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# Drilling, Tankers, and Oil Spills on the Atlantic Outer Continental Shelf

## Geologic conditions make drilling environmentally preferable to unchecked oil spills from tankers.

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The Atlantic Coast region of the United States is currently the nation's largest consumer of oil, yet it produces almost no oil. This region imports 90 percent of its crude and heavy fuel oils and an increasing share of its home heating oil. Two-thirds of its supply of light petroleum products comes from the U.S. Gulf Coast (*1*). This dependence on energy sources outside the Atlantic region for running the industries and heating the homes of one of the more productive areas of the world is becoming a major economic and environmental concern. Because the expenses of importing oil are continuing to increase, alternative and environmentally safe sources of fuel should be developed nearer the users.

Petroleum production from the Atlantic outer continental shelf could easily serve as an important resource for the energy requirements of the East Coast. In fact, it appears to us that natural gas reserves may exceed oil reserves on the Atlantic outer continental shelf (*2*, pp. 1–98). Natural gas, which is in short supply in the United States, is the more efficient fuel source and much needed on the eastern seaboard. Of considerable interest to those who live or take their vacations along our Atlantic beaches is the fact that petroleum production off the East Coast would prove ultimately safer to the environment than either drilling in other coastal areas of the United States or importing oil in tankers.

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The occasional, but spectacular, oil spills that have occurred during drilling and production have led to the notion that drilling for petroleum is very dangerous. On the Atlantic outer continental shelf, the geology is such that the high pressures which cause blowouts and consequent oil spills on the Gulf and West Coasts are unlikely to occur there. Actually, blowouts are rare even in high-pressure areas (Tables 1 and 2). Since 1953, more than 18,000 wells have been drilled offshore in U.S. waters with only 11 major oil spills (over 5000 barrels spilled). Since 1972 no major oil spills have occurred. In the past 5 years, 102 wells have been drilled on the Canadian Atlantic outer continental shelf without an incident (*3*). In the event that a blowout should occur during drilling on the Atlantic outer continental shelf, far less oil would be spilled from this source than from tanker operations. The largest oil spill from a blowout ever recorded, the 1969 Santa Barbara event, released less than 15 percent of the estimated amount of oil spilled that year from tanker operations. Offshore production and pipelines invariably introduce less crude oil and petroleum products into the environment than do tankers and sources of automotive waste oil (Table 3).

During all stages of drilling and production, well control is a primary concern. The average producing platform has more than 200 surface and subsurface safety and pollution control devices to protect men, equipment, and the marine environment from accidents. This equipment, as well as safe drilling operation procedures, are required by the U.S. Geological Survey which makes periodic inspections and unannounced visits to production platforms to enforce these requirements. Such equipment, much of it activated automatically, permits advance warning of impending dangers, such as high pressure zones, encountered during drilling. Further, each well is equipped with a subsurface safety valve which will halt production in case of surface equipment failure.

Improvements in drilling technology and practice are reflected in the diminishing numbers of drilling accidents which have occurred since 1968. The frequency of production accidents has not decreased as markedly as the frequency of drilling accidents, but this can be attributed for the most part to the fact that current U.S. Geological Survey regulatory requirements do not apply to production facilities and pipelines constructed before the adoption of these regulations in 1972 (*4*).

In this article, we discuss first the geologic conditions which have contributed to spills on the West Coast and Gulf Coast areas and then discuss those which will affect drilling on the Atlantic outer continental shelf. We then describe the dangers inherent in the continued dependence on tanker importation as opposed to offshore drilling on the East Coast. From these data we conclude that the exploration and development of petroleum resources on the Atlantic outer continental shelf would be the preferable alternative to increasing oil imports.

### Predicting Oil Spills from Geologic Conditions

In order to predict the possibilities of high subsurface pressures in the geologically poorly known Atlantic outer continental shelf, we compare and contrast its geologic history to the much better known Santa Barbara, California and Gulf Coast areas. We refer to the geomorphic continental shelf where water depths are conventionally approximately 200 meters or less.

