OIL AND GAS ASSESSMENT

- Methods and Applications -

edited by

Dudley D. Rice

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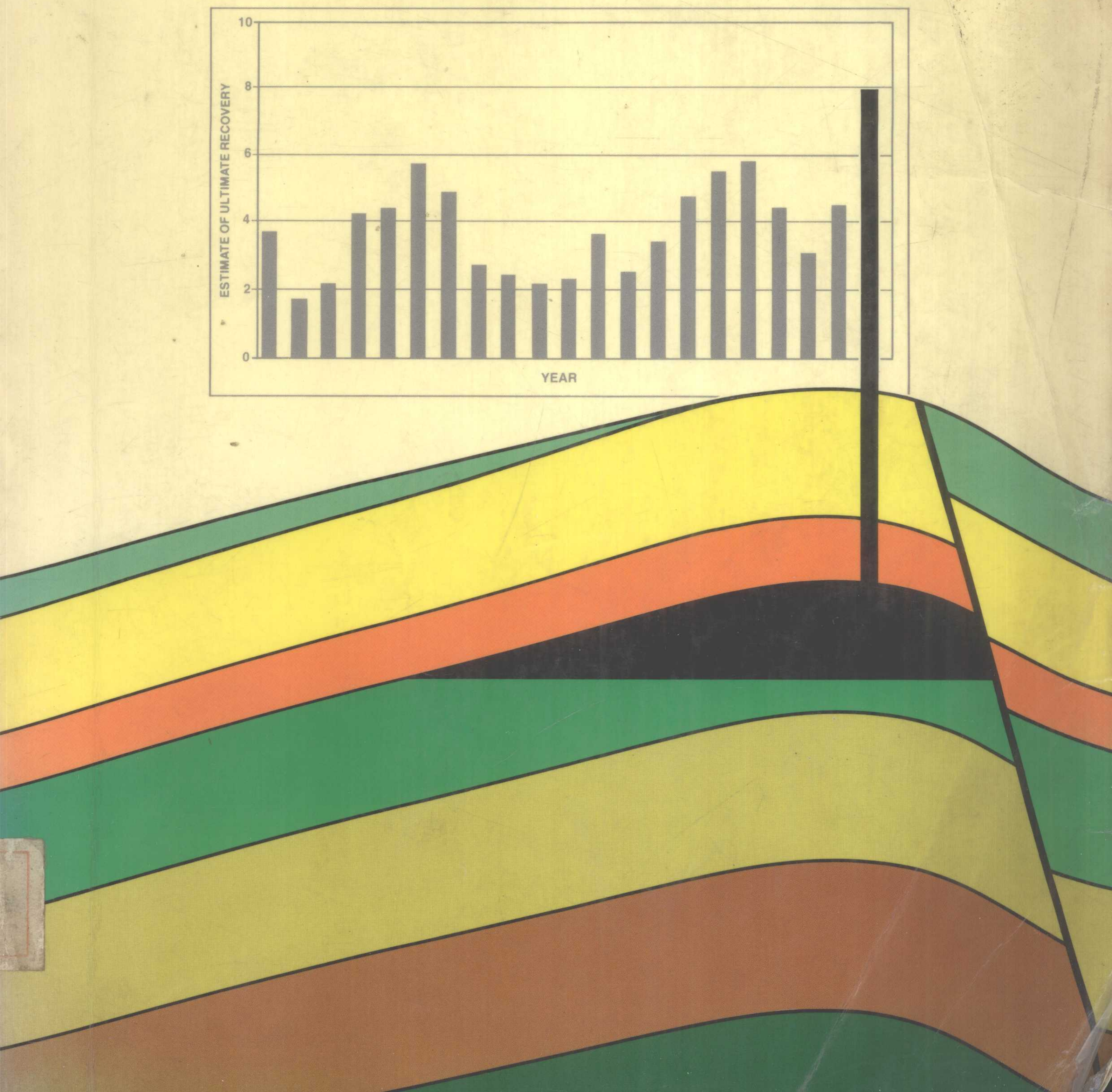

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PREFACE

There is a continual need to update estimates of oil and gas resources remaining to be discovered, and also to refine the methodologies for making these assessments. In 1974, AAPG sponsored a research conference dealing with the above topics. Many of the papers presented at that conference were published in 1975 in AAPG Studies in Geology No. 1, entitled "Methods of estimating the volume of undiscovered oil and gas resources." As a follow-up to that conference and volume, a USGS Workshop on "Oil and gas resource appraisal methodology for the future" was convened in 1983, and a special session for the 1984 National AAPG meeting was held on "Assessment of oil and gas resources." The purpose was to bring together the experts from government, academia, and private industry who were working on assessment of oil and gas resources. Written versions of many of the talks presented at these sessions, in addition to several other papers, are presented in this volume. The papers have been grouped into two types: those describing methodologies for evaluating resources and those presenting assessments of both conventional and unconventional resources.

This volume is the work of many dedicated authors, who were willing to meet deadlines and to make changes suggested by the editors. We thank the technical reviewers for their important contribution to the volume.

Dudley D. Rice
Denver, Colorado
May 1986

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Betty M. Miller
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An overview and critique are presented for five basic categories of resource appraisal methods used to generate petroleum resource estimates during the last three decades: (1) areal and volumetric yield techniques, in combination with geologic analogy; (2) Delphi or subjective consensus assessments; (3) historical performance or behavioristic extrapolations; (4) geochemical material balance techniques; and (5) combination methods using geologic and statistical models (e.g., exploration–play analysis). The results of selected resource estimates are compared from several geographic areas in which different methods have been used. Major issues fundamental to resource assessment discussed are (1) the basic requirements and criteria essential in a systematic approach to the selection of the resource appraisal methods to be used in assessing petroleum resources; (2) a critique of the strengths and weaknesses of the basic resource appraisal methods; (3) the differences among resource estimates that result from different methods being used in the assessments; and (4) the status of resource assessment methodology for the last decade and goals for the future.

A comprehensive analysis is provided for three case studies: nationwide resource assessments for both Canada and the United States and regional resource assessments for the Permian basin of western Texas and southeastern New Mexico. Evidence is presented that suggests (1) that a significant number of the differences among resource estimates result from the use of different appraisal methods, (2) that consistent patterns do occur in the magnitude of the estimates, and (3) that the relative magnitude of the estimates is predictable depending upon the specific method of assessment used.

INTRODUCTION

At the First IIASA Conference on Energy Resources, M. F. Searl, in his referral to the "methodology for assessing resources at the aggregate or macro level," stated: "The methodology of resource assessment is a much neglected topic of research in the United States." He continued: "There have been few systematic efforts at establishing resource assessment methodologies" (Searl, 1975, p. 71). My paper addresses the issue of resource appraisal methodology and whether the situation has shown improvement during the succeeding decade.

There are many methods now for estimating petroleum resource potential and innumerable variations on the basic techniques, each supported by its respective proponents. Each basic method requires a different level of geologic knowledge or degree of available information. For the application of these different appraisal methods, it is also important to consider the needs of the users and the purposes for which the assessments may be used.

To date, all the published methods have recognized limitations and have both strengths and weaknesses. Major problems, however, have arisen because of misinterpretation and misuse of the resulting estimates and because of the lack of recognition by the users (deliberate or not) of the limitations of the methods employed, the assumptions made, or the data used. No single method has universal application or acceptance, and until some petroleum province has been completely explored and completely produced, we will not know definitively the reliability of any of these methods for estimating oil and gas resources.

