APPLICATION OF GEOLOGICAL ISOMETRIC CROSS-SECTIONS TO SECONDARY RECOVERY PROJECTS

ROBERT J. QUANCE
Sun Oil Company

INTRODUCTION

Major assets of producing companies include reservoirs that are subject to secondary recovery operations. These secondary projects can be improved upon through the proper application of technical knowledge and experience.

During the past 10 years, large investments have been made in initiating new waterfloods and gas-injection projects. Improved recovery programs have been undertaken in existing secondary operations which include infill drilling, converting new or existing wells to injection service, and well workovers designed to control or improve injection profiles. With all this activity there is a definite need to monitor well and field performance to maximize both profit and recoverable hydrocarbon reserves.

Today, high pressure waterflooding is relatively common. Typically, injection may exceed reservoir voidage over a prolonged period of time and even after fillup of the free gas space. Under such conditions, it is advantageous that everything possible be done to maximize oil production. Isometric diagrams and calculations can be used to pin-point candidates for large volume lift, selective well completions, and additional infill or development drilling since increased withdrawals are often indicated to prevent reservoir pressure from increasing unnecessarily.

The use of geological isometric cross-sections in studying and monitoring secondary-recovery programs has wide application. The isometric cross-section provides a means of incorporating inherent geological parameters that materially affect all injection projects. Of primary importance is the geological interpretation presented on the isometric cross-section showing the continuity of the various layers which directly affects vertical and horizontal sweep efficiency in a secondary-recovery project. Since the unit displacement efficiency is fixed by the injection fluid selected, improvements in existing secondary-recovery projects require a better understanding and application of geological interpretive knowledge to develop practical means of improving the areal and vertical sweep efficiency of each pattern or tract.

During primary production operations, only limited geological information is required after development drilling operations are concluded. For example, isometric cross-sections could help in primary well completions. It is only during secondary recovery operations that a more detailed and reliable geological description of the reservoir is required for monitoring the progress of the flood throughout the reservoir. The need for geological definition may become quite apparent when secondary flood performance differs substantially from predictions and forecasts. Another basic use of geological data is in properly modeling the effects of stratification. This procedure is necessary in order to match reservoir performance history in reservoir simulation studies and make reliable predictions of future performance. Exotic or tertiary recovery programs will have to be selected by operators who have the necessary technology, including a better understanding of the inherent heterogeneous nature of reservoir rocks.

DESCRIPTION OF THE ISOMETRIC CROSS-SECTIONS

The isometric geological cross-section is used to identify and correlate porous and permeable beds on a well-by-well basis. The beds correlated include intervals that contain primary oil reserves, secondary reserves, both primary and secondary reserves, previously flooded zones, and water- and gas-bearing formations since they can materially influence secondary performance.

It is necessary that the geologist show the location of faults, unconformities and the other major geological features that influence secondary flood performance.

The geological isometric cross-section illustrates the reservoir (Fig. 1). Inherent complexities of oil reservoirs are well known. They include varying porosity, permeability, water saturation, beds of varying thickness and continuity, presence of faults, potential thief zones that can be pressure sensitive, and (in some cases) the presence of primary or secondary gas caps or underlying bottom water. These features cause each area of a secondary program to be unique and difficult to monitor on a well-by-well basis without an isometric geologic cross-section.

While the conventional oil-zone isopach map and structure map, as prepared by a geologist or engineer, is often used as an aid for predicting secondary performance, it fails to provide the zone-by-zone type of detail and well information required to properly *monitor and improve* a specific secondary-recovery program. Therefore, the three-dimensional or isometric geological cross-section requires specialized geologic expertise to portray the reservoir via inter-connected geological cross-sections. The important facets of isometric cross-sections are that (1) wells are shown in proper relationship to each other, (2) log data and core analysis information, etc., are required to properly define net pay, and (3) geological interpretation is required to estimate formation continuity between wells. When the isometric is completed, the engineer makes use of each well's injection and production performance history, logs, pressure history, etc., in making as complete an analysis as required to properly understand and determine the performance of specific wells in a secondary-recovery program. After this has been done, new programs and investment opportunities can be generated. Continuous monitoring is required to ensure that the project is performing up to expectations.

