3	34	26	222	0.75 (0.18–2.29)	
Cancer other than bone cancer v. nonmalignant disease‡	5	90	24	166	0.39 (0.14–0.94)	

*Case subjects are people in original case group; control subjects are those in original control group who died of cancer.
†Case subjects are people in original control group who died of leukemia; control subjects are all other subjects in original control group.
‡Case subjects are people in original control group who died of cancer; control subjects are all other subjects in original control group.

though there have been cases reported following radiotherapy for other types of cancer.[9] Among 218 children treated with ^{224}Ra for tuberculosis of the bone osteosarcoma or chondrosarcoma developed in 35, but there were no reported cases of Ewing's sarcoma.[9] Since Ewing's sarcoma is a disease that affects young people it is not surprising that it was not found among the dial painters, who were first exposed to radium as teenagers or adults.

Characteristic chromosomal abnormalities are present in both osteogenic sarcoma and Ewing's sarcoma. Osteosarcoma occurs with high frequency in people who carry a mutant tumour-predisposing copy at the retinoblastoma locus on chromosome 13.[10] Experimental evidence supports the theory that radiation destroys the remaining normal copy of this gene. The gene has apparently been inactivated and grossly altered in a number of cases of osteosarcomas that have no connection to radiation treatment.[10] In Ewing's sarcoma, there is a specific cytogenetic abnormality, a reciprocal translocation between chromosomes 11 and 22: (11;22) (q24;q12). Because of its ability to disrupt strands of DNA the production of translocations is one of the well-known genetic effects of ionizing radiation.

The main strength of this study was its population-based design. Study subjects were all Ontario-born people who died of bone cancer between 1950 and 1983. Cases were excluded only if a sampling location could not be identified or, for economic reasons, the people were living in the remote north. The control subjects were randomly selected from among Ontario-born youths who died of nonaccidental causes. Use of deceased control subjects does not introduce bias if one assumes that (a) exposure to radium in drinking water neither causes nor prevents death from any disease other than bone cancer and (b) there is no association between social factors that are linked to higher risk of childhood death and exposure to radium. These assumptions were supported empirically by the findings that the association persisted when the cancer victims from the control series were used as the comparison subjects and that there was no association between exposure to radium-containing water and any other type of cancer.

Because lifetime residence histories were not available, inferences were based on the results of the sampling at the birthplace residences. Given the metabolism and retention of radium it is plausible that prenatal and early childhood exposures are of prime importance in determining the dose during the first decades of life.

A source of uncertainty is whether the correct water supply was sampled. Because relatives of the subjects could not be contacted, there is no confirmation that the supply sampled was actually the source of the family's drinking water. However, it is expected that the misclassification due to sampling an incorrect water source is nondifferential. Studies of the temporal variability of the activity of radium isotopes in groundwater systems have revealed minimal variation.[11,12]

The association observed in this study was surprising because all of the radium concentrations measured were well within Canadian water-quality guidelines. In addition, the point estimate of risk was much higher than would be predicted from risk factors derived from populations occupationally or medically exposed to radium. There are three plausible explanations for the disparity. First, the observed association may be spurious and not causal. Second, the association may be causal and the point estimates of risk too high, the true risk lying toward the lower end of the confidence interval. Even though we included all cases of bone cancer occurring in Ontario, the power of the study was such that an observed odds ratio of 1.58 was of only borderline statistical significance, and the 90% CI ranged from 1.01 to 2.50. Third, the association may be causal and the risk factors derived from other exposure circumstances not valid for continuous exposure to the alpha radiation of radium beginning in the prenatal period. The results of studies of prenatal obstetric exposure to x-rays and of those involving atomic-bomb survivors suggest that fetuses and young children are more sensitive than older people to the carcinogenic effects of ionizing radiation. Nevertheless, both bone cancer and radium exposure are sufficiently rare that there are still substantial statistical uncertainties about the existence of an association between radium-containing drinking water and bone cancer and the size of the odds ratio.

If the observed association between environmental exposure to radium and an increased risk of bone cancer is real, the implications for public health depend on both the size of the risk factor and the proportion of the population exposed to radium. If 10% is the estimated proportion of the Ontario population exposed to radium and 1.58 is the estimated odds ratio, the population attributable risk[13] is 0.055. In this study 328 people died of bone cancer. Thus, the number of deaths possibly attributable to radium exposure is 18 (5.5%), one death occurring every 2 years on average.

A follow-up study of the association between nonfatal cases of bone cancer and exposure to radium-containing water has been funded. In that study, lifetime-residence histories will be obtained by questionnaire, and a more complete analysis of lifetime exposure will be possible. It is hoped that this next study will confirm or refute the findings reported here.

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Conferences continued from page 561

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Charleston, SC
Program Department, Society of Teachers of Family Medicine, PO Box 8729, Kansas City, MO 64114; tel (800) 274-2237, (816) 333-9700, ext. 4510

Mar. 1–5, 1995: 15th Annual Family in Family Medicine Conference — Taking Care: Healthy Healers, Families and Communities
Amelia Island, Fla.
Program Department, Society of Teachers of Family Medicine, PO Box 8729, Kansas City, MO 64114; tel (800) 274-2237, (816) 333-9700, ext. 4510

Mar. 20–25, 1995: Youth Health Assembly (includes 6th International Congress on Adolescent Health, Youth for Youth Health Conference and 27th Society for Adolescent Medicine Annual Meeting; cosponsored by the Society for Adolescent Medicine and the International Association for Adolescent Health)
Vancouver
Abstract deadline: Sept. 14, 1994
Venue West Conference Services Ltd., 645–375 Water St., Vancouver, BC V6B 5C6; tel (604) 681-5226, fax (604) 681-2503

Apr. 26–29, 1995: Canadian Association of Speech-Language Pathologists and Audiologists
Ottawa
Abstract deadline: Oct. 28, 1994
Linda J. Garcia, CASLPA Conference '95, Programme d'audiologie et d'orthophonie, University of Ottawa, 545 King Edward Ave., Ottawa, ON K1N 6N5; tel (613) 564-9918, fax (613) 564-9919

May 6–10, 1995: 28th Annual Spring Conference
New Orleans, La.
Program Department, Society of Teachers of Family Medicine, PO Box 8729, Kansas City, MO 64114; tel (800) 274-2237, (816) 333-9700, ext. 4510

May 11–14, 1995: American Association for the History of Medicine 68th Annual Meeting (in conjunction with meetings of other history of medicine and health care societies)
Pittsburgh, Penn.
Dr. Jonathon Erlen, 123 Northview Dr., Pittsburgh, PA 15209

Aug. 7–11, 1995: 4th International Congress on Amino Acids
Vienna, Austria
Abstract deadline: Apr. 30, 1995
Dr. Gert Lubec, Department of Paediatrics, University of Vienna, Währinger Gürtel 18, A-1090 Vienna, Austria; fax 011-431-40400-3238