The purpose of this paper is (1) to compare the results of selected resource assessments from several geographic areas in which different methods have been used, and (2) to answer certain fundamental questions raised. What should an estimator consider in making the selection of a method or combination of methods to conduct an assessment of the petroleum resources of a specified area? What should the user of the resource estimates be cognizant of regarding the inherent limitations of the estimates that result from the methods used in making the assessments? Is there a significant difference in the outcomes of the assessments relative to the selection of the methodology? Has any progress been made since Searl's observations in 1975 toward developing a systematic approach to a total resource appraisal methodology that addresses all basic issues relative to the petroleum potential of a designated area?

First, the basic types of resource appraisal methods referred to in this paper are reviewed, as well as their general data requirements. Second, the considerations that the estimator must analyze and resolve when selecting a resource appraisal method or combination of methods are summarized. Several case studies are analyzed and discussed demonstrating the outcomes of petroleum resource assessments that are significantly dependent on the choice of the resource appraisal method used. I will deal mainly with ideas and approaches to resource assessment problems based on my personal experience while in private industry and with the U.S. Geological Survey (USGS). No attempt is made here at complete coverage of any of the methods.

REVIEW OF BASIC ASSESSMENT METHODS

The many estimates of petroleum resources that have been made in the last three decades fall into five basic categories of methodology. These categories, simplified for classification purposes, are (1) areal and volumetric yield, in combination with geologic analogy; (2) Delphi or subjective consensus assessment; (3) performance or behavioristic extrapolation based on historical data; (4) geochemical material balance; and (5) combinations of geologic and statistical models. The optimum application of each category of methods is shown in Figure 1.

Resource estimates can be made on any level of basic geologic data. The amount of data available, however, can determine the quality of the estimate and should be the primary factor for determining the method(s) that might be used for the appraisal. The chosen methods or procedures may be altered as the amount and nature of the available data change for a specific basin, or if the purpose for the assessment should change.

The selection of resource appraisal methods should be dependent on the degree of geologic assurance at a given stage of exploration within a petroleum province. In the early frontier stages of exploration, when scant information exists concerning the gross interpretation of the basin geology and when the amount of data are minimal, an evaluator, applying the principles of petroleum occurrence from worldwide experience, may make use of subjective judgment to provide a basis for the assumption of whether or not potential hydrocarbons are present. As the data base grows due to increased knowledge accompanying exploration and as the results of geophysical surveys, drilling, and geochemical data become available, methods incorporating more objective data should be utilized. The methods used may evolve to the level of dealing with exploration plays, or they may focus on making estimates of undiscovered prospects. When abundant and detailed data are available, the choice of the method used may become more dependent on other factors, such as availability of the estimator's time, costs and efforts involved, the purpose and use of the resource estimate, and concerns regarding the credibility of the estimates. The credibility of the estimate, however, is dependent on the quality of the geologic data, the studies on which it is based, and the geologic experience and expertise of the estimators.

Areal and Volumetric Yield Methods in Combination with Geologic Analogy

Areal and volumetric yield techniques have been used in a wide variety of ways in making petroleum resource estimates. These techniques range from the use of worldwide average yields expressed in barrels of oil or cubic feet of gas per cubic mile of sedimentary rock, or per square mile of surface area (assuming constant rock thickness) applied uniformly over a sedimentary basin, to more sophisticated analyses in which the yields from a geologically analogous basin have been used to provide a basis of comparison. The pioneer works of Weeks (1950), Zapp (1962), and Hendricks (1965) are illustrative of early techniques (Meyer, 1978; Miller, 1979).

Some highly sophisticated refinements have been made on the basic volumetric techniques that are used in almost all present-day appraisal methods. In fact, close scrutiny reveals very few methods of petroleum resource appraisal that are not in some way, directly or indirectly, dependent on the basic concepts of volumetrics. The few exceptions may be the performance or behavioristic extrapolation methods and some of the purely subjective methods.

Geologic analogy enters into nearly every resource appraisal method. It is the key to the comparative input needed for the volumetric yield techniques. An example of its use was in the 1975 USGS national assessment of petroleum resources (Miller et al., 1975), in which the records of the oil and gas yields from well-explored areas within 75 North American basins were compiled to establish a scale of hydrocarbon yields for geologically analogous basins. The 1972 regional assessments for the provinces of Canada are another example of the use of volumetric yield methods based on a range of representative basin yields (McCrossan and Porter, 1973).

The accuracy of the volumetric yield and geologic analogy methods depends on the validity of the analog chosen before a hydrocarbon yield is selected to make a forecast for the potential of the unexplored basin or parts of a basin. The usual procedure is to select one analogous yield and derive a single value estimate. An approach I favor for this method, however, is the selection of a representative range of analogous basins and their respective yields with probabilities assigned to determine a minimum and maximum estimate for the potential resource. These estimates are made on the basis of the minimum and maximum favorable conditions for the occurrence of petroleum. The results obtained from the volumetric yield method can be useful on a broad regional basis or in a reconnaissance-type estimate of the resource potential, particularly in evaluation of frontier or unexplored geologic areas or as a cross check of resource estimates in areas where other methods have been used.

Delphi or Subjective Consensus Assessment Methods

In the Delphi approach, the estimation of the petroleum resources is the consensus of a team of experts. A group of experts usually reviews all the geologic information available in an area or basin, which sometimes includes detailed geologic basin analyses and the results of any previous