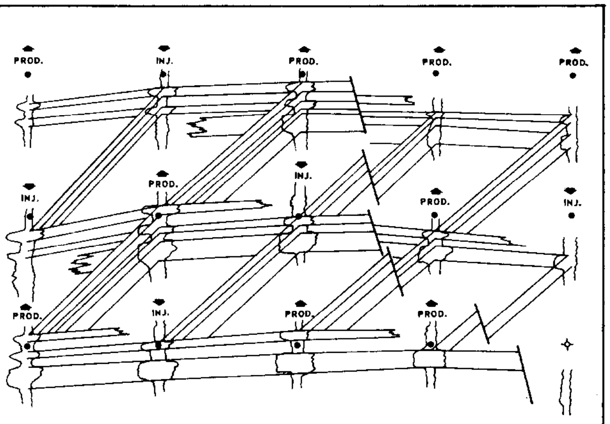

FIG. 1—GEOLOGICAL ISOMETRIC CROSS-SECTION

The need for better geological definition has been evident not only to define the net pay intervals at each well but also to show an interpretation of continuity between wells. In the case where sand is present in one well and not present in the offset well, some type of agreement between the 3-D and a pressure transient test can be sought. This work would help define the location of a permeability pinch-out or a fault.

Cross-sections have been used for the purpose of defining the reservoir, but a large number are required to interconnect all the wells. For example, with regular 40-acre spacing, there are 16 wells in a section. Four north-south and four east-west cross-sections are the minimum number of cross-sections required to correlate all 16 wells.

Essentially, this same amount of information can be shown on one isometric geological cross-section. In many cases, wells located along a north-south line should be rotated to an angle from 30^0 to 60^0 from the horizontal east-west line to eliminate hidden lines. Another practical step is to rotate the isometric diagram along the major axis of the field since the width of each panel is limited by the capability of the reproduction equipment (42 inches). Several panels are constructed to cover a reservoir containing numerous wells with the last row of wells repeated on the next panel. After reproduction, the panels can be overlapped to show a larger area of the reservoir.

In construction of an isometric diagram, it is often convenient to locate wells either on a geological correlation interval or on a subsea datum. A film of the log can be used as an overlay to aid correlation with adjacent wells. In a few cases, the wells are shifted in location to provide the best visual display of the reservoir. Further flexibility and speed of preparation can result from shifting wells to equal distances on the diagram where non-uniform spacing occurs since the isometrics are used to describe inter-reservoir flow. When volumetric data is required, it is of course necessary to construct zonal isopach or zonal porosity-foot isopach maps. It is only when the recovery performance is considered and evaluated on an individual-layer basis that can determine if adequate areal and vertical sweep can occur. All too often, only the most permeable layer is adequately depleted.

PREPARATION OF THE ISOMETRIC CROSS-SECTIONS

It is well known that oil reservoirs selected for secondary-recovery programs have widely varying geological characteristics and can be considered to be made up of isolated beds or layers. In other more exceptional cases, the formation may become massive with good-to-excellent horizontal and vertical inter-connection. Also, this variation between layered beds and a massive zone can occur over distances of less than the normal oil-well spacing. The type of geological interpretation required for the initiation of a project is often insufficient to monitor performance or make reservoir studies.

The three-dimensional (3-D) geological cross-section is uniquely applicable to defining the reservoir and assisting with engineering work since the oil-recovery program can best be reviewed in a three-dimensional arrangement where wells are located in their approximate relative position. The geologist uses the following information: electric-log analyses, core-analysis data, DST, and completion information. By interconnecting straight lines, the major zones of fluid flow are indicated.

Fig. 1 shows an idealized 3-D diagram for a portion of a hypothetical oil field. A basic porosity log, such as an electric log or a radioactive log, will usually be shown on a 3-D diagram and used as the basic correlation tool. Porous and permeable zones that correlate between wells are connected with lines showing the top and bottom of each major productive zone or interval. These porous and permeable zones should be colored on the final print to represent intervals where fluid flow can occur. The same color applied to several isolated layers would indicate that they are a part of the same geological unit or perhaps they become more massive or interconnected over part of the field. Dense zones are left blank.

