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Reservoir Heterogeneity Classification System for Characterization and Analysis of Oil Resource Base in Known Reservoirs

prepared by the
Reservoir Classification Task Force

on behalf of
U.S. Department of Energy
Office of Fossil Energy
Bartlesville Project Office

Geoscience Institute for Oil and Gas Recovery Research
A National Consortium

1990

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by

Geoscience Institute for Oil and Gas Recovery Research

The University of Texas at Austin
University Station, Box X
Austin, TX 78713-7508

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RESERVOIR CLASSIFICATION FOR RESOURCE ASSESSMENT

INTRODUCTION

The historical total resource base in known oil fields of the United States is estimated to be over 500 billion barrels. Of this volume, as of 1988, 145 billion barrels have been produced, and 27 billion barrels remain as proven reserves. On completion of conventional primary and secondary oil recovery, nearly two-thirds of all oil discovered in the United States will remain trapped in existing reservoirs. The critical point is that, under current operating practices, it is estimated that over 340 billion barrels of unrecovered oil resources will remain trapped in known reservoirs unless advanced recovery technologies can be developed to cost-effectively access and produce these resources (fig. 1).

Despite this huge remaining resource base, oil production and reserves in the United States are continuing to decline. Oil production peaked in 1970 at slightly over an average of 9 million barrels per day. Since the downturn in oil prices in 1985, production has rapidly declined to an average of about 8 million barrels per day in 1988. The decline accelerated in 1989 with an additional loss of 470,000 barrels per day producing capacity, and the decline is continuing in 1990. Development of advanced recovery technology can slow production decline and help stabilize supply.

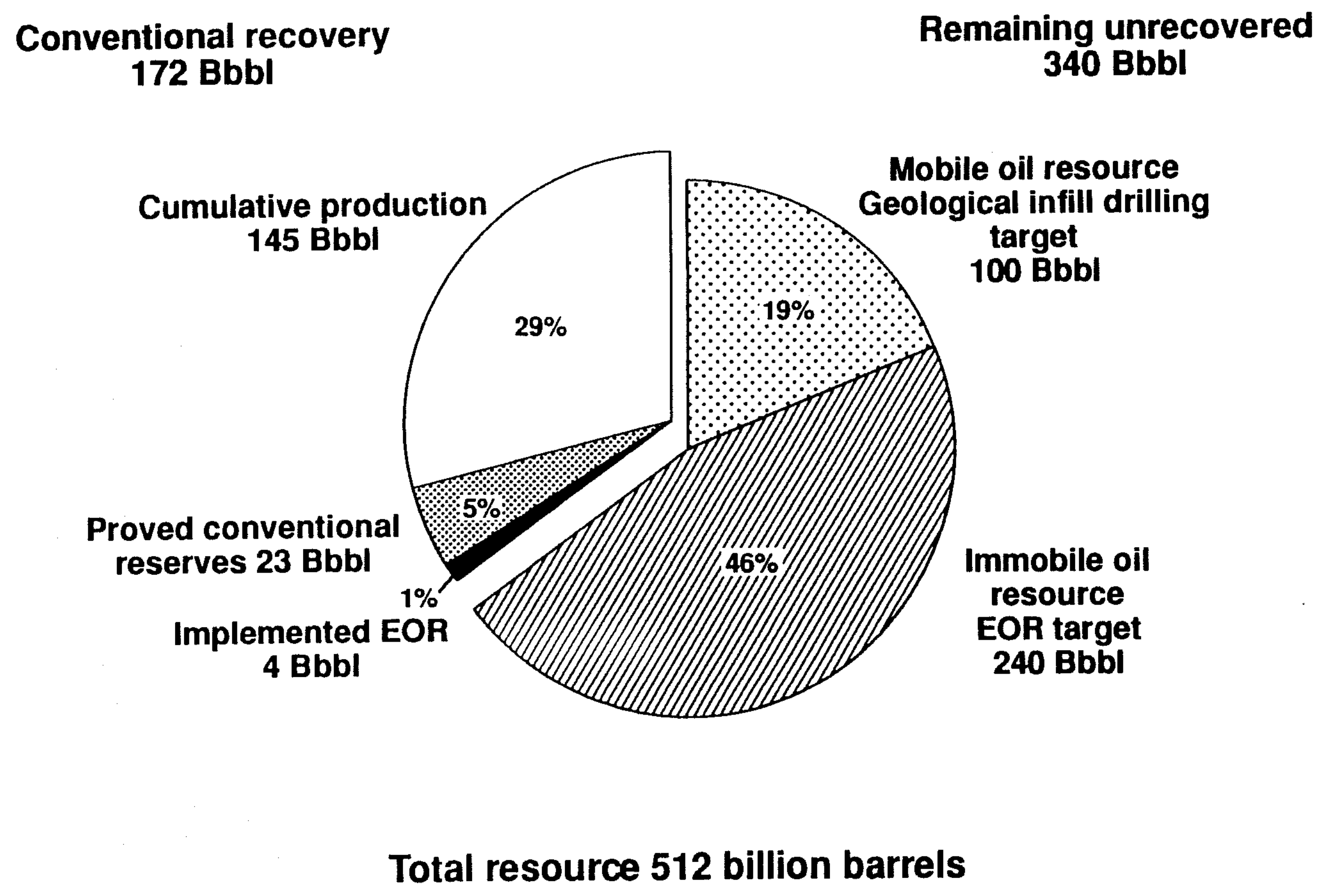
The remaining unrecovered oil resource base represents a significant target for development and application of advanced recovery concepts and technologies. For purposes of research and development considerations, the 340 billion barrels of unrecovered remaining oil resources can be grouped into two end-members or types. First, there is an estimated 100 billion barrels of conventional mobile oil and, second, there are 240 billion barrels of immobile or residual oil. The mobile oil, for the most part, occurs in uncontacted reservoir compartments and in unswept, bypassed zones that, if properly targeted, could be produced by conventional recovery techniques. The larger immobile oil resource base occurs in contacted and swept reservoir compartments as well as uncontacted zones and requires application of advanced extraction process technology for recovery.

Purpose of Study

The remaining mobile and immobile oil resources occur in a variety of geologic settings and reservoir types. Recovery efficiency of hydrocarbons from known reservoirs is largely controlled by internal reservoir architecture and primary and supplemental recovery mechanisms (Fisher and Galloway, 1983). The internal architecture and character of a reservoir are functions of its genesis, i.e., geologic evolution. A generally held hypothesis is that reservoirs with similar geological affinities have characteristic production constraints and respond to primary and advanced recovery applications similarly.

To develop and optimally deploy limited available recovery research support requires a better understanding of the distribution and nature of the remaining oil resources on the basis of geologic reservoir type. The Department of Energy's Bartlesville Project Office maintains the Tertiary Oil Recovery Information System (TORIS) data base which was

ESTIMATED U.S. OIL RESOURCES EXISTING FIELDS PRODUCED, PROVED, REMAINING IN PLACE



Source: BPO/TORIS, 1988

FIGURE 1

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developed by the National Petroleum Council for its 1984 study of enhanced oil recovery potential of major domestic reservoirs. It is the most comprehensive oil data base in the public sector and contains some 3,700 reservoirs which collectively account for more than 72 percent of the nation's known oil resources.

TORIS is a sophisticated, large-scale modeling and evaluation system useful for estimating recovery of oil from known reservoirs based on various scenarios. Despite this, the current configuration of the system does not permit identification or grouping of reservoirs based on geological criteria. The first step in systematically incorporating such a capability into the system requires establishing a procedure and mechanism for the geologic classification of reservoirs contained in the TORIS data base.

The geologic reservoir heterogeneity classification presented in this report is designed for use in identification and grouping of reservoirs with similar geological affinities into like classes. It is only through such a process that we can effectively assess the nature and character of the remaining oil resource base and achieve the maximum benefit from deployment of future research investments. Application of the proposed geologic classification for interrogation of reservoirs in the TORIS data base will provide a basis for: (1) selection of reservoir classes with the greatest resource potential for detailed study, and (2) prioritization of recovery research activities most appropriate to address program needs.

