Reports

Oil and Gas in Offshore Tracts: Estimates Before and After Drilling

Abstract. *Estimates of volumes of recoverable hydrocarbons underlying offshore tracts are made by the U.S. Geological Survey prior to the sale of leases and after drilling on those leases. Comparisons of these estimates show a moderate positive correlation and no evidence for relative bias, although the precision of the predictions is quite limited.*

The ability to evaluate the oil and gas potential of specific tracts of land prior to drilling is useful for developing rational exploration strategies under conditions of capital constraint. Prior to the sale of leases on the federal outer continental shelf (OCS) by the Bureau of Land Management (BLM) of the Department of the Interior, the U.S. Geological Survey (USGS) evaluates the resource potential of individual tracts to ensure that the government, representing the national interest, receives fair market value for leases granted on the federal domain. Several years later, after leasing, drilling, and some experience with production, it is possible to estimate proved reserves (*1*) with some reliability. Presale estimates of recoverable resources and postdrilling estimates of proved reserves each made independently by USGS personnel, exhibit a moderate positive correlation with very high statistical significance for those tracts on which oil and gas have been found and for which data are currently available.

The presale evaluation process conducted by the USGS consists of three parts: (i) a geologic evaluation of the potentially recoverable resources of each structure underlying the tract; (ii) an assessment of the risk that, for whatever reason, hydrocarbons are not in fact present in quantities foreseen as a result of the geologic evaluation; and (iii) an engineering and economic evaluation of the monetary value of those resources, which takes risk into account. The result is an estimate of the expected value of the tract as an independent investment, which BLM uses to determine whether high bids on tracts meet the criteria of fair market value. In this report, we are concerned only with the geologic evaluation of the potentially recoverable resources.

Data available with which to estimate potentially recoverable resources prior to drilling are typically limited to seismic records, stratigraphic tests, and the logs and production histories from wells on leased lands in the vicinity of the tract of interest. Seismic records and stratigraphic test well data are usually acquired under permit by consortia of companies who must submit the data to the USGS; these data are shared with all the companies who pay for them. Thus far, all deep stratigraphic tests have been drilled away from potentially productive structures. Until recently, well data from leased tracts were shared only with the lessees of those tracts, who are required to submit the data to the government (*2*).

Personnel of the USGS began making explicit presale evaluations, tract by tract, in 1968. At that time, they used available data to make their best single-value estimates of all the parameters used in the appraisal, which was based on standard principles of petroleum geology and engineering. Beginning with sale 30 in December 1972, probability distributions for a number of the more important geologic parameters were used in parallel with single-valued estimates as a test of methodology, and probability distributions of recoverable resources were calculated by Monte Carlo techniques (*3*). Beginning with sale 33, Monte Carlo techniques have been used exclusively in presale evaluations. The expected value determined from the probability distribution of recoverable resources is taken as the resource potential of a tract.

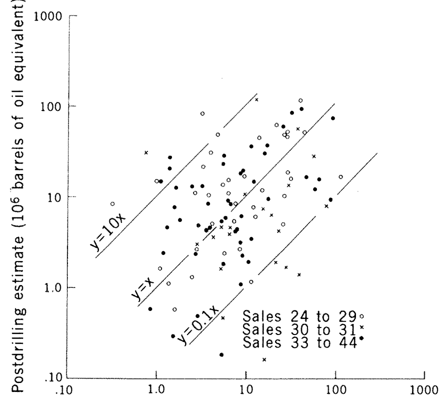

Fig. 1. Presale and postdrilling estimates of recoverable hydrocarbons for 108 tracts on the federal outer continental shelf.

Proved reserves may be estimated by standard techniques only after drilling has discovered economically recoverable oil or gas, or both. The USGS personnel use well logs, the results of core and pressure tests, and production records to estimate reserves. Under existing regulations, these data are submitted to the government by the operating companies. As more data become available through production experience, reserve estimates generally become more reliable.

Until recently, the USGS did not systematically make detailed estimates of proved reserves by tract. Beginning in 1975, however, the USGS began making independent estimates by reservoir and field for all OCS fields. These estimates are now being compiled in a field and reservoir reserve estimate (FRRE) file (*4*). Thus far, proved reserves have been estimated from available data for 108 tracts for which presale estimates of potentially recoverable resources also exist. Because of the time required to prove reserves once a tract has been leased, a comparison of presale with current (FRRE) estimates cannot be made for a number of years after the sale.

Figure 1 is a cross plot of the presale and FRRE estimates for each of the 108 tracts in the data set (Table 1). The unit of measure is millions of barrels of oil equivalent (BOE) based on energy content (*5*). Logarithmic scales are used. The tracts are divided into three groups: (i) sales 24 through 29, for which single-value inputs to deterministic equations were used; (ii) sales 30 and 31, for which both the deterministic analysis and a probabilistic method based on distributions for the parameters and a Monte Carlo simulation were used; and (iii) sales 33 through 44, for which the probabilistic method was used exclusively (*6*). Data are not available for more recent sales for which leases are currently being drilled.