The Santa Barbara oil spill of early 1969 in the Dos Cuadros offshore oil field was apparently caused by inadequate planning for the following geologic conditions: (i) extreme shallowness of most commercial oil reservoirs, (ii) abnormally high subsurface pressures, and (iii) active local faulting (*5*). Very shallow oil fields are defined as those that occur at drilling depths of 200 m or less. This is important because petroleum under abnormally high pressure is difficult to control at very shallow depths. We know of no major oil production at shallow depths unaccompanied by active natural seeps. Further, oil at such shallow depths is usually found in regions of active faulting. Oil seeps are unknown along the U.S. East Coast and no active faults are known in the offshore region. Blowouts during drilling in the U.S. Gulf Coast region have been caused by surprise encounters with abnormally high subsurface fluid pressures. These conditions are not likely to be found on the U.S. Atlantic outer continental shelf.

## Geologic Causes of the Santa Barbara Oil Spill

Folding and faulting of sedimentary strata are usually required to create underground petroleum traps. In the Santa Barbara Channel, newly generated and migrating petroleum is being trapped in large anticlines (domal structures of sedimentary strata) at very shallow depths beneath the sea floor. Faulting accompanies the arching of these anticlines. The faults can provide pathways for loss of drilling fluid during drilling and make difficult the control of subsurface fluids (water, gas, and oil), whose pressures must be counterbalanced by the weight of the column of drilling fluid.

As active faulting and folding continue in a nascent oil field, subsurface fluids are subject to changing pressures. Since oil structures are still forming, subsurface fluids often have not had time to adjust to normal hydrostatic, and therefore predictable, pressures for a given depth. These unstable conditions exist in the Santa Barbara Channel. In spite of active faulting and abnormally high subsurface pressures, however, the record of offshore drilling is good. Before the Santa Barbara oil spill of January 1969, more than 7000 wells were drilled under federal supervision in California, Alaska, and the Gulf Coast without a large oil spill occurring (*5*). Since the oil spill of 1969, federal regulations and supervision have tightened, and oil company technology and engineering have greatly improved. More important is the fact that the geologic conditions that produced the Santa Barbara spill do not exist on the Atlantic outer continental shelf. Consequently, an oil spill of the Santa Barbara type on the East Coast is virtually impossible.

Table 1. Major accidents on the U.S. outer continental shelf from 1953 to 1972 associated with offshore production platforms (*35*, p. 174).

| Offshore platforms | Cause | Date | Amount reported (barrels) |
|---|---|---|---|
| Union "A," Santa Barbara, Calif. | Blowout | 28 January 1969 | 77,400 |
| Shell ST 26 "B," Louisiana | Fire | 1 December 1970 | 52,400 |
| Chevron MP 41 "C," Louisiana | Fire | 10 March 1970 | 30,950 |
| MP gathering net and storage, Louisiana | Storm | 17 August 1969 | 12,200 |
| Signal SS 149 "B," Louisiana | Hurricane | 3 October 1964 | 5,000 |
| Platform, 24 km offshore | Unknown | 20 July 1972 | 4,000 |
| Continental El 208 "A," Louisiana | Collision | 8 April 1964 | 2,600 |
| Mobil SS 72, Louisiana | Storm | 16 March 1969 | 2,500 |
| Tenneco SS 198 "A," Louisiana | Hurricane | 3 October 1969 | 1,600 |

Table 2. Major accidents on the U.S. outer continental shelf, 1953 to 1972, associated with drilling and production (*36*).

| Results | Drilling | Production | Pipeline | Collision with platform | Weather | Total |
|---|---|---|---|---|---|---|
| Number | 19 | 15 | 4 | 2 | 3 | 43 |
| Oil | 0 | 3 | 4 | 1 | 3 | 11 |
| Oil and gas | 2 | 7 | 0 | 0 | 0 | 9 |
| Gas | 17 | 2 | 0 | 0 | 0 | 19 |
| Other | 0 | 3 | 0 | 1 | 0 | 4 |
| Oil spills | 2 | 10 | 4 | 1 | 3 | 20 |
| Oil volume (1000 barrels) | 18.5 to 780 | 84 to 135.4 | 175 | 2.6 | 9.2 to 9.7 | 290 to 1100 |