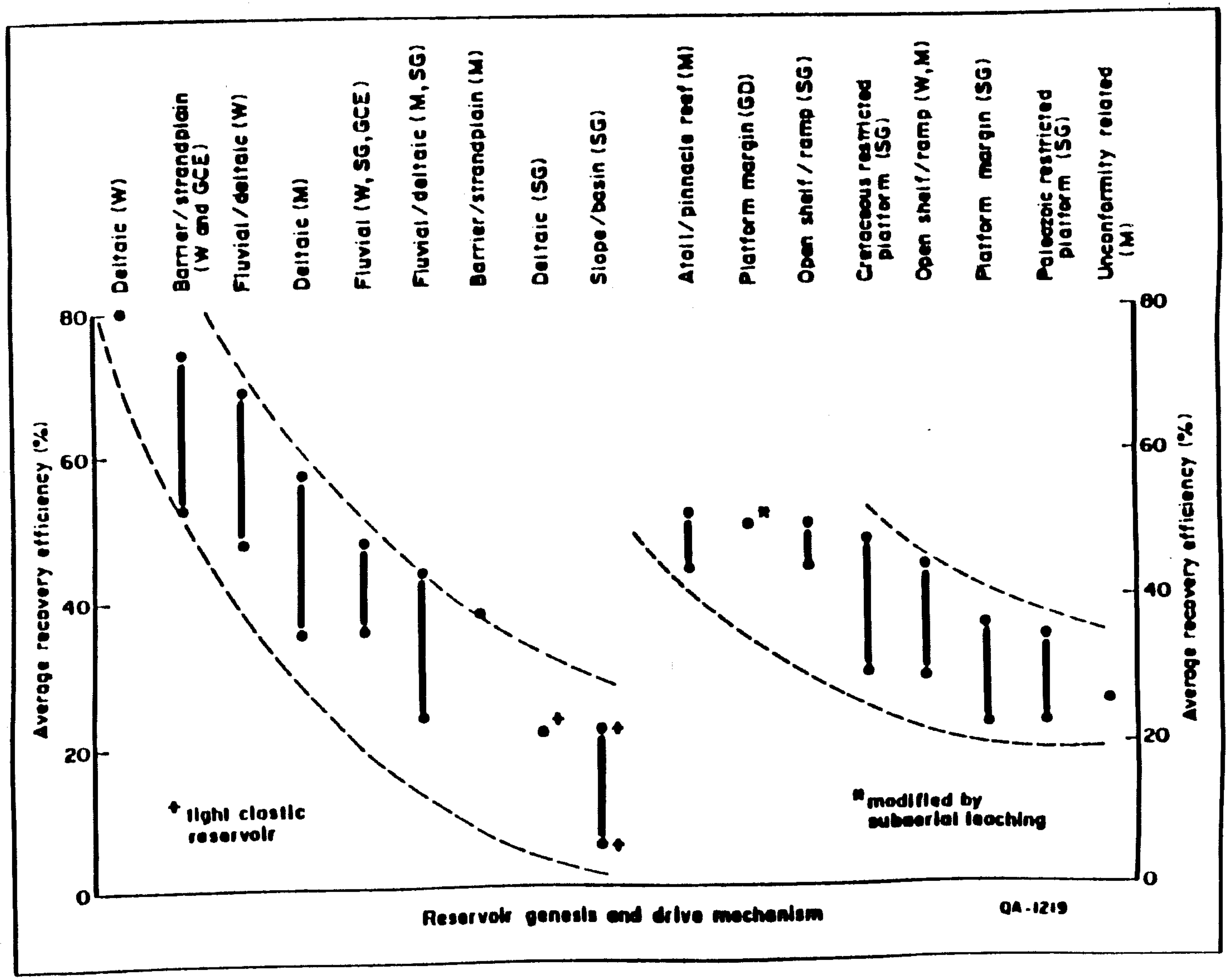
Previous Investigations

Based on an analysis of 500 of the largest Texas oil reservoirs, Tyler et al. (1984) were able to show that reservoir genesis clearly influences patterns of hydrocarbon recovery efficiency. They classified the 500 major Texas reservoirs into 48 geographic-geologic plays that were characterized by 11 reservoir depositional systems types. In addition, the reservoir types were also differentiated on the basis of primary drive mechanism.

The depositional system type determines the basic lithology and internal architecture or compartmentalization of a reservoir which control continuity of pay and other primary rock properties that are important variables in defining ultimate recovery efficiency. The relationship of depositional system and drive mechanism to recovery efficiency for the major Texas reservoirs is shown in figure 2. The indicated relationship provides a basis for identification of reservoir types with the greatest potential for increased recovery and helps in establishing priorities for maximizing recovery of remaining oil resources.

A recent joint study by ICF Resources and the Bureau of Economic Geology (1989) used a geological classification scheme to group and analyze reservoirs in the three-state area of Texas, Oklahoma, and New Mexico. The study demonstrated that most of the future mobile and immobile oil potential was concentrated in a limited number of reservoir types. The top five reservoir types were shown to contain more than 65 percent of the remaining potential, while the top 10 contained nearly 90 percent of the remaining oil resource base.

Recovery Efficiency is Correlated with Reservoir Genesis and Drive Mechanism



From Tyler, et. al. 1984.

FIGURE 2

Reservoir types with similar depositional histories are believed to have similar scale heterogeneities and production efficiency characteristics for given drive mechanisms and fluids. Therefore, research results based on analysis of selected representative reservoirs from a given class or type can be applied to other reservoirs in the same class for solution of similar recovery problems. Such an approach can focus research efforts on broad, well-defined reservoir recovery problems common to the class rather than on isolated, detailed individual reservoir issues. Extrapolation of research results to broad reservoir classes will provide for more cost-effective technology transfer and utilization of limited research support.

STUDY SCOPE AND APPROACH

The Geoscience Institute in consultation with the DOE Bartlesville Project Office established a multidisciplinary task force to develop a geological reservoir classification for characterization of the remaining domestic oil resource base. The task force consists of 20 representatives with a variety of technical backgrounds from both industry and academia.

The task force was charged with the responsibility of developing an expanded geological reservoir classification that could be used for interrogation and analysis of reservoirs in the TORIS data base system. The TORIS system currently contains adequate engineering elements and numerical modeling capabilities for predicting recovery of immobile oil resources. However, other than for the ICF/BEG three-state area of Texas, Oklahoma, and New Mexico, the system lacks sufficient geological criteria for determining reservoir types and prediction of mobile oil recovery potential.

Based on discussions with Bartlesville Project Office and ICF Resources personnel, the following general guidelines were established for developing the geological classification system:

1. First, the expanded classification, as much as possible, should build on previous studies and be based on those variables that have the greatest control on the internal architecture and heterogeneity of reservoirs and thus provide for grouping of reservoirs with similar affinities and production constraints.

2. Second, the classification must be relatively simple. It should have as few categories as possible, but the categories should cover the entire range of probable variables in order that, if needed, they could be easily subdivided in the future.

3. Third, there must be generally wide acceptance of the criteria and conceptual basis for the classification. The approach needs to provide replicative results when applied by multiple expert users.

4. Fourth, for widespread use, the types of data required for determination of classification variables must generally be currently available, either in the literature, public sector, or industry.

Reservoirs in the ICF/BEG three-state study were primarily classified on the basis of depositional systems type. In order to accommodate the wider range of reservoir variability in a national study, the expanded classification system proposed in this report includes additional primary classification parameters. A dual threefold heterogeneity classification system for carbonate and siliciclastic reservoirs is proposed that requires determination of not only the depositional system type but also the level of diagenetic overprint and the structural style as well (fig. 3). Reservoirs classified using the threefold system should more accurately reflect differences in recovery efficiency due to geologic factors.

RESERVOIR HETEROGENEITY CLASSIFICATION SYSTEM

The classification system used in earlier studies was focused on depositional system types and did not provide for a systematic assessment of the control of diagenetic overprint and structural compartmentalization on reservoir productivity. In general, the basic internal architecture and heterogeneity of reservoirs are dominantly controlled by processes operative at the depositional system level. However, in certain cases, diagenetic and structurally imposed reservoir attributes play a more dominant role in determining reservoir recovery efficiency. Therefore, the classification described here incorporates an individual assessment of (1) depositional system, (2) diagenetic overprint, and (3) structural compartmentalization, in order that the control of these three basic elements on recovery efficiency can be evaluated.

In practice, the primary decision in applying the classification first requires determining the lithology of the reservoir, i.e., carbonate or siliciclastic. Each lithologic type is secondarily characterized by the three basic elements as outlined in figure 3. Each element axis includes a series of categories that are designed to include the range of most likely possibilities for that particular element but still be mutually exclusive. Each category of the depositional systems axis has been further subdivided into subcategories in order to capture more detailed facies information if it is readily available.

Definition and characteristics of individual categories of the element axes are based on current acceptable usage as defined in standard geologic texts (Scholle and Spearing, 1982; Scholle et al., 1983a; Galloway and Hobday, 1983; McDonald and Surdam, 1984; and Roehl and Choquette, 1985). Because boundary conditions between categories are gradational and by their very nature interpretive, this creates a certain subjective element in the classification. However, an attempt has been made to make the categories sufficiently broad in order to minimize differences in interpretation.

Depositional System Element

The primary attributes of a reservoir are controlled by depositional processes. This is true because the physical, chemical, and biologic processes active in specific depositional environments and resulting depositional facies determine many attributes that are directly or indirectly related to hydrocarbon generation, migration, entrapment, and reservoir producibility (Fisher and Galloway, 1983).