If the presale and postdrilling estimates were in perfect agreement, all the points in Fig. 1 would lie along the central diagonal line ($y = x$). It is evident

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from the figure that there is a large amount of scatter; the great majority of points fall within a band defined by a factor of 10 above and below the central diagonal. However, without further analysis it is not evident whether any significant correlation exists, or if there is any tendency for presale estimates to be biased with respect to postdrilling estimates.

We performed a series of parametric and nonparametric statistical tests on the data of Fig. 1. Tests for correlation included the following: the parametric t-test (*7*, p. 184) based on the Pearson product-moment correlation coefficient calculated directly on the BOE values and on the logarithms of BOE values (*8*); Hotelling and Pabst's test for rank order correlation (*9*, pp. 91–96); and Kendall's test for correlation (*9*, pp. 284–287). The latter two tests are independent of the logarithmic transform. Tests for bias in presale versus postdrilling estimates included the following: matched-pair t-tests (*7*, pp. 91–96) based on BOE values and on the logarithms of BOE values; Wilcoxon's signed rank test (*9*, pp. 96–103) based on difference scores of BOE values and difference scores of logarithms of BOE values; and the sign test for median difference (*9*, pp. 170–174). All tests were performed on four groupings of data: all 108 points, the 38 points from sales 24 through 29, the 21 points from sales 30 through 31, and the 49 points from sales 33 through 44.

Strict application of statistical methods on these data is hindered because the tracts were not selected at random, nor are the estimates for tracts in all cases independent. Rather, the sample represents a census of all tracts for which both presale and postdrilling estimates are currently available, including some tracts that are adjacent to each other and cover parts of the same fields. No tracts for which both estimates are available were excluded from the sample, however, and we have no reason to suspect that the sample is biased. Moreover, the range and distribution of resource volumes appear to be representative for discoveries on such tracts; the number of tracts having common fields is not large compared to the sample size; and the degree of dependence between estimates for such tracts is limited because the geologic structures in the Gulf of Mexico are typically very complex and highly faulted. For these reasons, we believe that the results of the statistical analyses are representative for the leases issued in the time period studied.

The results of the statistical analyses are summarized as follows. Except for the data of sales 30 and 31, there is a highly significant positive correlation between the presale and postdrilling estimates (sample correlations in the range .3 to .5) and no significant evidence to reject the hypothesis that the presale estimates are unbiased with respect to the postdrilling estimates. For the data of sales 30 and 31, however, the estimates do not show significant correlation, and the presale estimates are significantly higher than the postdrilling estimates.

Table 1. The date of the sale and the number of tracts in each sale included in our data set.

Sale	Date	Number of tracts
24	14 January 1969	1
25	16 December 1969	7
26	21 July 1970	6
27	15 December 1970	20
29	12 September 1972	4
30	19 December 1972	19
31	19 June 1973	2
33	28 March 1974	24
34	29 May 1974	3
36	16 October 1974	13
38	28 May 1975	3
38-A	29 July 1975	2
35	11 December 1975	3
44	16 November 1976	1

Of the 36 tests performed, only one was inconsistent with these conclusions. This exception resulted from the matched-pair t-test on BOE values for sales 30 and 31, where the test failed to reject the hypothesis that the presale estimates were unbiased with respect to the postdrilling estimates. The other four tests for bias for sales 30 and 31 resulted in rejection of this hypothesis at least at the .05 level, with the consistent result from all five tests that presale estimates were higher than postdrilling estimates.

On balance, it appears as if the data for sales 30 and 31 (*10*) are not representative of those for earlier or later sales. We attribute some of this peculiar behavior to the fact that the presale estimates in these cases were made during a period of transition from a familiar, deterministic method of evaluation to a probabilistic method which was unfamiliar to many of the resource specialists who were carrying out these evaluations. We can devise plausible arguments to explain the apparent tendency to overestimate resource volumes in the presale evaluations in this circumstance, but we are at a loss to explain the apparent lack of correlation.

We are not aware of other published data that compare geological predictions of potentially recoverable resources made prior to drilling with estimates of reserves made subsequent to discovery. The estimates made by the USGS for oil and gas in OCS tracts, both prior to leasing and after drilling, employ state-of-the-art techniques and all available data. Comparison of estimates indicates a moderate positive correlation between the predicted volumes and the volumes discovered when hydrocarbons were found to be present. There is no statistical evidence of bias. Even so, available data indicate that the ability to predict the volume of recoverable resources under OCS tracts (if any is discovered) appears to be limited to within a factor of 10 (Fig. 1).