## Geologic Causes of Oil Well Blowouts Along the U.S. Gulf Coast

Failure to predict and plan for unusually high subsurface pressures on the U.S. Gulf Coast has caused oil spills during drilling. High-pressure zones usually occur at depths between about 2200 and 3600 m (*6*). Sand lenses tightly enclosed in thick shale strata can have pressures that are nearly twice the normal pressures. For abnormally high subsurface pressure to exist, the very thick shale strata must be composed largely of montmorillonite clay. Montmorillonite clay originates from the weathering of volcanic ash in arid climates (*7*). The arid and semiarid Rocky Mountain region of the United States witnessed intervals of volcanic activity many times in the past 150 million years. An ancestral Mississippi River carried montmorillonite clays in great quantity to the Gulf Coast region. Since water adheres to montmorillonite clay crystals, strata with a large component of montmorillonite clay do not compact by normal loading as do other nonmontmorillonite clay strata. Since water cannot easily escape, and since the desorption of water is a continuing process, excessive pressures build up and are maintained for long time periods (*8*).

Fortunately, high-pressure zones can be predicted and planned for so that the chances of a blowout can be nearly eliminated (*9*). No blowouts have occurred during drilling in the U.S. Gulf region in the past 5 years, and this achievement in drilling safety can be attributed both to the techniques that have been developed by geologists and seismologists for locating some high-pressure zones before drilling begins (*10*), and to advances in oil industry drilling technology for detecting and controlling potential blowouts.

These improvements in prediction, detection, and control of high-pressure strata make drilling in difficult regions, such as the Gulf Coast and the Santa Barbara Channel, much safer than in 1969. Moreover, when applied to the geologically safer Atlantic outer continental shelf, the possibility of a blowout is nearly eliminated.

## Subsurface Pressures on the Atlantic Outer Continental Shelf

It is highly improbable that the geologic conditions necessary to generate high pressures have ever existed on the Atlantic outer continental shelf. Although few actual subsurface pressure measurements have been made in the area, at the Esso Hatteras Light Well in North Carolina, normal pressures were recorded at 2000 and 2200 m (*2*, pp. 59–60).

The origins of high pressures in certain areas, particularly the Gulf Coast region, have been investigated for many years (*6, 11, 12*). High pressures can be created in several ways, but the maintenance of these pressures for long periods of geologic time requires that high-pressure zones be enclosed within thick shale strata of very low permeabilities. In the Gulf Coast region, this pressure sealing is achieved where thick, impermeable shale strata surround the high-pressure zones. These thick, clay shales had to be present at the time the high pressures were generated.

High fluid pressures are usually attributed to the desorption of interlayer water during the conversion of the clay mineral montmorillonite to illite (*6, 12*). In this process, adsorbed interlayer water moves outside the clay crystal lattice to become pore water at temperatures of about 94° to 116°C. In a sedimentary basin with a normal geothermal gradient (increasing temperature with depth) these temperatures are reached at depths of 1800 to 3600 m. As water is desorbed from the clay crystal, a volume increase in the shale strata occurs by an increase in the amount of void space between clay minerals because of the intrusion of the desorbed water. Since water at these temperatures and pressures is virtually incompressible, the clay particles are pushed apart. The total overburden load of sediments is thereby partly transferred from a state of particle loading to a state of fluid loading. That is, the normal stress decreases as the fluid pressure increases (*13*).

These excess pressures cannot be maintained unless shale strata permeabilities to fluids are extremely low. Thus clay-shale strata must already have low permeabilities due to compaction before the desorption of water takes place. The loss of permeability during compaction in thick clay shales could, by itself, cause high pressures (*14*). However, when abnormally high subsurface pressures exist, the thick enclosing shales are rich in montmorillonite clay. Further, high pressures can only occur if permeable layers of sand or limestone are not interlayered with the thick shales. Excess pressure will not last if permeable strata of sandstone or siltstone are interlayered with clay shale strata because permeable strata are conduits for fluid escape. Consequently, for dangerously high subsurface pressures to exist along the Atlantic outer continental shelf, thick strata of montmorillonite-rich clay must have been deposited without interbedded permeable strata. We suggest that the likelihood of such deposition is extremely small because the area drained by rivers of the U.S. Atlantic coast has had a humid climate and no volcanism in the past 150 million years. Studies of recent sediments have shown that little montmorillonite is present (*15*). Therefore, we conclude that the Atlantic outer continental shelf has never had a large and constant source of montmorillonite clay.