The concept of depositional systems (Fisher et al., 1969) encompasses interpretation of depositional environments and implies that component facies are spatially related and comprise predictable three-dimensional stratigraphic units. Recognition and delineation of depositional systems provide a framework for facies differentiation and mapping. This approach to facies analysis relies heavily on reconstruction of basin morphology and bedding architecture, determination of gross lithology, and recognition of vertical and lateral succession of facies that comprise individual reservoirs.

The key attributes of a reservoir that are commonly related to its depositional system include (Fisher and Galloway, 1983):

- Primary rock type and facies;
- External geometry and configuration of the reservoir body;
- Internal architecture which controls vertical and lateral variations in both pay and nonpay zones;
- Reservoir facies relationships which may control the sealing and trapping of hydrocarbons;
- Aquifer support which controls the effectiveness of natural water drive reservoirs; and
- Control or modification of subsequent diagenetic history and the type and abundance of porosity and permeability.

Individual facies components of a depositional system can have gradational or sharp lateral and vertical boundaries. Delineation of facies components provides the basis for establishing the field-wide internal reservoir architectural style. In most cases, individual reservoirs produce from a variety of laterally and vertically associated facies within a single depositional system. Variations within and between individual facies components produce reservoir heterogeneities at an intra-reservoir scale.

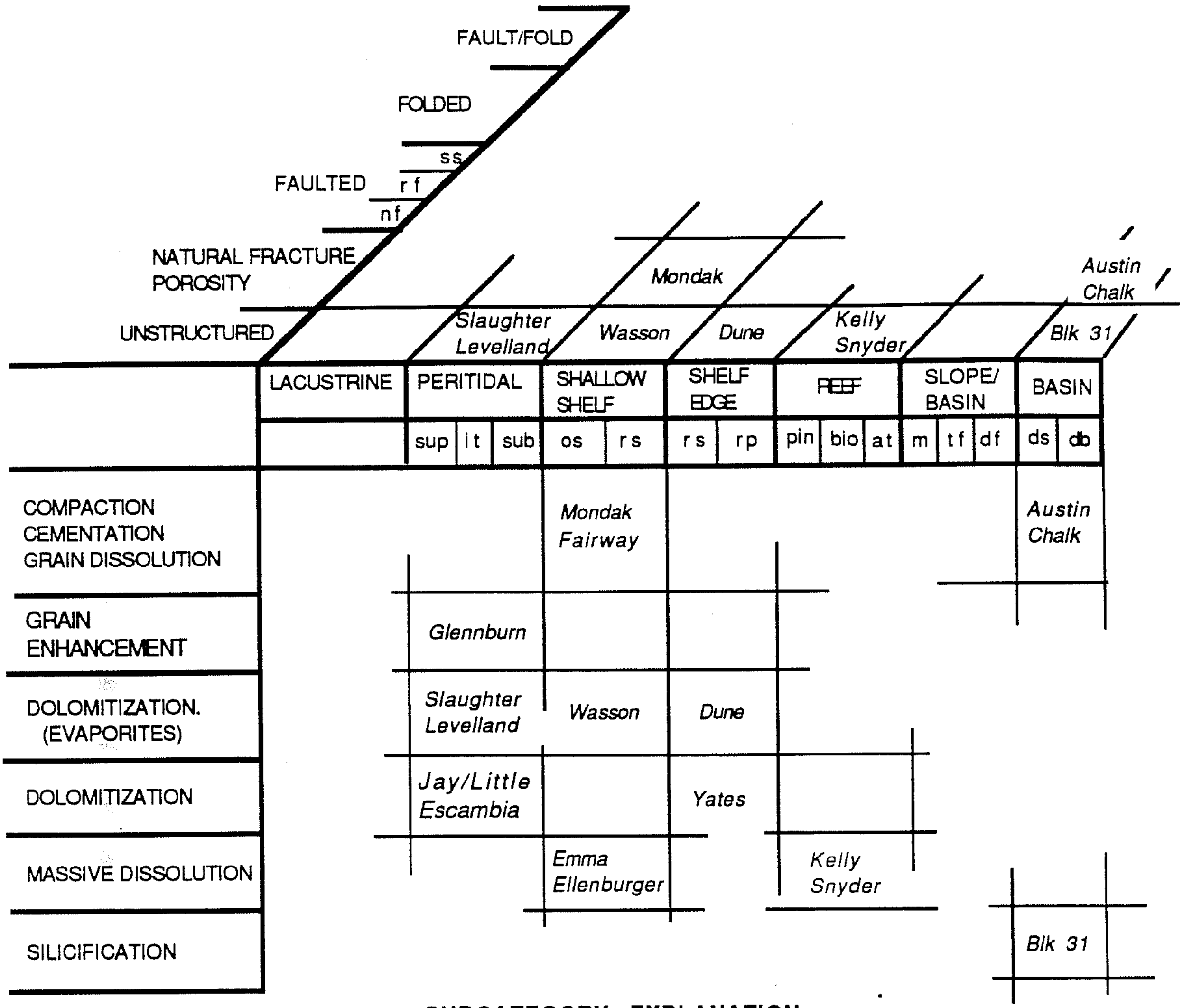
Carbonate Depositional Systems

In the classification used here seven major carbonate depositional systems categories are recognized (fig. 4). The categories are differentiated primarily based on position of their depositional environment as a function of relative water depth and basin morphology. Fifteen subcategories are identified to capture more detailed facies information if readily available.

Lacustrine carbonates are best known as source rocks for lacustrine siliciclastic reservoirs (Dean and Fouch, 1983). They form the principal oil-shale deposits of the Green River Formation in the western United States. Carbonate lacustrine reservoirs are not common, but fractured carbonates of the Green River Formation produce in the Unita Basin in Utah.

Peritidal reservoirs are composed of sediments that were deposited in subtidal to supratidal environments on and adjacent to tidal flats. Fenestral and pisolite porosity is locally well developed in supratidal mudstones and grainstones, but most production is from subtidal grainstones deposited as bars and beaches and associated dolomitized wackestones. Examples are the Slaughter/Levelland (San Andres) reservoirs in the Permian Basin and the Red River reservoirs in the Williston Basin.

GEOLOGIC CLASSIFICATION - CARBONATE RESERVOIRS



SUBCATEGORY EXPLANATION

DEPOSITIONAL SYSTEM

Peritidal
- Supratidal (sup)
- Intertidal (it)
- Subtidal (sub)

Shallow Shelf
- Open shelf (os)
- Restricted shelf (rs)

Shelf Edge
- Rimmed shelf (rs)
- Ramp (rp)

Slope/Basin
- Debris fan (df)
- Turbidite fans (tf)
- Mounds (m)

Basin
- Drowned shelf (ds)
- Deep basin (db)

Reef
- Pinnacle (pin)
- Bioherm (bio)
- Atoll (at)

STRUCTURAL STYLES

Faulted
- Normal fault (nf)
- Reverse fault (rf)
- Strike-slip fault (ss)