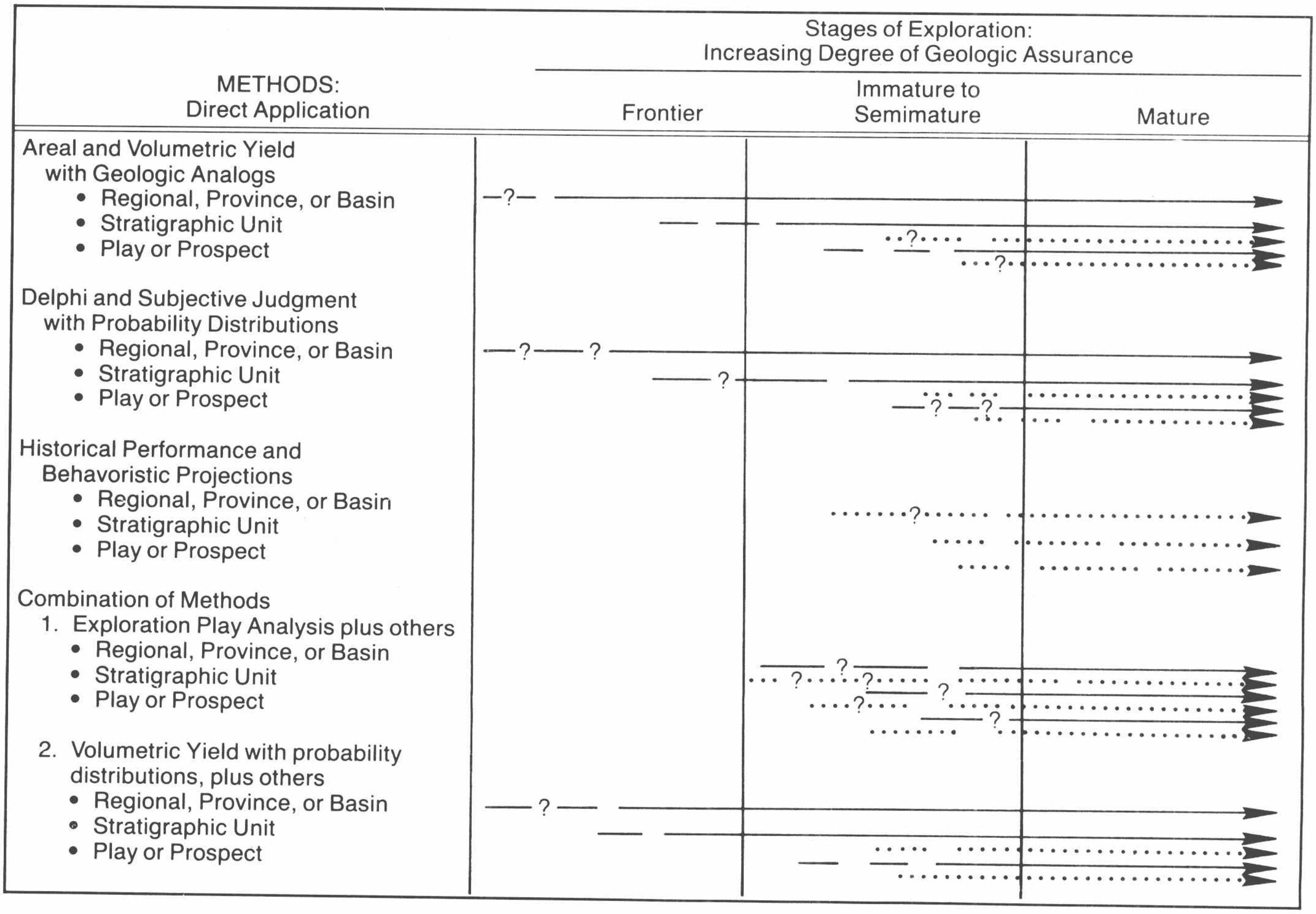

Figure 1. Resource appraisal methods applicable for the various stages of exploration in a petroleum province, given in order of an increasing degree of geologic assurance. Modified from figure 9 of Miller (1983). The solid lines indicate long-term applications and dotted lines short-term applications. Where lines are continuous it indicates that the variations in the resource methods are applicable at different stages in exploration; dashed lines indicate that the application of the methods may generate less reliable estimates at the respective stages in exploration; question marks indicate concern over the application of the method at that stage of exploration with questionable resource estimates.

assessments by other estimators and/or by other methods. Usually each member of the team constructs his or her own probability distribution of the estimated potential resources. The group reviews all the individual results and makes modifications where considered necessary. The final probability distributions are determined either by consensus of the group or by averaging the individual probability distributions (Miller et al., 1975; Dolton et al., 1981). A special National Petroleum Council (NPC) study on the petroleum assessment of the Arctic region of the United States was derived as the consensus of a group of geologists representing over 20 oil companies, a good example of the use of this methodology (National Petroleum Council, 1981).

The main advantages of the Delphi technique are that (1) it can be used at all levels of data availability, from frontier to maturely drilled basins; (2) it is basically a fairly rapid and simple procedure (but dependent on the amount of effort that goes into the compilation of data on the assessed area); and (3) the results can be expressed as probability distributions, which reflect the uncertainties in the estimates. The biggest disadvantage in the method is the lack of documentation of the data input, assumptions, and basic logic that are used throughout the crucial steps of the Delphi process and for the resulting estimates that are reported as probability distributions. One of the major concerns of many estimators and users of these estimates is that "one must know how expert are the experts in order to assess the assessment" (White and Gehman, 1979, p. 2186), This issue is important regardless of the method of assessment being used, but it is rarely addressed in any resource assessment publications.

Historical Performance or Behavioristic Methods

Performance or behavioristic methods are based on the extrapolation of historical data, such as discovery rates, drilling rates, productivity rates, and known field size distributions. Historical data are fitted into logistic or growth curves by various mathematical derivations that extrapolate past performances into the future. These techniques are not directly applicable to unexplored or nonproducing areas or to any area that is not a geologic and economic analog of the historical model. They are generally most applicable to the later stages of exploration in a maturely explored area. Well-known examples of these models are Hubbert's (1962, 1974) growth curve projections; Arps and Roberts (1958) Denver–Julesburg basin study; Moore's (1962, 1966) rate of discovery curves; Kaufman's (1965) and Kaufman et al.'s (1975) field size studies; and the NPC's (1973) projected price and supply studies.

Most published studies to date have based projections of estimated resources primarily on statistical studies of historical data and have purposely included little or no geologic information. This emphasis on historical drilling data and more recently on field size distributions rather than geologic data is due in part to the very large sample areas that generally have been evaluated by this method, such as the entire conterminous United States or other large geographic regions. To improve on finding rate and field size distribution methods so that they can be applied more realistically to resource assessment work, we should use them only in specific cases: (1) where they can be directly related to the geologic settings that control the field size distributions and finding rates; (2) where the area of study is limited to well-defined geologic basins or petroleum provinces or; (3) better yet, where the area is limited to specific stratigraphic units or geologic sections in a basin or province. If the finding rate projections or projected field size distributions were related more directly to the geology of the basin or province, more reliable analog projections could be provided for application to lesser explored and frontier areas. This is particularly true where discoveries and production take place in formations of differing lithologies and trapping mechanisms in a basin.

The major shortcoming of the finding rate and field size distribution techniques for projecting remaining resource estimates is that they can be applied directly only to semimature and maturely drilled producing areas. They are considered to be conservative techniques for estimating resources, because they do not allow for any surprises in petroleum exploration in new areas or plays within a basin or from geologic zones where production had not yet been found previously. They do not allow for improvements in exploration technology or economics. Many classical examples can be cited where new discoveries within an area or basin have completely changed the entire resource assessment outlook for that area. The recent discoveries in the Michigan basin, the Wyoming overthrust belt, and the North Sea are just a few of many examples.

Encouraging developments in the use of performance or behavioristic methods in more recent resource assessment work include the following: (1) efforts to relate the finding rates or field size distributions to the geology of the basins (Ivanhoe, 1976a, b, c; Klemme, 1971, 1983); (2) efforts to evaluate the economic factors relative to finding rates and field size distributions (USGS, 1980); and (3) the incorporation of historical data from analogous geologic basins or producing areas as input into the more detailed resource estimating methods combining geologic and statistical models. The third development will be discussed more fully in the section entitled *Combined (Integrated) Methods*.

Geochemical Material Balance Methods

The geochemical material balance methods are a special type of volumetric resource appraisal procedure by which one can estimate the amount of hydrocarbons generated in the source rocks, the amount of the hydrocarbons involved in migration, the probable losses of hydrocarbons during the migration process, and the quantity of hydrocarbons that have accumulated in the deposits. This approach has been utilized by Russian geologists (Neruchev, 1962; Semenovich et al., 1977), and its use has been illustrated by McDowell (1975).