Additional data from recent drilling in the outer continental shelf and from onshore studies of strata that project into the outer continental shelf (*16*) enable us to predict with some confidence the prospects for abnormal subsurface pressures. Drill cores taken by the Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES) during drilling along the Florida coast showed that montmorillonite was the most abundant clay mineral (*17*). However, the total amount of clay compared to other sediments in most cores was very small. The principal minerals were carbonates. Individual beds of montmorillonite-rich clays were only a few centimeters to a few meters thick and therefore too thin to develop high pressures. Montmorillonite is also the main clay mineral in Cretaceous strata (about 100 million years old) that outcrop in the Cape Fear region (*18*). Montmorillonite apparently is carried by the Gulf Stream from the Gulf of Mexico to the Atlantic outer continental shelf but in quantities too small to produce thick clay strata. Clay minerals found in the Pleistocene and Recent sediments on the New England continental rise (Georges Bank area) are mainly illite, chlorite, and kaolinite (*19*). These clays do not develop high pressures.

Other studies of recent sediments along the U.S. Atlantic coast have revealed montmorillonite in estuaries and bays (*20*). Quantities (thickness and areal extents) of these clays are unknown. Again, the source of montmorillonite is the Gulf Stream which appears to transport montmorillonite in suspension from the Gulf of Mexico along the U.S. Atlantic coast. The Gulf Stream undoubtedly transported montmorillonite in the geologic past, but how much and for what time periods is unknown. More important, however, is an assessment of the possibility that thick layers of clay were deposited. Nearshore marine sediments of the Florida east coast contain 50 percent montmorillonite while those of the Carolinas contain 35 percent (*21, 22*). However, along the Atlantic coast, clays show a net shoreward transportation by bottom currents (*23*). Consequently, montmorillonite will be more abundant in nearshore estuarine sediments than in offshore marine sediments. Thus, *thick* strata of mostly montmorillonite likely to contain high pressures should be rare because the amount of clay reaching the Atlantic outer continental shelf and the rate at which it is deposited on the sea floor is probably small compared to other sediment input. In fact, the prospects for petroleum entrapment may be reduced because thin and discontinuous shale beds may provide inadequate seals around potential reservoir strata (*2*, pp.

Table 3. Sources of crude oil and petroleum products introduced into the ocean each year (1 metric ton equals about 7 barrels) (*37*).

| Source | Amount (metric tons) |
|---|---|
| *Tanker operations* | |
| LOT* cleaning and ballasting | 84,499 |
| Non-LOT cleaning and ballasting | 455,708 |
| Product tankers using store reception facilities | 19,492 |
| Product tankers not using store reception facilities | 63,832 |
| Ore, bulk, and oil carriers cleaning and ballasting | 119,543 |
| Additional cleaning and disposal prior to drydocking | 91,895 |
| Tanker bilges | 9,573 |
| Tanker barges | 12,787 |
| Terminal operations | 31,933 |
| Total from these sources | 889,262 |
| *Other ship operations* | |
| Bunkers | 9,055 |
| Bilges, cleaning, ballasting | 292,481 |
| Total from these sources | 301,536 |
| *Vessel accidents* | |
| Tankers and tank barges | 124,071 |
| All other vessels | 48,972 |
| Total from these sources | 173,043 |
| *Offshore production* | |
| Total | 118,126 |
| *Natural seepage* | |
| Total | 600,000 |
| *Nonmarine operations and accidents* | |
| Refinery and petrochemical plant waste oils | 195,402 |
| Industrial machinery waste oil | 718,468 |
| Automotive waste oil | 1,034,588 |
| Pipelines | 25,574 |
| Total from these sources | 1,974,032 |
| Overall total | 4,055,999 |

*LOT, load on top, is an oil loading technique which minimizes the disposal of oily water ballast into the ocean.

60–61). During recent drilling on the Atlantic outer continental shelf, JOIDES has not encountered thick clay shale strata. Therefore, we conclude that some montmorillonite clay has been deposited on the Atlantic outer continental shelf during the past 150 million years, but not in sufficiently thick layers to maintain abnormally high pressures.

In summary, we regard the existence of abnormally high subsurface pressures on the U.S. Atlantic outer continental shelf as highly improbable. The difference in geologic history of the U.S. Atlantic coast versus the California coast and the Gulf of Mexico supports this conclusion. Given the unlikely circumstances that such conditions do occur, means of detection exist that will permit proper planning to prevent loss of well control. In the past 5 years drilling technology has greatly improved. Operations in high-pressure areas will be even safer in the future (*24*).