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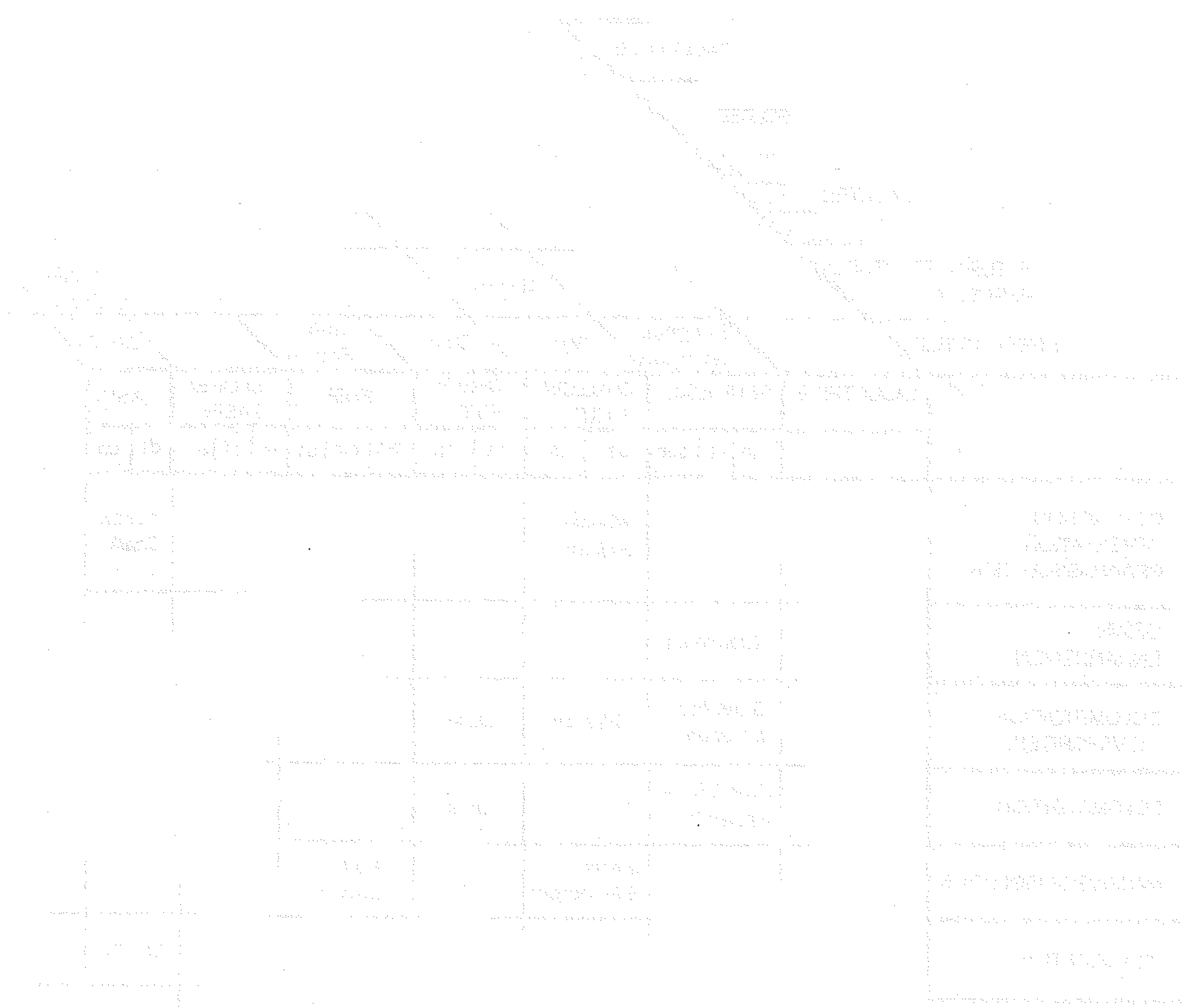
FIGURE 4



These reservoirs produce from stacked subtidal-supratidal cycles. Supratidal, intertidal, and subtidal facies are broken out as subcategories.

Shallow shelf reservoirs are developed in a wide variety of facies that were deposited on a broad carbonate platform under shallow water depths. The best reservoir facies include locally developed grainstones, deposited as bars, reworked beaches, and isolated patch reefs. Associated widespread burrowed wackestones and packstones represent carbonates deposited under quiet-water conditions below wave base. These low-energy carbonates comprise reservoirs particularly where regionally or locally dolomitized. Examples are the Wasson (San Andres) reservoir in the Permian Basin and the Mondak (Mississippian) reservoir in the Williston Basin. Open shelf and restricted shelf subcategories are based on open marine versus restricted marine fossil assemblages.

Shelf-edge reservoirs produce from thick sections of subtidal grainstone bars and banks deposited along the outer edge of carbonate platform or ramps. Carbonate facies deposited in these settings may contain reefs but are chiefly characterized by broad, low-relief bar, bank, and island facies deposited under low- to high-energy conditions. The Grayburg reservoirs of the Dune and McElroy fields along the eastern edge of the Central Basin Platform, West Texas, are examples of this type of reservoir. Two subcategories of shelf-edge reservoirs are recognized: rimmed shelves, which may contain a barrier reef facies, and ramps.

Reefal reservoirs produce from stratigraphic reefs which commonly attain significant topographic relief. Framework and binding organisms are common constituents in the reef facies; associated facies include grainstones that accumulated as flanking beds around the reefs. Reefal reservoirs include the Michigan Basin pinnacle reefs and the Pennsylvanian/Permian Kelly Snyder reservoir of the Horseshoe Atoll, Midland Basin, Texas. Reefal reservoirs are further subdivided into pinnacle reefs, atolls, and bioherms.

Slope/basin reservoirs are developed in carbonate submarine-fan and debris-flow deposits associated with basin slopes. Reservoirs developed in these deeper basinal positions are not common, but examples are known in the Bone Springs Formation in the Delaware Basin, West Texas, and the Poza Rica trend in northern Mexico. This category is subdivided into turbidity flows, debris flows, and carbonate mounds.

Basinal reservoirs occur in chalk deposits that accumulated from the raining down of pelagic organisms (coccoliths, coccospheres) onto drowned platforms and basin floors. Scholle and others (1983b) recognize three categories of chalk reservoirs: (1) those that have never been deeply buried, lack significant compaction, and have high primary porosity (Niobrara Formation of western Kansas, eastern Colorado, and Nebraska); (2) those that have been buried to a moderate depth and must be extensively fractured to enhance porosity (Austin Chalk on the Texas Gulf Coast); and (3) those that have been deeply buried but with high pore pressure to preserve high primary porosity. The category is subdivided into basin floor and drowned platforms based on basin morphology.

Siliciclastic Depositional Systems

Nine categories of siliciclastic depositional systems are defined in the classification (fig. 5). The categories are differentiated, similar to the carbonates, on the basis of depositional environment as a function of water depth and inferred sedimentary processes. Twenty-three subcategories are provided to capture more detailed facies information if readily available.

Eolian reservoirs can develop in a variety of depositional environments, e.g., associated with alluvial fans and braided streams, coastal zones, as well as desert regions. The geometry and internal characteristics of eolian reservoirs vary as a function of their depositional environment. In general, they are characterized by their complex internal stratification and limited lateral continuity. Eolian subcategories include ergs and coastal dunes. The Rangely field (Weber) is an example of an erg-type eolian reservoir in western Colorado.

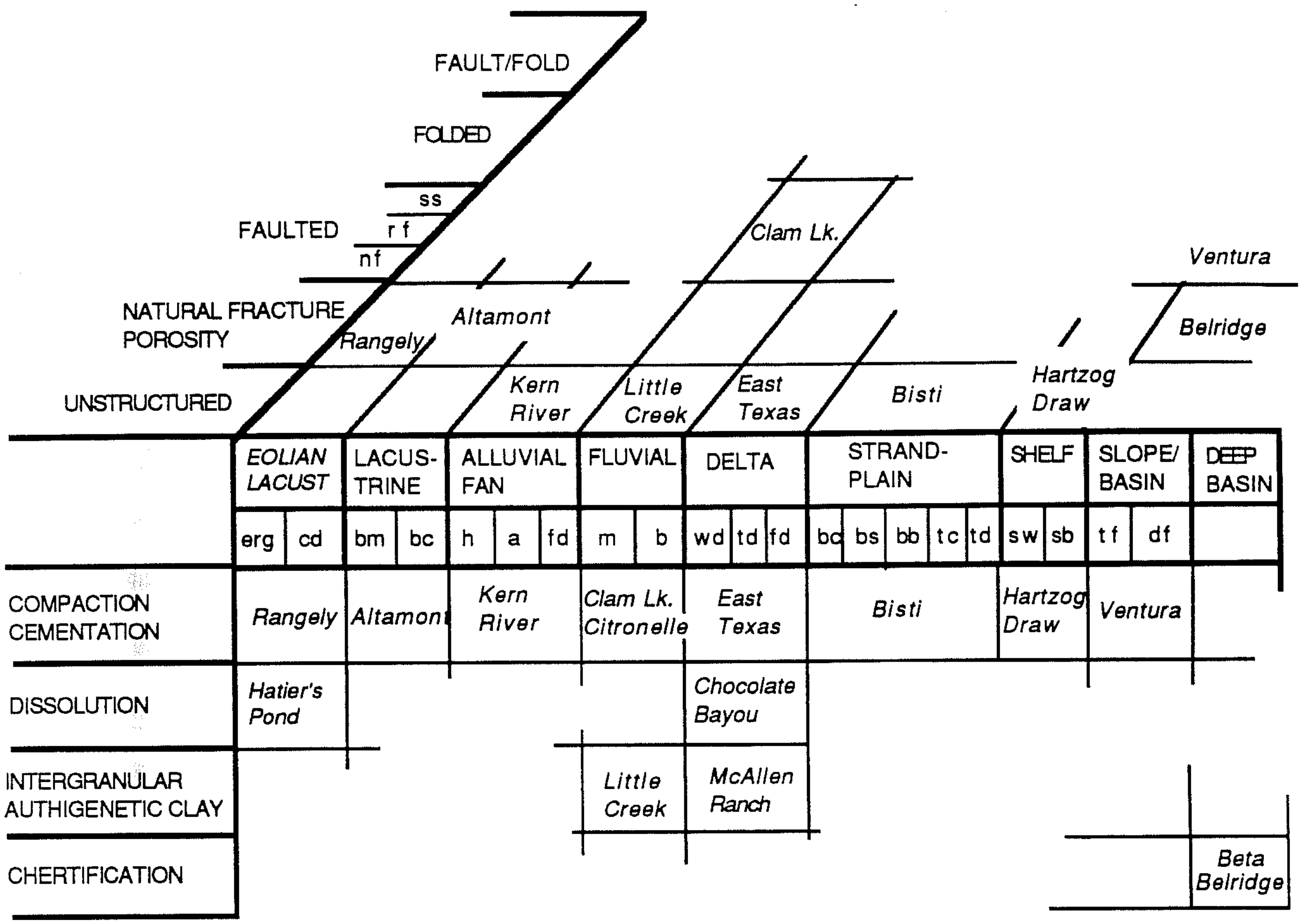
Lacustrine reservoirs can be composed of a variety of sand-body types, e.g., beaches, deltas, and turbidite fans that occur within lakes. Examples of lacustrine reservoirs in the U.S. are the Duchesne field and Altamont field (Eocene) in the Uinta Basin in western Wyoming. Subcategories have been simply designated as basin margin and basin center.