Although geochemists have made major contributions in our understanding of the processes of hydrocarbon generation (e.g., Hunt and Jamieson, 1956; Philippi, 1956, 1976; Vassoyevich and Neruchev, 1964; Tissot et al., 1971, 1974; Hood et al., 1975; Dow, 1977), much remains to be learned and understood regarding the theory of hydrocarbon generation and the mechanics of hydrocarbon migration in buried strata. This lack of understanding of the major fundamentals of petroleum generation, migration, and entrapment has resulted in limited use of this method in petroleum assessments in the United States. New applications of geochemical methods to quantified hydrocarbon predictions that seem promising are reported by Demaison (1984), Sluijk and Nederlof (1984), Welte and Yukler (1984), Bishop et al. (1984), Ungerer et al. (1984), and Kontorovich (1984). If and when we have a better understanding of these fundamentals, geochemical methods may gain wider acceptance and increased application for assessing large regional areas.

Combined (Integrated) Methods

Combined methods are based on an amalgamation or integration of some or all of the methods that are described above and that incorporate geologic and statistical models. These methods consist of more sophisticated techniques that usually require larger amounts of data as well as more complicated mathematical and computer methods for handling the information. Combining many of the previously discussed methods is becoming the more frequently used approach to resource estimation procedures. The various combinations of methods are too numerous to describe here. For the most part, they involve (1) geologic basin analysis, in which geologic models and basin classification techniques are used; (2) play analysis or prospect analysis techniques; (3) statistical, economic, and supply projection models; and (4) more comprehensive petroleum province analog systems.

Combined methods can range from the simple combination of a performance or behavioristic method (i.e., field size distributions) and a geologic basin classification system (Ivanhoe 1976a, b, c; Klemme, 1983), to the well-documented methodology of the Potential Gas Committee (PGC) (1984) that combines volumetric yields with the estimated probabilities for trap accumulations and risk factors. Combined methods also include the presently popular play analysis or prospect analysis techniques, which may incorporate some or all aspects of the resource appraisal methods discussed above.

I will address only the exploration play analysis methods, which have been designed to assess conventional petroleum resources in identified or conceptual exploration plays in a basin or province (Miller, 1981a). They are usually applied to smaller areas of appraisal than are the previously described methods, areas such as a geologic trend consisting of a reef play or a channel or bar sand. However, many variations of the play analysis definition and the basic assumptions applied to play concepts have been used by resource estimators when applying play analysis techniques. In some studies the play analysis procedure has been applied to an entire stratigraphic unit or geologic zone. Although the resource estimators may call their procedure a "play analysis," the basic concepts are no longer those of the original definition. Thus, there are some extreme variations in the assumptions and resulting estimates used in this method from one assessor to another. The basic techniques, however, require more detailed data than do the volumetric yield methods. The play analysis methods utilize all the data in the field size distribution approach, as well as the additional geologic data on the individual fields within a play, plus the basic information on the reservoir characteristics in these fields.

An estimate of conventional petroleum resources is usually expressed as an equation in a play analysis procedure that relates a series of geologic and reservoir variables to the amount of potential oil or gas within the reservoir. Probability values are assigned to the favorability of a play and to the probable exploration success of the prospects within the play. Most of the geologic and reservoir variables are described by subjectively derived probability functions that are based on the judgment of the estimators; others are described by use of selected analogs. The data formats are commonly designed for computer processing. The estimates of the resource are derived by means of the equation for each play using Monte Carlo methods. The total resource estimate for the area or basin is determined by aggregating the potential of all plays, or all prospects within the plays, also by using Monte Carlo techniques. The estimate is in the form of a probability distribution for the total resource assessment.

The play analysis approach simplifies, or appears to simplify, the task of the geologist in evaluating the resource of an area because it provides a fixed format for the variables he or she must evaluate, and because the actual resource assessment is determined directly by means of a mathematical computation using a computer model. Such sophisticated computerized procedures, however, do not necessarily mean that the accuracy in the resource assessments has been increased over those assessments made by means of other resource appraisal methods.

The following comments are based on events experienced by geologists in the USGS during the application of play analysis procedures to four separate petroleum assessments of the National Petroleum Reserve of Alaska (NPRA) during 1978–1980, and to an assessment in 1980 of the Arctic Wildlife Range of Alaska (Mast et al., 1980; Miller, 1981a, b). Geologists concerned over the results from their input to these programs became increasingly concerned over weaknesses in the assumptions and mathematical manipulations within the computer system. Frequently these systems are designed by technical personnel who are not familiar with the basic concepts regarding petroleum geology (Miller, 1981a). One such weakness in the play analysis model is the assumption that all the variables assessed in each play, as used in the Monte Carlo simulation, are independent. Many of the geologic and reservoir variables are directly correlated. This often creates a conflict for the geologists who are asked to assign the values to each variable and to assign the degree of risk or success for the occurrence of a favorable play and a favorable prospect in that play.

Another area of concern in resource assessment studies is the application of play analysis techniques to frontier areas where limited data are available and where geologists must base their subjective evaluations for the attributes only on comparative analogs. The resulting resource assessment can be only as good as the geologic analogs selected by the geologists, which may or may not match the frontier basin. When the play analysis method is used in a frontier basin, all the potential plays are assumed to have been identified and adequately described. However, after further exploration, even in fairly well-explored basins, many unanticipated resources in unidentified plays have been found. Thus, the initial assessments in those basins were too conservative. In frontier areas where the subsurface geology is little known and highly speculative, the identification and adequate description of all probable plays are often difficult to make, if not impossible (Miller, 1981b).

The current literature shows that applications of the play analysis method range from the fairly simple to the highly sophisticated. Probably one of the most publicized play analysis methods has been that of the Geological Survey of Canada (Canadian Department of Energy, Mines and Resources, 1974, 1977; Porter and McCrossan, 1975; Roy, 1975; Lee and Wang, 1983; Proctor et al., 1984). Play analysis and prospect analysis techniques used by the petroleum industry have been reported by Mobil Oil Corporation and Exxon Production Research (Roadifer, 1975; White et al., 1975; White, 1980; Baker et al., 1984). The applications by the USGS of play analysis to petroleum resource assessments for the NPRA and the Arctic Wildlife Range of Alaska have been published by the U.S. Department of the Interior (1979), White (1979), and the USGS (Mast et al., 1980; Miller, 1981a, b). Additional play analysis concepts were first modified and used by the USGS (Conservation Division) in 1978 for the assessment of presale offshore continental shelf tract evaluations (G. L. Lore, personal communication, 1985).

A SYSTEMATIC APPROACH TO THE SELECTION OF RESOURCE ESTIMATING PROCEDURES

In estimating resources, as in any other technical endeavor, the estimator should make a conscientious effort during the early planning stages of the assessment to review information input, to define the limits of the study, and to consider the purpose of the resource assessment and the nature of the output. These steps should be done before the finally selection of the resource appraisal methods to be used in the study. The estimator should follow a systematic approach to the selection of the resource appraisal methods by reviewing a checklist of the basic requirements and criteria to be considered for the specified project. It is not feasible to develop a complete checklist here of all the criteria an estimator should consider relative to a particular assignment: Some of the key issues that should be a part of such an approach are as follows.