### Oil Spills from Tankers

Increased foreign tanker traffic poses a much greater danger to the marine environment than oil production and transportation from offshore platforms. One of every five ships in the world merchant fleet currently is engaged in transporting petroleum, often with minimal safety regulation. Over 60 percent of the crude oil and petroleum products consumed by the Atlantic coastal states arrives by way of tanker or barge.

Tankers are the source of the highest volume of oil spilled (0.016 percent of the total volume of oil handled); platforms have the lowest volume spilled (0.006 percent) (*25*). Without petroleum production from the Atlantic outer continental shelf, imports of crude oil and petroleum products will increase and the concomitant use of more tankers will increase the number of collisions and accidental and deliberate spills occurring in Atlantic coastal waters.

A larger tanker fleet will increase congestion in the six major oil importing harbors on the East Coast, and cause more accidents. Eighty percent of all accidents occur in coastal or harbor regions (*26*). Terminal spills reported from tankers and barges are very large. In 1971 and 1972 alone, they amounted to over three times the volume of oil spilled from all offshore production facilities including pipelines (see Table 4). The U. S. tanker fleet, engaged exclusively in domestic transport, consists of only 235 tankers which average 30,000 dead weight tons (dwt) (*27*). By 1985, crude oil imports will require an estimated 2700 ships at an average size of 47,000 dwt (*27*). Most of them will be foreign tankers which often operate at the expense of adequate safety regulations. It is now projected that there will be two strandings and one collision or accident for every 50 tanker service years, or an estimated 1100 or more mishaps per year (*26*). With each additional ship, the probability of accidents occurring increases.

The possibility of using larger tankers, or so-called supertankers, to reduce the amount of congestion in harbors presents another set of problems. Supertankers cannot operate within the rules set out in the 1960 International Regulations for Preventing Collisions at Sea. Although cheaper to build and operate per barrel of hauling capacity, supertankers have limited maneuverability and deep drafts; this decreases their ability to avoid collision and running aground. The crash stop distance for a 200,000-ton tanker is approximately 2 miles (3.2 kilometers) or 11 minutes (*28*). During a crash stop, the engines are in full reverse and the ship cannot be steered (*28*). In addition, new port facilities will be required to receive tankers over 80,000 tons.

All tankers, especially the new supertankers, require adequate equipment and qualified personnel for safe operation. Eighty-five percent of all accidents involve some type of human error (*26*). Unfortunately, many tankers are registered with "flag of convenience" states which seek fees for registration but do not control the qualifications of ship personnel or specify necessary safety equipment as a requirement for registration (*29*). State and national authorities can prohibit any ship which does not meet domestic safety requirements from crossing their territorial seas and entering domestic ports. In offshore waters beyond the territorial sea and contiguous zones, however, there is little such authorities can do except report violations to the guilty ship's country—which has exclusive control over violations committed by its ships on the high seas (*29*). An international convention is needed that would specify the design of vessels and equipment, the correct use of navigation instruments, the qualifications of officers and crew, and the maximum speeds for each type of vessel; the use of traffic lanes and pilotage will have to be compulsory before the dangers of oil spills

Table 4. Oil spill statistics (*35*, pp. 91 and 94).

| Spills | 1971 | | 1972 | |
|---|---|---|---|---|
| | Number | Volume (barrels) | Number | Volume (barrels) |
| All spills | 7,461 | 205,028 | 8,287 | 517,674 |
| Noninland, petroleum industry spills | 4,023 | 150,535 | 4,028 | 141,297 |
| Terminal | 1,475 | 125,807 | 1,632 | 54,686 |
| Tanker and barge | 917 | 61,595 | 912 | 19,938 |
| Refineries | 167 | 52,319 | 172 | 824 |
| Bulk storage transfer | 391 | 11,893 | 548 | |
| Ships (offshore) | 22 | 388 | 32 | 51,638 |
| Offshore production facilities | 2,452 | 15,598 | 2,252 | 5,702 |
| Offshore tower | 1,087 | 2,801 | 2,211 | 5,517 |
| Offshore pipelines (within 3 mile limit) | 1,204 | 12,283 | 36 | 174 |
| Offshore pipelines (outside 3 mile limit) | 156 | 346 | 5 | 10 |
| Onshore pipeline | 74 | 8,765 | 162 | 29,270 |