Alluvial-fan reservoirs are comprised primarily of braided-stream deposits and are generally formed under relatively high-energy conditions, commonly along the front of higher standing mountain blocks. Alluvial-fan environments commonly grade downstream into braided-stream and/or playa-lake environments. Some fans build directly into standing bodies of water and are then referred to as fan deltas. Examples of alluvial-fan reservoirs include the Prudhoe Bay field (Triassic), North Slope of Alaska, and the Kern River field (Jurassic) of the San Joaquin Basin in California. Subcategories include stream-dominated fans, fan delta, and arid/semi-arid fans.

Fluvial reservoirs are composed of sand-body types ranging from braided-stream sheets to coalescing point-bars of meandering streams. Fluvial reservoirs in general are characterized by their lack of lateral and vertical continuity. Meandering fluvial sheet sands in the form of coalescing point-bars are not as continuous as braided-sheet sands and are characterized by oxbow clay plugs that form lateral flow barriers and seals. Examples of fluvial reservoirs are the Cutbank field (Cretaceous) of northern Montana and the incised Morrow Channel fields (Pennsylvanian) of southeast Colorado and southwest Kansas. Subcategories are meandering and braided.

Deltaic reservoirs in the main are characterized by distributary channel and stream-mouth bar type sand bodies and associated delta fringe strike sands. Based on the dispersal energy of the receiving basin relative to the volume of sediment being introduced, deltas can be generally placed into one of three subcategories. Fluvial-dominated deltas are characterized by higher concentrations of sand in distributary channels and stream-mouth bars. Wave-dominated deltas are characterized by thick sequences of well-sorted, strike beach deposits. Tide-dominated deltas are characterized by tidal channel and delta deposits. Examples of deltaic reservoirs are the Mercy and Livingston (Eocene) fields in southeast Texas and the giant East Texas Woodbine field (Cretaceous).

GEOLOGIC CLASSIFICATION - SILICICLASTIC RESERVOIRS



SUBCATEGORY EXPLANATION

DEPOSITIONAL SYSTEMS

Eolian
- Ergs (erg)
- Coastal dunes (cd)

Lacustrine
- Basin margin (bm)
- Basin center (bc)

Alluvial Fan
- Humid (stream-dominated) (h)
- Arid/semi-arid (a)
- Fan deltas (fd)

Fluvial
- Meandering (m)
- Braided (b)

Delta
- Wave-dominated (wd)
- Fluvial-dominated (fd)
- Tide-dominated (td)

Strandplain
- Barrier core (bc)
- Barrier shoreface (bs)
- Back barrier (bb)
- Tidal channel (tc)
- Washover fan/Tidal delta (td)

Shelf
- Sand wave (sw)
- Sand ridge/bars (sb)

Slope/Basin
- Turbidite fan (tf)
- Debris fan (df)

Deep Basin
- Pelagic

STRUCTURAL STYLES

Faulted
- Normal fault (nf)
- Reverse fault (rf)
- Strike-slip fault (ss)

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FIGURE 5

Strandplain reservoirs occur in long narrow belts paralleling paleoshorelines. They are subdivided into a number of sand-body types: barrier core, barrier shoreface, back barrier, tidal channel, washover fan, and tidal delta. Barrier island core sand bodies are the highest quality strandplain reservoirs and are characterized by laterally continuous reservoirs in a strike sense. Examples of strandplain reservoirs are the Bisti field (Cretaceous) in the San Juan Basin and the TCB-East field (Oligocene) of South Texas.

Shelf reservoirs are usually relatively thin and form poorer quality reservoirs. For the most part, they are comprised of sand ridge/bars composed of reworked deposits formed during a transgression. There are exceptions where thick sand waves can develop on shallow marine shelves and serve as excellent high-quality reservoirs. Examples of shelf reservoirs are the House Creek and Hartzog Draw fields (Cretaceous) in the Powder River Basin of Wyoming.

Slope/basin reservoirs are divided into turbidite fans and debris fans. Submarine fans typically contain three distinct sand-body types: (1) thicker channel sands occur across the length of the upper and middle fan and thin downfan, (2) thinner lobate suprafan sands associated with distributary channels occur across the middle to distal end of the fan, and (3) thinly bedded sheet sands occur basinward of the fan proper. Fans, in general, provide excellent quality reservoirs. Examples of submarine-fan reservoirs are provided by the Tertiary fields in southern California, in particular the Elk Hills fields (Miocene) in the San Joaquin Basin and the Ventura field (Pliocene) in the Santa Barbara Basin.

Deep-basin reservoirs are reserved for those pelagic siliceous deposits that have accumulated in deep ocean basins and tectonic trenches. In many instances these types of deposits serve as both a major hydrocarbon source and reservoir. Four conditions are required for their formation: (1) high production rates of diatoms, radiolarians, etc., (2) low dilution by terrigenous sourced sediments, (3) adequate burial for advanced diagenesis, and (4) fracturing of the resultant deposit to increase permeability and porosity. The most important deep-basin siliceous reservoirs in North America are those associated with the Monterey Formation (Miocene) in the southern California area.

Diagenetic Overprint Element

Diagenesis can be generally defined as the chemical, physical, and biologic changes and alterations undergone by a sediment after its initial deposition and during and after its burial and lithification. It encompasses a wide range of processes, such as compaction, cementation, authigenesis, replacement, crystallization, leaching, hydration, karsting, etc. Whereas depositional systems occupy a specific time and space and can be defined to have finite spatial boundaries, diagenetic processes cannot be so delineated. In contrast, multiple diagenetic processes can occur in the same space over variable time spans and with varying intensities.

Over the past few years, the importance of diagenetic processes in controlling reservoir quality has been better recognized. Many hydrocarbon reservoirs have significant diagenetic components directly affecting porosity and permeability characteristics. Modification of reservoirs by diagenetic processes can either reduce or enhance reservoir heterogeneities depending on specific circumstances.

In the classification presented here, diagenetic effects are not defined in spatial terms but in terms of the diagenetic processes that most directly influenced the present-day flow characteristics of the reservoir. The focus of the diagenetic overprint categories is on: (1) pore types present in the reservoir, (2) the diagenetic process most responsible for producing the pore types, and (3) the relationship of the pore types to reservoir-flow characteristics.

Carbonate Reservoirs

The most common diagenetic processes that most all carbonate reservoirs have undergone are compaction, cementation, and some degree of selective grain dissolution. Collectively, these processes are referred to as lithification. The most common pore types for this stage of diagenesis are intergranular and separate-vug (Lucia, 1983). Compaction and cementation directly reduce intergranular pore space. Selective grain dissolution creates ineffective, nonconnected separate-vug pore spaces and provides a source of $CaCO_3$ for cementation of adjacent intergranular pore space. All three processes reduce reservoir quality. Examples of reservoirs in this category are Fairway (Cretaceous) reservoir of the East Texas Basin and the Mondak (Mississippian) reservoir in the Williston Basin.

The grain enhancement category is included to identify reservoirs in which early subaerial diagenetic processes improve reservoir quality by altering mud-dominated tidal-flat sediment to fenestral and inter-pisolitic pore types. An example is the Glenburn field, Mississippian of the Williston Basin.

The dolomitization with evaporites category includes those reservoirs that produce from dolomites that contain considerable volumes of anhydrite or gypsum and whose principal pore types are intercrystalline, intergranular, and separate-vug. Examples are the Dune (Grayburg) reservoir and the Wasson (San Andres) reservoir of the Permian Basin.

The dolomitization category is included to identify dolomite reservoirs that produce from intercrystalline, intergranular, and separate-vug pore types but do not contain sulfates. Yates (San Andres) field is an example of this category.