1. Establish the short- and long-term purpose(s) of the resource assessment. Short-term uses may include, for example, projected future supplies relative to price and quantity under short-term time constraints, such as 5–10 years or less; projected supplies under economic and technological constraints; exploration planning purposes; and presale offshore lease estimates. Long-term uses of estimates (> 10 years) may include, for example, long-term supply development; resource base information, with assessments free (as much as possible) of economic, technical, and political constraints; problems of resource exhaustion; and determination of long-range national energy policy.
2. Identify the area to be assessed by defining the area, with boundary limitations, and by determining all levels of knowledge relative to the area (e.g., stage of exploration and history, geologic and geophysical data, well data, field data, and production and reserve data).
3. Set consistent standards of terminology to be used for commodity classifications and reserve and resource classifications.
4. Define, clarify, and establish all basic assumptions to be used consistently throughout study.
5. Establish resources available to the study, including human resources, financial resources, time available to deadlines, computer facilities, and information data systems (field data and well data).
6. Determine the resource appraisal methods that best fit requirements based only on available data considerations.
7. Determine the resource appraisal methods that best meet the purposes of the resource assessment.
8. Determine the resource appraisal methods that are feasible with available human and financial resources under the time constraints imposed on the assessment.
9. Determine which of the resource appraisal methods best meet all the requirements of the assigned resource assessment project.
10. Determine what compromises have to be made in the final selection of the assessment methods.
11. Determine whether a credible resource assessment can be made that will meet the basic criteria for the project.
12. Prepare documentation on all of the above issues.

If the estimator has the freedom to meet the considerations in items 1 and 2 reasonably without having to compromise too much for the probable limitations of item 5, he or she could make a rational selection of resource appraisal methods that would accomplish the specific assignment of assessing the petroleum resources.

The problem for the geologist is how to maximize the input of all available geologic data, personal experience, and the developing knowledge of the fundamental principles that control the generation, migration, and accumulation of petroleum. The purposes to be served by the resource assessment, however, may modify the approach to the assessment procedures. The purposes and methods of a resource assessment developed for short-term uses in the exploration and economic planning of an oil company, for example, are considerably different from those of an organization such as the USGS or the Geological Survey of Canada, which are involved in national assessments of the long-term resource base.

I emphasize that it is just as important for the users interpretating the results of these resource assessments to be cognizant of the criteria, limitations, and purposes that influenced the selection of the assessment methods as it is for the estimator in making the assessments. There is a strong need for clear and complete documentation of the methodology in resource appraisal work. Thoroughly adequate documentation may eliminate a great deal of the misinterpretation and misuse of resource estimates.

Figure 1 is a simplistic guide to the selection of the basic resource assessment methods at various stages of exploration and different levels of knowledge for designated areas. The figure shows selections of the basic resource methods as they relate to stages of exploration for a basin or province, a stratigraphic unit, or a play or prospect and as they relate to either a long- or short-term application. On the basis of my experience in resource assessment work, some methods are better suited and provide more credible results for long-term applications and others are better for short-term applications. Also, some methods are better suited to assessments of frontier and immaturely explored areas, while still others are better for the semimature and maturely explored areas. Each resource estimator should assume the responsibility of a similar exercise for his or her assignment, as demonstrated in Figure 1, to aim for the optimum credibility essential in resource assessment work.

DIFFERENCES REFLECTED IN RESOURCE ESTIMATES DEPENDENT ON METHODOLOGY

In this section, I would like to examine the following question: Is the outcome of the resource asessment significantly dependent on the selection of the methodology?

Comparisons of resource assessments and appraisal methods from published resource estimates during the last four decades or more for any specific area are difficult to make for many reasons. The following are just a few of the basic problems: lack of documentation; disagreement on definitions and terminology; lack of specified boundaries or variations in boundaries for given areas selected by estimators; different areas included for offshore and in varying water depths; differences in commodities included in the estimates; differences in assumptions on geology, economics, and technology regarding recovery efficiency; and different resource appraisal methodology (Miller, 1979; Thomsen, 1979; Dolton et al., 1981).

At the 1979 AAPG Annual Convention, H. L. Thomsen presented the results of a preliminary study comparing 14 different resource assessments for oil in the United States completed in the period 1965–1978. He separated the assessments into three categories according to the basic resource appraisal methods used (Table 1). These three categories of methods were defined as (1) geologic analysis, which assumes that the appraisal is backed by a large amount of pertinent geologic information; (2) volumetric yield methods, which assume that the estimate was made primarily by relating ultimate recovery per unit area or per unit volume of tested areas to untested areas; and (3) projection analysis, which assumes that the primary method involves projection of past experience in discovery and drilling. Thomsen (1979) concluded that, "The most pessimistic estimates are those made by the projection method, the highest are the ones in the volumetric box [category], and the geologic estimates are in between. In my opinion these are probably the best estimates available [referring to the 14 assessments] and when categorized by method, they show a remarkable consistency" (Thomsen, 1979, p. 9).

To answer the question posed above, I have made a comprehensive survey of the literature on oil and gas resource estimates as a followup to Thomsen's work in an attempt to determine whether patterns of differences in resource assessments significantly depend on the assessment methodology used. My objective was to find a series of resource estimates that have been conducted over a period of time on a given area, either by the same group of estimators using different methods or by different estimators using different methods. Three areas were selected for case studies. They are reviewed here as examples that illustrate the complexities in making resource assessments, the difficulties in making comparative studies, and some explanations for the differences among the resource estimates that depend significantly on the methodology used in the assessment. The three studies are the petroleum resource estimates for Canada, the United States, and the Permian basin of western Texas and southeastern New Mexico.

Table 1. Ultimately recoverable crude oil resources (billion bbl) for the United States for selected estimates, 1965–1978.[a]

		Methods Used		
Year	Source	Geologic Analysis	Volumetric Yield	Projection Analysis
1965	Weeks	230[b]	—	—
1965	Hendricks	—	320	—
1968	Inst. Gas Tech.	—	—	225
1970	NPC (AAPG)	259	—	—
1971	Cram (AAPG)	224	—	—
1971	Moore	—	—	188
1972	Theobald et al.	—	517[b]	—
1974	McKelvey	—	423[b] (mean)	—
1974	Mobil	230[b]	—	—
1974	Hubbert	—	—	213
1975	NAS	236[b]	—	—
1975	Miller et al	250	—	—
1975	Exxon	244[b]	—	—
1978	Shell	211	—	—
Averages		236	420	209

[a]The estimates are separated into three categories according to the basic resource appraisal methods used for the assessments. Courtesy of H. L. Thomsen (1979).
[b]Crude oil assumed to be 85% of total liquids.

Assessing Canada's Oil and Gas Resources from 1969 to 1983

Estimates of undiscovered oil and gas potential for Canada have been prepared by the Canadian Petroleum Association (CPA), the Canadian Society of Petroleum Geologists (CSPG), and the Geological Survey of Canada (GSC). The Department of Energy, Mines and Resources in the GSC began an inventory of Canada's undiscovered oil and gas in 1971. The first GSC estimates were published in "An Energy Policy in Canada—Phase 1" (Canadian Department of Energy, Mines and Resources, 1974). Three detailed earlier resource estimates of Canada's oil and gas potential are available for comparison with the GSC 1973 and later estimates (Canadian Department of Energy, Mines and Resources, 1974). These estimates were prepared by the CPA in 1969, the GSC in 1972, 1973, 1976, and 1983, and by the CSPG in 1973. Each of these approaches involved different methods and different data; they are each presented here in some detail.