Table 5. Major accidents on the U.S. outer continental shelf, 1953 to 1972, associated with offshore pipelines (*35*, p. 174).

| Offshore platform | Cause | Date | Amount reported (barrels) |
|---|---|---|---|
| Louisiana, West Delta | Anchor dragging | 15 October 1967 | 160,000 |
| Louisiana, coastal channel | Hit by tug propeller | 18 October 1970 | 25,000 |
| Chevron MP 299 | Unknown | 11 February 1969 | 7,500 |
| Louisiana, Gulf S 131 | Anchor dragging | 12 March 1968 | 6,000 |
| Louisiana, coastal channel | Equipment failure | 12 December 1972 | 4,000 |
| Louisiana, coastal waters | Leak | 17 March 1971 | 3,700 |
| Texas, coastal channel | Leak | 30 November 1971 | 1,000 |
| Louisiana, coastal channel | Leak | 28 September 1971 | 1,000 |

from foreign tankers can be controlled (*30*).

Estimates of oil spilled from tankers are probably too low. After the reporting of oil spills became mandatory in U.S. waters in 1970, the number of reports increased 400 percent. Unreported spills have been significant because official offshore reports have not included tanker spills occurring in harbors or near terminals, and the Coast Guard's authority for reporting vessels extends only to the 3-mile territorial waters limit (*25*, p. 90).

Ninety percent of the estimated 17 million barrels of oil spilled annually by tankers is spilled deliberately (*29, 31*). The inefficiency of unloading tankers is such that large petroleum residues are not pumped out on delivery of the petroleum product to its ultimate destination. It is convenient for tankers to use seawater to clean and provide ballast in empty cargo tanks (*31, 32*). Oil tankers coming to the United States often take back grain as a return load (*33*). Their tanks must be cleaned prior to reloading. Although this could be done in port, this would hold the ship an extra costly day. A deliberate "accidental" oil spill on the high seas, but sometimes near a U.S. coast, is the solution too often adopted (*33*). If no cargo is to be carried on the return trip, seawater is pumped into cargo tanks for ballast. It, too, must be pumped out prior to reloading with more petroleum. Since the oil residue floats on the ballast water, the oil is discharged together with the seawater.

The dangers of transporting oil from production platforms off the East Coast to land are not great and are certainly less than those of importing more oil via foreign tankers. Since most of the geological formations with a potential for oil production are within 320 km of the coast, new discoveries of oil will probably require pipelines to transport the petroleum to shore. There has been more danger from pipeline breakage in the past than there is likely to be now. All pipelines in less than 60 m of water must now be buried (*4*, p. 65). Such burial minimizes the potential of pipeline breaks from natural and artificial forces. Even in the past, however, pipeline spills were still less than those from tankers [0.011 percent as opposed to 0.016 percent (*25*)]. The largest domestic oil spill resulting from a pipeline break was caused by a dragging anchor which ruptured an unburied pipeline in less than 60 m of water (see Table 5).

International agreements on the regulation of the shipping industry in terms of uniform equipment and safety requirements are extremely difficult to negotiate and appear virtually impossible to enforce. Production platforms and pipelines are stable objects. They do not move from place to place. A surveillance system can be efficiently maintained over their operation, and regulations governing uniform equipment and safety requirements can be easily imposed.

## Conclusion

The geology of the Atlantic outer continental shelf is very different from that of offshore California and the Gulf of Mexico. The potential petroleum structures of the Atlantic outer continental shelf have been buried and sealed with younger sedimentary deposits which are hundreds of meters thick. No faults extend upwards into the sea bed as in the Santa Barbara area and thus no natural oil seeps have been discovered. Unlike the Louisiana area, the Atlantic outer continental shelf does not have the requisite geologic history to produce high subsurface pressures. From a geological perspective, the Atlantic outer continental shelf represents the safest region in domestic offshore waters for the development and production of petroleum resources.

Offshore production on the Atlantic outer continental shelf will take place approximately 30 to 300 km from the coast. To the extent that such production will offset domestic needs for foreign petroleum products, it will cause a decrease in tanker traffic because the oil produced from these fields can be piped directly to shore.

The implementation of tighter safety standards and closer supervision and surveillance by state and federal government officials would diminish any adverse effects of offshore drilling, production, and transportation on the marine environment. These operations should be continually monitored, inspected, and evaluated by both industry and government through each phase of development and production.