The massive dissolution category is included because carbonates are susceptible to karsting processes that result in collapse breccias, connected vugs, cave fills, and fracturing. These processes are independent of lithology and, indeed, often provide flow paths for later dolomitizing solutions. The primary pore types in these reservoirs are fractures, interbreccia-block, large connected vugs, and caverns. Intercrystalline, intergranular, and separate-vug pore types may also be present. The Emma (Ellenburger) reservoir in West Texas is an example of this category.

Silicification of carbonate sediment is the dominant diagenetic process in some reservoirs. Pore space is located between small quartz crystals or globules and in small separate vugs. The Block 31 reservoir (Devonian) of the Permian Basin is an example.

Siliciclastic Reservoirs

Compaction and cementation are the major processes that reduce primary, intergranular porosity in sandstones. All sandstones lose some porosity by compaction and cementation, but extreme amounts of compaction, cementation, or both, can destroy almost all original porosity. Examples of reservoirs in this category include portions of the Nugget Sandstone in Anschutz Ranch East field, Utah, which have lost porosity dominantly by mechanical compaction and intergranular pressure solution, and the Travis Peak Formation in North Appleby field, East Texas Basin, which has lost porosity mainly by extensive quartz cementation.

The dissolution category is restricted to intergranular dissolution. This process improves reservoir quality. Many oversized pores are probably hybrid, representing primary pores that have been enlarged by dissolution. An example of a reservoir in which porosity has been secondarily enhanced by dissolution is the Frio Formation in Chocolate Bayou field in coastal Texas.

The interstitial clay category identifies reservoirs that contain significant volumes of authigenic clay. In a sandstone, authigenic clay can alter reservoir characteristics by increasing water saturation and decreasing permeability, while having little effect on porosity. Preservation of porosity at depth has been ascribed to the presence of clay coatings on sand grains. The most common authigenic clays are illite, smectite, mixed-layer illite-smectite, chlorite, and kaolinite. Dissolution of unstable framework grains, such as feldspars and rock fragments, results in the formation of grain molds and in the precipitation of interstitial clay. Examples include reservoirs that produce from the Aux Vases Formation in the Illinois Basin and the lower Tuscaloosa Little Creek reservoir in Mississippi.

Chertification of siliciclastic sediments is not a common process, but it strongly influences reservoir properties where it occurs. Silica for chertification is derived from diagenetic alteration of siliceous organisms, forming a porcelaneous cement that later recrystallizes to chert. Reservoirs that contain abundant porcelaneous cement are characterized by high porosity but relatively low permeability. Much of the total porosity in the rock is microporosity contained within the porcelaneous cement, and fluid flow is restricted in the micropore system. Examples include reservoirs in the Miocene Monterey Formation, California, and laterally equivalent turbidite sandstones in Beta and Wilmington fields, Los Angeles Basin.

Structural Compartmentalization Element

The structural compartmentalization element has been incorporated into the classification in order to identify those reservoirs where structural complexities have induced intra-reservoir heterogeneities that effectively compartmentalize and significantly alter production response of reservoirs. Examples include reservoirs where natural fracture porosity controls production performance, faulting partitions the reservoir, and where folding subdivides the reservoir. Structural compartmentalization is not to be confused with the concept of structural traps. A structural trap defines the reservoir boundaries, not its internal heterogeneity.

As in the case of diagenesis, structural activity can be recurring and results in superimposed structural elements. Therefore, the object of the classification is to select the structure category that best characterizes reservoir productivity. Five broad categories have been selected: (1) unstructured, (2) natural fracture porosity, (3) fault partitioned; (4) fold compartmentalized; and (5) combined folded and faulting.

Many reservoirs are not structurally compartmentalized and for purposes of this classification are considered unstructured at an intra-reservoir scale. Examples of unstructured reservoirs are the Dune (Grayburg) field in the Permian Basin and the East Texas (Woodbine) field.

The natural-fracture porosity category is used to classify those reservoirs where tectonic fracture porosity is the principal permeability control in the reservoir. This category is reserved for fracture porosity produced principally by tectonic forces. Thus, massive dissolution reservoirs with fracture porosity resulting from collapse should not be included in this category. Examples of tectonically fractured reservoirs are Mondak (Mississippian) field, Williston Basin, and Spraberry (Permian) field, Permian Basin.

The fault category should be selected only for those reservoirs where faults effectively compartmentalize the reservoir at the intra-reservoir scale and where natural fracture porosity is not significant. The Clam Lake field, a piercement salt-dome field in the Texas Gulf Coast, is an example of a fault-partitioned reservoir. The fault category has been further divided into normal, reverse, and strike-slip faults.

The fold category is proposed for those instances where the reservoir has been effectively compartmentalized by complex folding. The combined fold and fault category has been added to classify those reservoirs where folding and faulting are equally important in compartmentalizing the reservoir.

APPLICATION AND IMPLEMENTATION

Standardization and Documentation

The application of the reservoir heterogeneity classification system presented here is proposed to be applied by local experts with a working knowledge of regional oil and gas fields. The classification as proposed is envisioned as a working system that requires testing and evaluation on a regional basis. Through wider spread application of the system recommendations from users will help improve it for specific program design needs. The ultimate goal, after an appropriate test phase, is to be able to quantify the classification element categories. The viability for development of a quantified classification system can only be evaluated after appropriate use and testing and thus is a longer range objective.

A reservoir heterogeneity classification checksheet has been designed to help standardize and document data collection for the classification effort (fig. 6). A detailed procedural guide to aid in the task of completing the checksheet is presented in Appendix I. After the reservoirs have been classified, engineering data can be added from data bases such as TORIS and groups of reservoirs with common geological

Reservoir Heterogeneity Classification System for TORIS

1. Reservoir Identification

Reservoir Play: ____________________

Reservoir Name: ____________________ Geologic Province: ____________________ Date: __________

Field Name: ____________________ Geologic Age: ____________________ Prepared By: __________

State: ____________________ Formation: ____________________ Version: __________

2. Depositional System ☐ 1 ☐ 2 ☐ 3 Degree of Confidence in Selection (1=Highest, 3= Lowest)

Carbonate Reservoirs

☐ Lacustrine

☐ Peritidal
- ____ Supratidal
- ____ Intertidal
- ____ Subtidal

☐ Shallow Shelf
- ____ Open Shelf
- ____ Restricted Shelf

☐ Shelf Margin
- ____ Rimmed Shelf
- ____ Ramp

☐ Reefs
- ____ Pinnacle Reefs
- ____ Bioherms
- ____ Atolls

☐ Slope/Basin
- ____ Debris Fans
- ____ Turbidite Fans
- ____ Mounds

☐ Basin
- ____ Drowned Shelf
- ____ Deep Basin

Clastic Reservoirs

☐ Eolian
- ____ Ergs
- ____ Coastal Dunes

☐ Lacustrine
- ____ Basin Margin
- ____ Basin Center

☐ Fluvial
- ____ Braided Streams
- ____ Meandering Streams

☐ Alluvial Fan
- ____ Humid (Stream-Dominated)
- ____ Arid/Semi-Arid
- ____ Fan Deltas

☐ Delta
- ____ Wave-Dominated
- ____ Fluvial-Dominated
- ____ Tide-Dominated

☐ Strandplain
- ____ Barrier Cores
- ____ Barrier Shorefaces
- ____ Back Barriers
- ____ Tidal Channels
- ____ Washover Fan/Tidal Deltas

☐ Shelf (Accretionary Processes)
- ____ Sand Waves
- ____ Sand Ridges/Bars

☐ Slope/Basin
- ____ Turbidite Fans
- ____ Debris Fans

☐ Basin
- ____ Pelagic

3. Diagenetic Overprint ☐ 1 ☐ 2 ☐ 3 Degree of Confidence in Selection (1=Highest, 3= Lowest)

Carbonate Reservoirs

☐ Compaction/Cementation ☐ Dolomitization (Evaporites)

☐ Grain Enhancement ☐ Massive Dissolution

☐ Dolomitization ☐ Silicification

Clastic Reservoirs

☐ Compaction/Cementation ☐ Authigenic Clay

☐ Intergranular Dissolution ☐ Chertification

4. Structural Compartmentalization ☐ 1 ☐ 2 ☐ 3 Degree of Confidence in Selection (1=Highest, 3= Lowest)

☐ Natural Fracture Porosity ☐ Unstructured ☐ Faulted ☐ Fault/Fold ☐ Folded

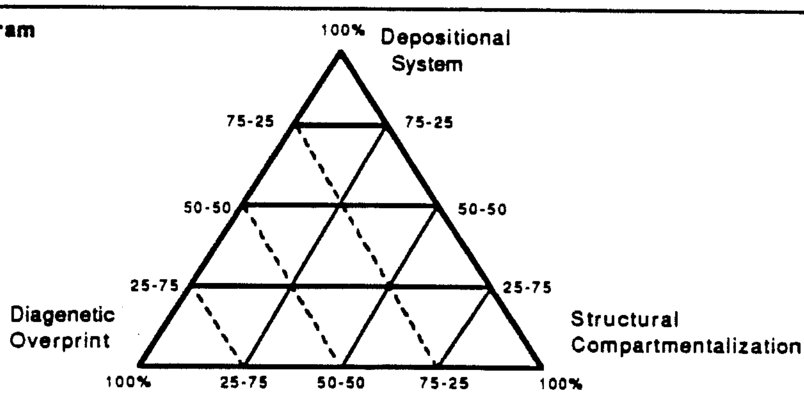
Faulted:
- ____ Normal Fault
- ____ Reverse Fault
- ____ Strike-Slip Fault

Fault/Fold:
- ____ Normal Fault
- ____ Reverse Fault
- ____ Strike-Slip Fault

5. Reservoir Heterogeneity Ternary Diagram

Predominant Element of Reservoir Heterogeneity:
(Check Only One)

- Depositional System ____
- Diagenetic Overprint ____
- Structural Compartmentalization ____



6. Trap Type ☐ Stratigraphic ☐ Structural ☐ Combination

7. Optional Comments (References, Details on Above Selections, Etc.) ____________________

____

____

____

____

FIGURE 6

(prepared by ICF Resources, Inc.)

affinity, geographic proximity, and hydrocarbon type can be defined as reservoir play groups.