Canadian Petroleum Association, 1969

Although there had been earlier attempts, the 1969 estimates by the CPA were one of the first published. The method of estimating the potential resources was purely volumetric. It involved multiplying figures representing the volumes of sediment covering eight large regions (each of which included one or more sedimentary basins) by a yield factor in barrels of oil per cubic mile. The yields used were selected as representative of the average for such large heterogeneous regions. The resulting ultimate potential oil resources (expressed in barrels) were multiplied by a conversion factor to give an ultimate potential gas resource in cubic feet. The gas–oil factor was considered to represent the average proportion of gas to be discovered in each region; an average of 6,000 cu ft of gas to 1 bbl of oil was used. The study included the sedimentary volume to a depth of 25,000 ft and, offshore, to a water depth of no greater than 600 ft (Canadian Department of Energy, Mines and Resources, 1974). The results of the study are shown in Tables 2 and 3.

Geological Survey of Canada, 1972

The GSC embarked on a systematic program of estimating the petroleum potential of Canada that was completed by the end of February 1972. The study, which represented the GSC's first departures from a strictly volumetric approach, divided Canada into 32 basins for regional analyses. The volumetric method consisted of the determination of the volume of the sedimentary rocks found in each basin, multiplied by a yield factor, to arrive at an oil and gas potential estimate for each basin. The yield factor for each basin was determined on the basis of knowledge of the basin with respect to a worldwide basin classification scheme. The GSC used a preliminary basin analysis approach for the characterization of each basin. They then used the resulting information to qualify the sedimentary volume and yield factor and initiated the use of a probabilistic approach by determining minimum, maximum, and "best estimate" figures of potential for each basin.

The GSC had confidence in its method, and eventually the process led to the systematic basin analysis, the

Table 2. Comparison of liquid hydrocarbon potential estimates of Canada, crude oil and natural gas liquids (in billions of bbl).

	CPA 1969	GSC 1972	GSC 1973	CSPG 1973A	CSPG 1973B	GSC 1976[a]			GSC 1983[b]		
						90%	50%	10%	High (95%)	Average (50%)	Speculative (5%)
Ultimate recoverable oil potential[c]	120.9	134.4	99.2	85.2	23–98	25	30	43	29.4	49.8	76.7
Estimated cum. production liquid hydrocarbons[d]	4.66	6.413	7.168	7.168	7.168		8.499			12.382	
Established reserves:[e]											
Crude oil	10.495	9.603	9.018	9.018	9.018		7.842			6.433	
Natural gas liquids	1.746	1.575	1.498	1.498	1.498		1.523			1.247	
Total liquids	12.241	11.178	10.516	10.516	10.516		9.365			7.680	
Total discovered liquid hydrocarbon resources	16.901	17.591	17.684	17.684	17.684		17.864			20.062	
Undiscovered liquid hydrocarbon resources[f]	104	117	82	68	5–80	7	12	25	9	30	57[g]

[a]GSC 1976: offshore estimates of continental slopes were not included. Accessible offshore areas included in assessments: Atlantic Shelf south, East Labrador and Newfoundland Shelf to 1,500 ft water depth, and MacKenzie Delta–Beaufort Sea to 600 ft water depth. All other offshore areas were considered inaccessible and not included in assessment.

[b]GSC 1983: maximum offshore water depths include from 660 ft west and Arctic coast, to 1,300 ft for the Labrador and Newfoundland shelves; the Scotian shelf and Georges Banks were included to 4,920 ft and Baffin Bay–Lancaster Sound with an estimated 6,500 ft of water depth.

[c]Ultimate recoverable oil and gas potential includes cumulative production, established reserves and undiscovered resources. All were taken as direct assessments from published reports except GSC 1983. See footnote g.

[d]Estimated cumulative production: all figures for crude oil and natural gas liquids were taken from Canadian Petroleum Association (1982) to report a consistent series of figures. Some figures were not the same as those published in the Geological Society of Canada reports.

[e]The expression "established reserves" is used by the GSC to describe those reserves that, on the basis of identified economic considerations and within a specified time frame, are recoverable with a high degree of certainty from known reservoirs. This does not include discovered reserves in frontier areas that are not fully delineated (Procter et al., 1984).

[f]Calculated undiscovered potential equals the ultimate recoverable oil or gas potential minus the discovered resources (cumulative production and established reserves). All the estimates cited, except the 1983 study, were assessed as the ultimate recoverable potential resource.

[g]Undiscovered potential resources were directly assessed in the 1983 study. Ultimate recoverable potential is undiscovered plus discovered liquid hydrocarbon resources or discovered gas resources.

identification of plays, and the probabilistic curve determination for potential resources used in its 1973 estimates. The GSC results in 1972 did not differ greatly from those of the CPA in 1969 for oil, although there were differences between specific regions. The GSC 1972 gas estimates, however, were considerably higher than the CPA 1969 figures for gas. Areas included for the estimates, however, were different: the CPA 1969 study included only areas in water depths of 600 ft or less, whereas the GSC 1972 (and 1973) estimates included the entire area of the Atlantic offshore continental slope (Canadian Department of Energy, Mines and Resources, 1974) (see Tables 2 and 3).

Canadian Society of Petroleum Geologists, 1973

In the meantime, in 1969, the Canadian Association of Petroleum Geologists, which is now the Canadian Society of Petroleum Geologists (CSPG), was meeting to plan a study of Canada's petroleum and natural gas resources. It was felt that this study would complement the project being undertaken by AAPG for the evaluation of the petroleum potential of the United States. The AAPG study was published as Memoir 15, entitled "The Future Petroleum Provinces of the United States—Their Geology and Potential" (Cram, 1971).

The CSPG study was described by 27 authors and covered approximately 38 sedimentary basins in at least 7 distinct geologic categories. Because of the variations in the approaches to the studies by the different geologists, a complete synthesis of the principal observations of the various contributors and their estimates of the petroleum potential in each of the basins was prepared by McCrossan and Porter (1973). The detailed results of the basin studies and the potential estimates were published by the CSPG in 1973 as "The Future Petroleum Provinces of Canada—Their Geology and Potential" (McCrossan, 1973).

The CSPG released its results of the potential estimates in a press conference in Calgary on March 19, 1973. They were based on a variety of methods, primarily volumetric yield techniques and basin classification systems. Each estimate was based on a sound knowledge of the geology (known at the time) for each basin. Individual estimates were compiled and modified to achieve overall consistency with a basin classification scheme modified from Klemme (1971). This first set of CSPG estimates is given as CSPG 1973A in Tables 2 and 3.