Strict supervision and surveillance are possible on offshore operations because development and production facilities are stationary. Even if the transportation requirements of various locations dictated that petroleum be shipped by tankers to onshore refineries, domestic shipping could be the required mode of transport, traffic could be controlled by the use of mandatory sea lanes, and strict standards could be imposed relating to safety equipment, operating procedures, and qualifications of ship personnel.

More than 18,000 wells have been drilled in the offshore waters of the United States and these wells have produced over 7 billion barrels of crude oil and 33 trillion cubic feet ($10^{12}$ cubic meters) of natural gas with few major catastrophes. There is always a potential for oil spills from offshore production that might have a negative impact on the Atlantic marine and coastal environments, but without such production, imports will increase. More than 95 percent of these imports would be carried by tankers with foreign flags essentially outside direct U.S. regulatory control (*34*). Because tankers are the major source of oil spills, we conclude that exploration for and development of petroleum resources on the Atlantic outer continental shelf is the environmentally preferable alternative to increasing oil imports by tankers.

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# Structural Domains of Transfer RNA Molecules

## The ribose 2′ hydroxyl which distinguishes RNA from DNA plays a key role in stabilizing tRNA structure.

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DNA and RNA are the major macromolecules used for the transfer of information in biological systems. They differ from each other principally by the presence of a hydroxyl group on the 2′ position of the ribose sugar in RNA. This systematic difference in the polynucleotide backbone is likely to be related to significant structural and functional differences. DNA is used solely as an information carrier; certain kinds of RNA are also used in this role, including viral RNA and messenger RNA. However, other classes of RNA such as ribosomal and transfer RNA seem to play a significant structural role as well. Ribosomal RNA is believed to form a three-dimensional lattice on which ribosomal proteins are placed in the assembly of the functioning organelle. In the transfer RNA molecule, only the three anticodon nucleotides play a direct role in the transfer of genetic information through their interaction with the three nucleotides in the codon of messenger RNA. Nonetheless, transfer RNA molecules have 74 to 91 nucleotides (*1*, *2*). The vast bulk of these are involved in forming a complex three-dimensional structure whose functional role is only partly understood at the present time. For several years, we have been studying the three-dimensional structure of yeast phenylalanine transfer RNA ($tRNA^{Phe}$). This work has led to an understanding of the three-dimensional conformation of this molecule and to some understanding of the three-dimensional structures of tRNA molecules as a class (*3*).

In this article, we review aspects of the three-dimensional structure of yeast $tRNA^{Phe}$ and, in particular, discuss some of the more recent structural findings, which are based on a refinement of the molecular structure. This has led to the recognition that this tRNA molecule has several domains which essentially repeat certain structural features or motifs. In a striking fashion, the refinement has revealed the critical role played by the ribose 2′ hydroxyl group in stabilizing important features of the folding of the RNA polynucleotide chain in the nonhelical regions of the molecule. This has provided us with some perspective on the manner in which nature has utilized RNA molecules to form complex three-dimensional structures. It is likely that some of these features will be seen in the future as we come to understand the three-dimensional structure of other types of RNA, including ribosomal RNA.

Transfer RNA plays a central role in protein synthesis. An amino acid is attached enzymatically to the 3′ end of the molecule, which then enters the ribosome and forms a specific interaction with a codon base triplet of messenger RNA. The growing polypeptide chain is transferred to the amino acid, and the complex of messenger RNA, tRNA, and polypeptide chain is moved to an adjacent site in the ribosome. The polypeptide chain is then transferred to the amino acid attached to a subsequent tRNA which has entered the ribosome, and the original tRNA is released from the ribosome. We would like to understand the molecular basis of these key events in the expression of genetic information.

In 1965, Holley *et al.* (*4*) sequenced the first tRNA and noted that it could be folded into a cloverleaf arrangement in which the stem regions contained complementary bases. Since then, the sequences of some 75 different tRNA molecules have been determined (*1*, *2*) and all of them can be organized into this same general cloverleaf folding, which is illustrated for yeast $tRNA^{Phe}$ in Fig. 1a (*5*). From these results has come an awareness that a large number of the positions in the cloverleaf sequence are occupied by constant or invariant nucleotides (en-

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