Implementation Approach

The classification is designed to be optimally applied by regional expert users. First, the most direct and best approach in application of the system is by local workers with firsthand knowledge of the nature and character of regional oil and gas fields. Second, in addition to expert user input, information pertaining to reservoir type and properties can be obtained from published technical journals and other public records. In addition, individual field operators can be contacted to determine availability of information through private company sources.

The primary or first-order determination for classification of a reservoir is lithology type (fig. 7), e.g., carbonate or siliciclastic. Once the lithology type is determined, the reservoir is interrogated based on the threefold element classifiers, e.g., depositional system, diagenetic overprint, structural style. Individual categories from each major element are selected that best characterize the reservoir based on available data and the judgment of the user.

An alphanumeric coding system is proposed for input into data-base systems. As outlined in figure 7, a lithologic designation, C for carbonates and S for siliciclastics, is proposed which is followed by a three-digit number set. Each digit refers to the individual element category that best characterizes the reservoir. Additional digits can be added for subcategories.

Engineering Data Modifiers

The heterogeneity classification system can be enhanced by including engineering data-based modifiers. Engineering data pertaining to individual reservoirs are contained in TORIS. The two key engineering parameters required to synthesize recovery efficiency or reservoir classes are: (1) primary drive mechanism, and (2) hydrocarbon type (API gravity). Reservoir drive mechanism is one of the more obvious engineering factors determining recovery efficiency. In most cases, strong natural water-drive reservoirs are characterized by higher than average recovery rates. In contrast, solution gas-drive reservoirs have lower recovery efficiencies. The specific gravity of the oil, expressed in API gravity units, limits recovery in some reservoirs. However, in most plays, gravity varies within narrow limits and thus does not normally account for variability of recovery efficiency in an individual play.

Reservoir Play Groups

The geologic play concept provides a basis for grouping reservoirs with similar affinities on a basin-wide scale. Such an approach provides for reservoirs with similar characteristics to be grouped together into meaningful geological plays. The plays have finite geological and geographic limits which can be delineated on maps to define their distribution and occurrence.

An exploration play as defined by White (1980) is an assemblage of geologically similar prospects and leads with the same source, reservoir

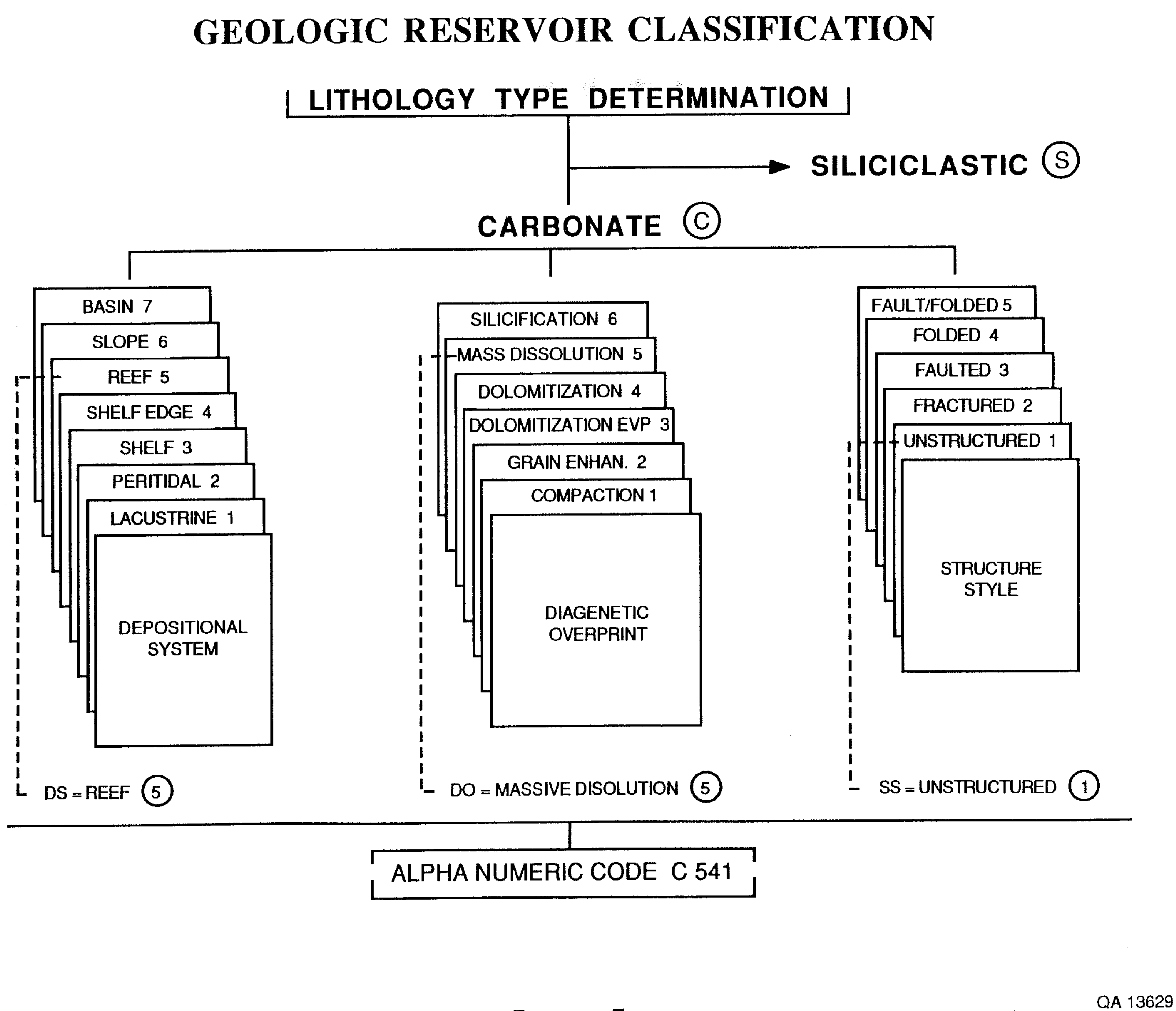
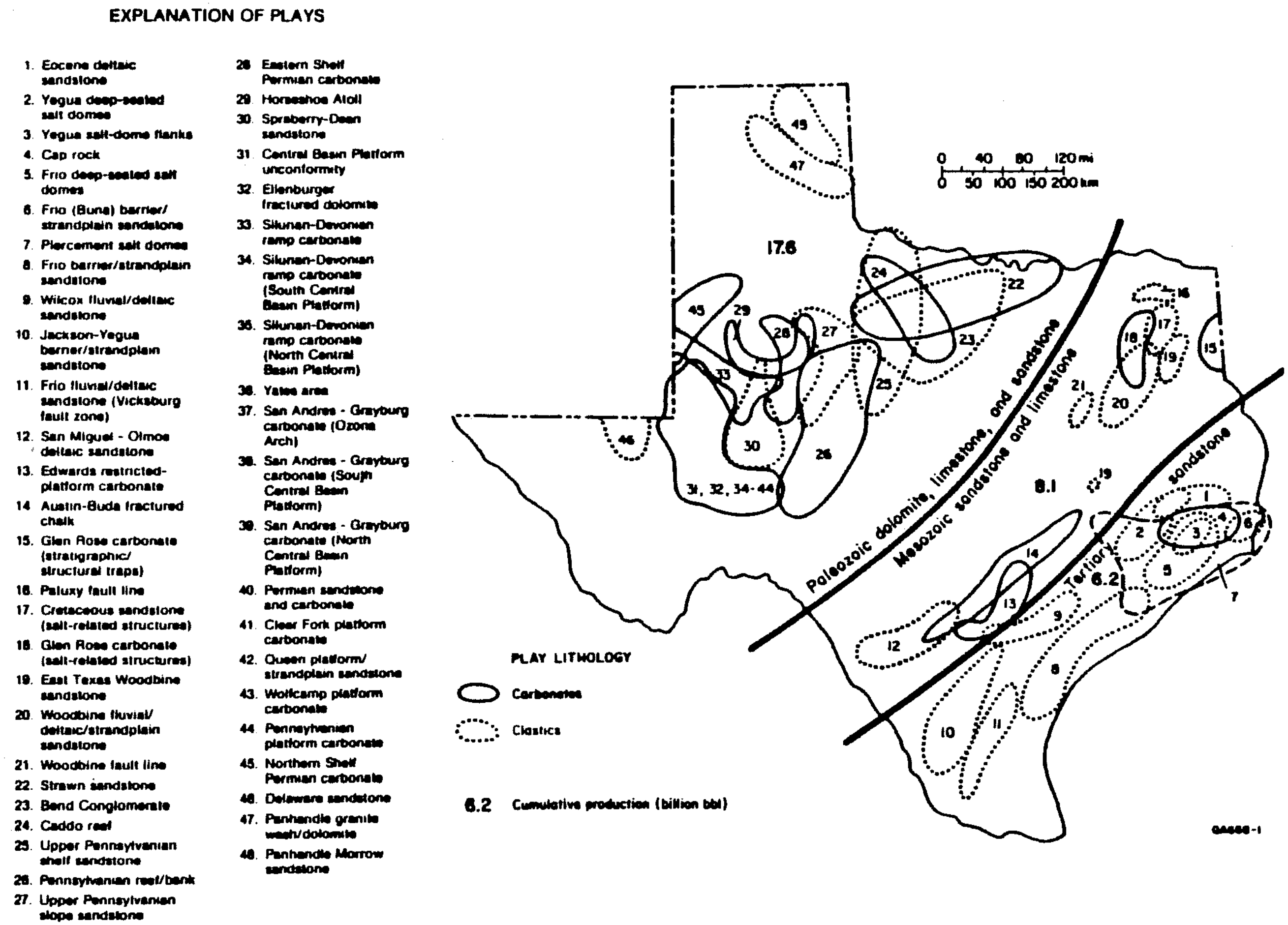