At the 1973 press conference in Calgary, it was reported that there was incomplete agreement within the CSPG

Table 3. Comparison of natural gas potential estimates of Canada (in trillion cu ft).[a]

	CPA 1969	GSC 1972	GSC 1973	CSPG 1973A	CSPG 1973B	GSC 1976			GSC 1983		
						90%	50%	10%	High (95%)	Average (50%)	Speculative (5%)
Ultimate recoverable gas potential	724.8	906.2	782.9	577.5	157–655	229	277	378	301.5	483.9	793.7
Estimated cum production natural gas	17.0	24.948	28.146	28.146	28.146		34.399			56.726	
Established reserves: natural gas	57.833	60.786	61.022	61.022	61.022		78.749			91.464	
Total discovered natural gas resources	74.833	85.734	89.168	89.168	89.168		113.148			148.190	
Undiscovered natural gas resources	650	820	694	488	68–566	116	164	265	153	336	645

[a]See footnotes to Table 2 for further details.

regarding the estimates. Subsequently, in a submission to the Science Council of Canada, dated March 27, 1973, the CSPG presented a second set of figures (reported in Tables 2 and 3 as CSPG 1973B) that were apparently based on an entirely different method. By this latter approach, CSPG attempted to estimate potential volumes of oil and gas in place using 10 and 90% confidence limits. No estimates of recoverable potential were provided. Using recovery factors of 33% for oil and 85% for gas (Canadian Department of Energy, Mines, and Resources, 1974) and applying them to the CSPG 1973B estimates, one has a rough basis for comparison of the potential estimates. This would result in a potential ultimate recoverable oil range of 23–98 billion bbl and a potential ultimate recoverable natural gas range of 157–655 trillion cu ft. These ranges were considered too broad at the time by the GSC to provide a basis for further analysis. However, under the assumption of a 50% probability of occurrence of potential on the order of 61 billion bbl of oil and 406 trillion cu ft of gas, these estimates were less than any of the previous ones. Because the methodology of estimating the resources was not discussed in the CSPG brief and a breakdown of potential areas was not presented, it is not possible to analyze the differences between the two methods or the estimates. More is said later on methods for estimating in-place potential resources.

Geological Survey of Canada, 1973

According to the GSC, their 1973 study was an improvement on their original estimate. It incorporated all geologically conceivable "exploration plays" or groups of "plays" in a given basin, it adopted a probabilistic approach, it compared all new estimates with estimates derived by "volumetric" analysis, and it was based on comprehensive basin analysis studies, including geochemistry and geophysics. Both the GSC 1972 and 1973 estimates included Atlantic offshore slope sediments, and thus they encompassed a greater volume of sediments than in either the CPA 1969 or CSPG 1973 studies.

For the first time, consideration was being given in the methods to the size of the oil and gas pools that would be anticipated with each play. A lognormal distribution was assumed for each play, and the largest pool size for each play was estimated; then an array of pool sizes for each basin was calculated (Canadian Department of Energy, Mines and Resources, 1974). The results of the GSC 1973 estimates are shown in Tables 2 and 3.

A comparison of the estimates for the undiscovered oil and gas potential, as determined by the GSC in 1972 and 1973, show that the 1973 estimates were smaller. The 1973 estimates for oil (but not for gas) were also smaller than the CPA 1969 estimates. Both the oil and gas estimates of the CSPG 1973A and 1973B studies were less than either the CPA 1969 study or the GSC 1972 and 1973 studies. The CSPG 1973B study was the smallest estimate reported through 1973.

Geological Survey of Canada, 1976

In 1975, the Canadian Department of Energy, Mines and Resources (Geological Survey of Canada), through a continuation of its successive basin analysis studies and resource estimating procedures, completed a new assessment of the oil and gas resources for nine regions of Canada. The offshore inaccessible areas were not included in the assessments—these were the continental slopes and rises off the Scotian shelf, Grand Banks, northeast Newfoundland and Labrador shelves, the Baffin Bay shelf and slope, and the Arctic Coastal Plain shelf. The west coast shelf and slope were assessed on the basis of the available data, but the assessments were not included in the calculation of the total Canadian oil and gas estimate as reported in the publication, "Oil and Natural Gas Resources of Canada 1976" (Canadian Department of Energy, Mines and Resources, 1977).

In the GSC 1976 study, the play analysis technique was more clearly defined and documented in the report. All exploration plays were defined in a given area for each basin. The estimate of hydrocarbon potential was expressed by one of two equations: (1) the "volumetric" type, which made use of analogs of the basin, area, or rock unit under consideration; and (2) the "exploration play" equation, which calculated the prospect potential and which was basically a reservoir engineering equation for determining the volume of oil or gas in a reservoir. The volumetric approach was used as a check on the exploration play method, and where few data were available, the volumetric approach was considered the best alternative. The geologic parameters in the exploration play equation were described, where necessary, by subjectively derived cumulative distribution functions based on the judgment of the estimators. These distributions were "risked" by applying marginal and conditional probabilities assigned by the experts for all the equation variables. Pool size distributions were assumed to be lognormal and were generated for each play. This enabled a direct tie-in with economic studies that were to be conducted later by the GSC. The estimates of individual plays within a sedimentary basin were summed by means of a statistical technique known as the Monte Carlo method. The estimates for nine separate geologic–geophysical regions of Canada were then aggregated for a single cumulative probability curve for total oil and total gas. The results of the study are reported in Tables 2 and 3.

Estimates of both oil and gas resources for Canada were substantially lower in the GSC 1976 study than those published in 1973. One of the major reasons stated for the reduction was that the 1976 estimates excluded offshore areas considered to be inaccessible using known industrial technology in 1976, whereas the 1973 estimates included such areas as the continental slopes and rises and the offshore Arctic Coastal Plain. This exclusion was thought by the GSC to be responsible for approximately one-third of the reduction from the 1973 estimate. They reported in the 1976 study that the "decrease also results from the new and predominantly disappointing flow of information that has been generated by exploration in the interim period. Certain of the changes in estimates have resulted from an increased capability to process information and improvements in methodology" (Canadian Department of Energy, Mines and Resources, 1977, p. 4).

Geological Survey of Canada, 1983

In 1984, the GSC published a summary of the "Oil and Natural Gas Resources of Canada 1983," which is drawn from their continuing petroleum resource evaluation program in which the detailed appraisals of individual basins or regions are periodically reviewed. The petroleum resource evaluation activities of the GSC were focused primarily on the undiscovered or potential components of conventional oil and gas resources. Compiled data from the literature and provincial government agency publications on Canada's nonconventional resources were also reported by the GSC (Procter et al., 1984).

The GSC began in 1972 with estimates from rather simplistic volumetric calculations, which have now evolved to what are described in the current study as "a probabilistic methodology conducted at the exploration play level, incorporating both objective data and informed geological opinion. A few years ago, this would have been referred to as the Monte Carlo approach. However, methodology has now advanced well beyond the Monte Carlo stage with more rigorous and more powerful mathematical procedures being incorporated into the system" (Procter et al., 1984, p. 7). In addition to estimates of basin potential, the present operating methodology used by GSC can produce an array of hypothetical pools with attached reservoir characteristics consistent with the input geology and data. Additional information on the probabilistic methods was published by Lee and Wang, 1983.

The GSC publication of 1983 continued to report the estimates in probabilistic terms, although they now expressed a range of values as having a "high confidence" (95% probability), "average expectation" (50% probability), or "speculative estimate" (5% probability), rather than giving values at the 90, 50, and 10% probability ranges used in their 1976 study (Procter et al., 1984, Figure 2.1). The resource estimates included sediments out to water depths of 600 ft in the Beaufort Sea and MacKenzie Delta areas and off the west coast of British Columbia, and to water depths of 1,200 ft on the Newfoundland and Labrador shelf areas. These offshore areas included in this report are comparable to those of the 1976 estimates. The results of the 1983 GSC resource estimates are shown in Tables 2 and 3.

In the 1983 assessments, the "average expectation" for undiscovered liquid hydrocarbons of 30 billion bbl is higher than the average estimate of 12 billion bbl in the 1976 estimate. For undiscovered gas, the 1983 average of approximately 336 trillion cu ft is more than double the 1976 average estimate of 164 trillion cu ft. The major differences between the 1976 and 1983 estimates appear to reflect the enthusiasm generated by the oil and gas discoveries off the east coast and the Beaufort and MacKenzie Delta areas.