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References and Notes

1. *Principles of the Mineral Resource Classification System of the U.S. Bureau of Mines and U.S. Geological Survey* (Bulletin 1450-A, U.S. Geological Survey, Washington, D.C., 1976).
2. Regulations adopted in 1976 require data from wells on federal leases be made public 2 years after they are submitted (30 CFR 250.97).
3. J. M. Hammersley and D. C. Handscomb, *Monte Carlo Methods* (Methuen, London, 1964).
4. F. T. Bryan and J. H. Knipmeyer, *Estimated Oil and Gas Reserves, Gulf of Mexico Outer Continental Shelf, January 1, 1976* (Open-File Report 77-71, U.S. Geological Survey, Washington, D.C., 1977).
5. One million barrels of oil occupy 159,000 m^3 and contain energy approximately equivalent to 6×10^{12} Btu or 6.3×10^{15} J.
6. Both methods were used for sales 30 through 32 to test the correspondence between methods. By the time of sale 33, USGS geologists and engineers had gained enough experience and confidence in the probabilistic method to use it exclusively. Regrettably, direct comparison of the results of the two methods during the transition from one method to the other, sales 30 through 32, is not possible because the estimates obtained from the deterministic equations are not available. The presale estimates from sales 30 and 31 in our data set were obtained with the probabilistic method.
7. G. W. Snedecor and W. G. Cochran, *Statistical Methods* (Iowa State Univ. Press, Ames, 1967).
8. Statistical tests were performed both on the logarithms of the BOE values and on the BOE values themselves for the following reason. The distribution of BOE values is strongly skewed (is long-tailed for high values), a property typical of distributions of in-place mineral resource volumes. The probability levels associated with parametric tests for correlation are derived on the assumption that the observations are samples from a normal distribution, an assumption that is clearly and grossly violated for the BOE values. Moreover, the error terms in the various parameters used in estimating resource volumes (for example, pay thickness, productive acreage, recovery factors) tend to be proportional to rather than independent of the true values; these parameters combine multiplicatively rather than additively, accentuating the dependence of the error component on the resource volume. Using the logarithmic transform greatly reduces the skewness of the sample distribution and converts proportional errors into additive ones, thus improving the validity of the parametric statistical tests. One effect of the logarithmic transform is to give small and large resource volumes equal weight in the analysis, an undesirable feature if the absolute volumes of the discrepancies in estimates is the major interest. Here, however, we are primarily interested in the overall performance of methodologies, which is independent of the actual volumes estimated. Another potential disadvantage of the use of the logarithmic trans-

form is in the interpretation of results: conclusions based on analysis of the logarithms are not necessarily valid for the values. Therefore, we tested both the values and the logarithms. Of the 12 sets of tests performed on both the BOE values and the logarithms of BOE values, in only one instance were the two results different at a 95 percent rejection level (see text).
9. J. V. Bradley, *Distribution-Free Statistical Tests* (Prentice-Hall, Englewood Cliffs, N.J., 1968).
10. Sale 31 contributed only two tracts to the analysis, neither of which was particularly unusual in the same sense as the 19 tracts from sale 30. We therefore caution the reader not to extrapolate our statements about the "transition period" to the entire suite of leases issued in sale 31.
11. We thank J. R. Pearcy, T. G. Crawford, B. S. Dickerson, and J. Hunter of the U.S. Geological Survey, Metairie, La., for their help in compiling data, and G. W. Horton, L. J. Drew, and R. Kasper for their critical comments. Supported in part by USGS contract 14-08-0001-17217.

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Magnetospheres of the Galilean Satellites

Abstract. *The plasma and field perturbations of magnetospheres that would surround magnetized galilean satellites embedded in the corotating jovian plasma differ from those produced by interaction with an unmagnetized conductor. If the intrinsic satellite dipole is antiparallel to that of Jupiter, the magnetosphere will be open. It is predicted that Io has an internal magnetic field with a dipole moment of 6.5 × 10*^{22} *gauss–cubic centimeters antiparallel to Jupiter's, and Io's special properties can be interpreted on the basis of a reconnecting magnetosphere.*

The intriguing speculation that the galilean satellites of Jupiter may possess intrinsic magnetic properties (*1, 2*) gains support from Voyager's photographic evidence of surface activity consistent with a molten interior for Io (*3*). If some or all of the galilean satellites are magnetized, the properties of the magnetospheres that will result from their interaction with the corotating jovian plasma can account for numerous puzzling features of the jovian system in a way that avoids inconsistencies inherent in earlier models of satellite-planet interactions.