GEOLOGIC RESERVOIR CLASSIFICATION
LITHOLOGY TYPE DETERMINATION
SILICICLASTIC (S)
CARBONATE (C)
BASIN 7
SLOPE 6
REEF 5
SHELF EDGE 4
SHELF 3
PERITIDAL 2
LACUSTRINE 1
DEPOSITIONAL SYSTEM
SILICIFICATION 6
MASS DISSOLUTION 5
DOLOMITIZATION 4
DOLOMITIZATION EVP 3
GRAIN ENHAN. 2
COMPACTION 1
DIAGENETIC OVERPRINT
FAULT/FOLDED 5
FOLDED 4
FAULTED 3
FRACTURED 2
UNSTRUCTURED 1
STRUCTURE STYLE
DS = REEF (5)
DO = MASSIVE DISOLUTION (5)
SS = UNSTRUCTURED (1)
ALPHA NUMERIC CODE C 541
QA 13629

FIGURE 7

types, and trap characteristics. In a like fashion, a reservoir play group can be defined as a set of major reservoirs that have a common geological affinity, geographic proximity, and hydrocarbon type. A major reservoir can be included in only one group, while a field that is comprised of a number of stacked reservoirs may be included in more than one group. By definition, a reservoir play group is limited to a single geologic basin. The play has finite geologic and geographic limits and can be identified by its basin location and specific name to denote reservoir type and geologic age.

An example of the methodology used to group and delineate plays is provided by a study of the 500 major oil reservoirs in Texas by Tyler et al. (1984). The reservoirs were grouped into 48 plays which account for 71 percent of all historical production in Texas (fig. 8). Aggregating reservoirs using the play concept permits analysis of attributes common to the reservoir classes and the ability to compare and contrast differences between classes. Such an approach establishes a framework and provides a starting point for the assessment and analysis of remaining unrecovered oil resources.



Geographic distribution of the 48 major oil plays in Texas, modified from Fisher and Galloway (1983).

FIGURE 8

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APPENDIX I

Procedure for Classification of Reservoirs

The following procedural guide is provided to aid in the task of completing the reservoir heterogeneity classification form (fig. 6).

Before completing the classification form, first locate fields to be classified on the USGS Tectonic Province Map and then outline groups of reservoirs that have geographic proximity and geologic similarities (age, lithology, etc.). This is a first pass at defining a play to give the groups of reservoirs tentative play names. Final play names should be determined after the reservoirs have been classified.

Reservoirs should be classified starting with the largest (i.e., OOIP) reservoirs.

Section 1. Geologic Location

Geologic Province - Use USGS Tectonic Map.

Play Name - Tentative definition. Final play name to be determined after reservoirs have been classified.

Formation - Local usage is preferred.

Geologic Age - System or better using local usage.

Reservoir Name, Field Name, State - Provided by ICF.

Section 2. Depositional System

Refer to Description of Geologic Reservoir Classification System for definitions of depositional-system categories. Select the one depositional system that best characterizes the most productive section of the reservoir. Rank the certainty of your selection 1, 2, or 3, with 1 signifying most confident. If you can further describe the reservoir using the subcategories from readily available data, please do so.

Section 3. Diagenetic Overprint

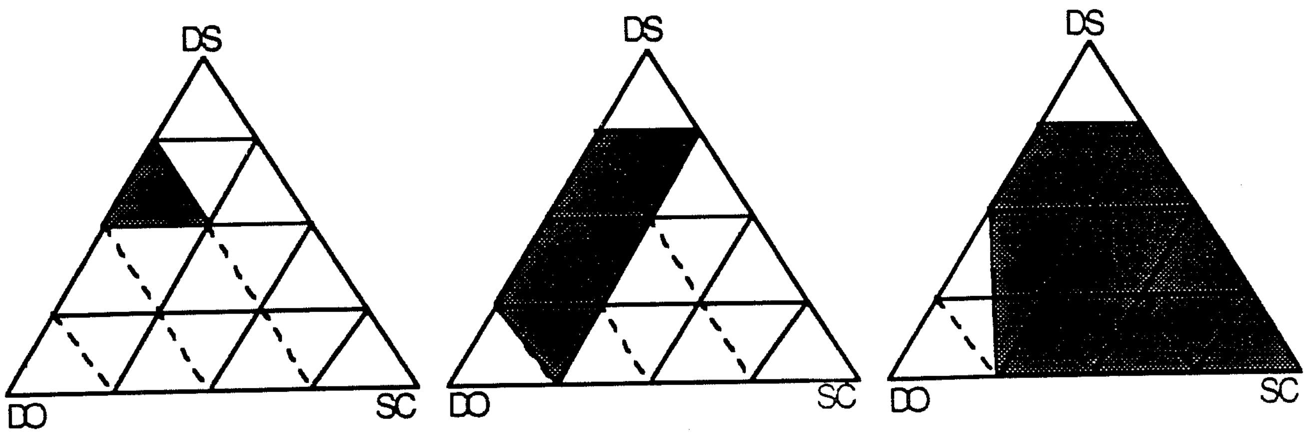
Refer to Description of Geologic Reservoir Classification System for definitions of diagenetic-overprint categories. Select the one diagenetic process that has the most dominant control on the productive characteristics of the reservoir. Rank the certainty of your selection 1, 2, or 3, with 1 signifying most confident.

Section 4. Structural Compartmentalization

Refer to Description of Geologic Reservoir Classification System for definition of structural-compartmentalization categories. Select the one structural category that best describes the structural controls on reservoir heterogeneity. The unstructured category should be selected for all reservoirs except where fracture permeability dominates production performance or where faulting and/or folding significantly compartmentalize the reservoir at an intra-reservoir scale. Rank the certainty of your selection 1, 2, or 3, with 1 signifying most certain. If readily available for fault compartmentalized reservoirs, indicate the type of faulting that compartmentalizes the reservoir.

Section 5. Reservoir Heterogeneity Ternary Diagram

Select the predominant element that, in your judgment, controls reservoir heterogeneity. On the ternary diagram, indicate the relative importance of the three elements by selecting the appropriate area. The degree of confidence can be indicated by the area selected. Three examples are shown below.



Confident of all three elements

SC - Confident
DS,DO - Little Confidence

DS,DO Confident
SC - Little Confidence

Section 6. Trap Type

This is not part of the classification and has been added to capture this information for future reference. Select the trap type that, in your judgment, best characterizes the reservoir. Please note that unconformity traps are considered a type of stratigraphic trap.