The 1983 estimates (just as the 1976 estimates), however, are considerably less than the 1973 and earlier estimates for Canada's undiscovered resources. In light of the continuing decline in Canada's established reserves of crude oil and natural gas liquids (from more than 8 billion bbl in 1976 to 7 billion bbl in 1980 and a slight increase to more than 7 billion bbl in 1982), the estimates for the remaining oil resources reflect that no major changes are expected in exploration concepts. Because of the new offshore discoveries, however, estimates of natural gas reserves continued to increase from 75 trillion cu ft in 1976 to more than 90 trillion cu ft in 1982, and the increase in the gas resource estimates between 1976 and 1983 are consistent with these changes (Figure 2). The maximum (or "speculative estimate") for the undiscovered natural gas resources of 645 trillion cu ft in the 1983 study was influenced by the new gas discoveries and is thus now back in the range of the single value estimate of the CPA 1969 study of 650 trillion cu ft, which was determined by the all-inclusive volumetric yield method.

Results

I have reviewed in some detail the background of the oil and gas resource estimates for Canada, assessed from 1969 to 1983, beause these seven assessments document the evolution of the resource appraisal methods used in these

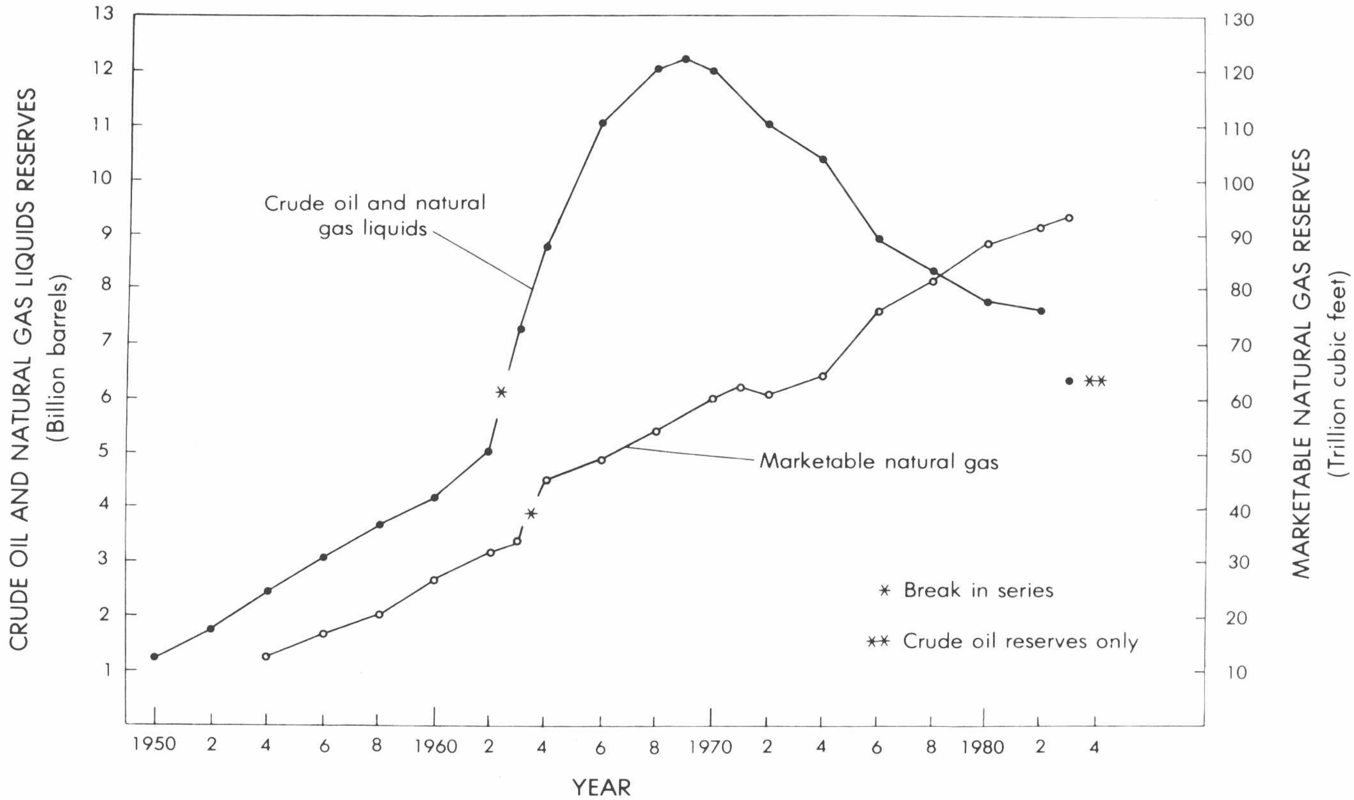

Figure 2. Established petroleum reserves in Canada for crude oil and natural gas liquids and for marketable natural gas. Source of 1950–1982 data was CPA (1982) and of 1983 data, Oil and Gas Journal (1984).

estimates and the actual exploration in Canada that took place during this period in the offshore and Arctic discoveries, particularly those of natural gas resources.

The categories of resource appraisal methods in these studies basically evolved from the purely volumetric yield methods, through modifications of these methods that incorporated probability distributions, basin classifications, and subjective probability (or Delphi) techniques, to a simplified play analysis technique. In the latest study, the methods have evolved to a more sophisticated play analysis technique incorporating field size distributions and economic considerations. No time limitations are documented for the earlier resource studies; however, the 1983 study refers to petroleum supplies through the 1990s.

To compare resource estimates is very difficult, and in some cases impossible and often misleading, but it is a necessary and unavoidable exercise. All the liquid hydrocarbon potential estimates and natural gas estimates were converted either to the ultimate recoverable potential or to the remaining undiscovered recoverable potential, and comparisons were made for those commodities (Tables 2 and 3).

The 1972 study of the GSC (Canadian Department of Energy, Mines, and Resources), which used a volumetric method, has the highest estimates for the petroleum resource potential. The lowest petroleum estimates were generated by the GSC in their 1976 study, in which a well-developed play analysis methodology was used. Reasons for the reduction in the resource estimates from the GSC 1972 and 1973 studies are documented as follows. First, the 1976 study excluded offshore areas considered to be inaccessible using known technology, whereas the 1972 and 1973 estimates included such areas as the continental slopes and rises and the Arctic Coastal Plain offshore. The exclusion was reported to be responsible for approximately one-third of the reduction of the 1973 estimates. Second, the decrease was also reported to be from the new and disappointing flow of information generated by exploration in the interim period. Third, it was reported that certain changes in estimates resulted from an increased capability to process information and improvements in methodology (Canadian Department of Energy, Mines and Resources, 1977).

Improvements have been made in methodology, but I think that the changes in the methods of assessing the resources from the 1972 volumetric yield study to the 1976 play analysis study account for the greater part of the differences between the earliest and latest estimates.

The 1983 GSC estimates incorporated additional modifications to the play analysis method and showed some increase in the oil resource potential and a significant increase in the gas resource potential compared to the 1976 study. These increases are probably due to certain offshore areas being reincorporated into the total assessments and to newly acquired geologic data from exploration and discovery of new plays on the offshore east coast, in Arctic areas, and in western sedimentary basins (Figure 2).