In our initial arguments we assume the magnetic moments (M_s) proposed by Neubauer (*2*) on the basis of Busse's (*4*) scaling law. "Bode's law" estimates (*5*) differ by less than a factor of 2. Neubauer's magnetic moments and other parameters needed for the arguments presented here are listed in Table 1. Voyager measurements may change these estimates, but the burden of this report will be unaffected provided the ratio of the thermal plasma pressure to the magnetic pressure and the ratio of flow velocity to Alfvén velocity remain less than 1. Because Pioneer 10 and Pioneer 11 measurements show little departure from a dipole magnetic field in the vicinity of Io and Europa, we are confident that the required conditions are met, at least inside of 10 R_J [R_J (Jupiter radius) = 71,000 km].

Suppose that the dipole moment of the satellite is strictly aligned with that of Jupiter. The satellites are embedded in the jovian plasma. Relative to the more slowly moving satellites, the flow arrives from behind and is diverted by the satellite magnetic field. A closed magnetosphere should form around the satellite as the highly conducting corotating jovian plasma moves by. The total external pressure (P_{tot}) at the nose of the magnetosphere is the sum of the ram pressure, the thermal pressure, and the magnetic pressure (Table 2). The standoff distance, R_m, satisfies

$$R_m{}^6 = \kappa(M_s{}^2/P_{tot})$$

where $\kappa = 1.7$ for Earth's magnetosphere and M_s is the satellite's magnetic moment (*6*). The magnetic pressure dominates or equals the other contributions, at least for Io and Europa (Table 2). This means that the satellite magnetosphere would form a bubble with little asymmetry between upstream and downstream dimensions and with little disruption of jovian plasma in this aligned-moment configuration. We suggest that this occurs at Europa and possibly at Ganymede and Callisto.

The occurrence pattern of jovian decametric radiation (*7*) suggests that Io alone is strongly coupled to the jovian magnetosphere and ionosphere (*8–10*), and this can occur if its dipole is approximately antiparallel to that of Jupiter. As in the earlier case, we focus on an extreme by taking the dipoles to be exactly antiparallel. We now expect a Dungey-type (reconnected) magnetospheric configuration (*11*). This expectation is consistent with the results obtained for the lowest Alfvénic Mach number (M_A = 1.5) flow recently reported for terrella experiments (*12*).

The antiparallel jovian and ionian field lines will extend from Io's ionosphere to Jupiter's. Field lines will be dragged ahead of Io in its orbit and will skew toward Jupiter as their feet in the jovian ionosphere corotate. Stress is transmitted along this extended tail by field-aligned currents. The tail length can be readily estimated. If the electric field imposed across Io's magnetosphere is reduced by a factor ϵ from the corotation field upstream and A is the fractional area of Io with field lines connecting to Jupiter, a straightforward calculation (*13*) yields a length 5.6 A/ϵ in units of Io radii, ϵ measures the efficiency of reconnection and is about 0.1 at Earth. For $A/\epsilon \sim 10$, the tail is 56 r_{Io} long and subtends an angle of 14° ahead of Io. We picture the field moving through the ionian ionosphere and frozen to Jupiter, in contrast with some earlier accounts (*9*). The high conductance of Io's ionosphere (*10*) is not high enough for us to modify this view. The field-aligned current system connecting ionian and jovian ionospheres has an associated magnetic perturbation, δB, that, unlike the main field, is roughly independent of the distance from Jupiter. If δB is constant and azimuthal, we can give an expression for the equatorial trace of Io's flux tube. If χ is the angle between that trace and the radial direction, then tan χ is the ratio of δB to the radial component of the approximately dipolar jovian field and varies with radial distance r (in R_J) as

$$\tan \chi = (\delta B/2B_J)(1 - r/6)^{-1/2}(r/6)^3$$

The skewing of the field toward Jupiter increases rapidly as the flux tube moves inward from Io at r = 6.

The open ionian magnetosphere provides a model which can explain many Io-related phenomena, some of which have been hard to understand until now. First consider Io's ionosphere, whose density profile Kliore *et al.* (*14*) established with Pioneer 10 occultation data. Cloutier *et al.* (*15*) have pointed out the difficulty of understanding how Io's weak gravity (1.8 m/sec^2) can hold an ionosphere against the large electromagnetic ($\mathbf{j} \times \mathbf{B}$) forces produced by ionospheric currents and the ram pressure of the corotating jovian plasma (Table 2). In addition, both the strong day-night asymmetry of the measured ionosphere (Table 2) and the sharp cutoff of the "nightside" or upstream electron density at an altitude of 200 km have been hard to understand.

Our open magnetosphere model readily explains the retention of the ionosphere. The magnetic field of Io shields the ionosphere from the flowing jovian plasma and produces a strongly asymmetric cavity. On the upstream side, which is (fortuitously?) the nightside in the observations, the cutoff of ion density could be the magnetopause. Were this so, the magnetic moment would need to be half Neubauer's value. The observation is suggestive enough that we

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