In the preparation of the 3-D diagram, logs are reduced on film to a selected vertical scale. These films are applied to the reverse side of transparent material of the size selected for the final 3-D panel. Correlation work is done on a blue line print and the beds can be colored to check the accuracy of this work. The finished isometric can be completed by design draftsmen.

In a practical application, high porosity zones can be indicated by a darker color, while lower porosity zones in the same bed can be shown in a lighter shade of the same color. To do this work, the geologist needs to be able to incorporate log-analysis work and estimate the porosity levels found in each well. A simple code or color number can be shown to indicate the coloring selected for the final prints; eg., "H" could represent a dark color, "L" could represent a light color, and "X" could represent dense zones. Dashed lines can be used to separate different colors or shades.

The essential concept is that the isometric cross-section need not be 100-percent accurate since knowledge of reservoirs is often quite limited and a revised isometric can be prepared whenever more basic reservoir data becomes available.

The 3-D diagram is a compact method of showing what can be depicted on a multiple series of cross-sections. Basically, they both show stratigraphy, structure and continuity of porous intervals in a reservoir. From the 3-D diagram, which is a more sophisticated study, isopore volume maps can be prepared for each net pay interval or bed to permit engineering calculations to be prepared showing original oil in-place, oil recovery performance, and flood-out patterns by layers using hand or computer-simulation methods.

Often, several panels are required to cover an entire reservoir of 100 wells or more. One large 3-D project consists of over 24 panels, each 4-feet x 20-feet long, and required several man years to prepare and update.

ENGINEERING USES OF ISOMETRIC CROSS-SECTIONS

Geological isometric cross-sections, in summary, are required to find the extent of each producing zone in a reservoir and *whether it is effectively interconnected between the injection and producing wellbore system*. At the injection well, injection-profile surveys and temperature surveys are normally taken once a year, for example, to quantatatively measure the injection volume into each layer or zone. Then cumulative injection volumes are compared to a fraction of the displaced oil-pore volume by the use of the isopore-volume maps and a basic knowledge of reservoir displacement efficiency. Here the reader is referred to references 1 and 2.

Zones which are found from production data to be fully depleted should be considered as candidates for zonal isolation to prevent cycling of unnecessarily large volumes of injection fluid which is both wasteful and may lose reserves because counterflow can occur in the producing wellbore. Also, new injection wells, producing wells, or both may have to be drilled to improve sweep efficiency, both areally and vertically.

All this work requires that geological isometric cross-sections be made and updated where necessary, using all pertinent geological and production data. Particular attention should be paid to areas of low recovery which may indicate potential trapped-oil or by-passed locations. These areas may require infill drilling or modified injection patterns to provide satisfactory reservoir sweep. Before such wells are actually proposed for drilling, it is perhaps necessary to consider the effect of potential thief zones on well performance. In some cases by-passing, unless controlled and managed at the injection well, could be so severe as to make the drilling of such wells extremely risky.

Reservoirs subject to secondary recovery projects are generally layered or stratified. This means that the flood front has progressed varying distances from the injection well, dependent upon each zone's injectivity and pore volume. The relative injectivity into each layer is usually determined by injection profile surveys, packer isolation tests, temperature surveys, etc. With the completion of a geological isometric cross-section, it is then necessary to prepare net pay or porosity-foot maps of individual pays within the total productive horizon.

Calculation of the water bank radius for each individual zone, previously open or currently open to injection, can be generated using information obtained from injection-well profile surveys and cumulative injection volume of each well. Neglecting the interference effect of waterflood fronts, one can calculate the water-bank radius in an individual pay zone for a given cumulative injection volume assigned to that layer by the following.

$$r_i = \left(\frac{5.61\,(W_i)}{\pi\, \phi_i h_i\, (1-S_{cw}-S_{or}-S_{gr})} \right)^{1/2}$$

Where:

r_i = Water bank radius, ft.
W = Cumulative water injected, bbl.
ϕ = Porosity, fraction
h = Net pay thickness (ft.)
S_{cw} = Connate water saturation, fraction
S_{or} = Residual oil saturation, fraction
S_{gr} = Residual gas saturation, fraction

Subscript:

i = Layer 1, 2, 3, . . .

After the water-bank radii are calculated, maps can be prepared for each layer to show the location of the water-flood front, assuming radial flow. Although interference effects and permeability variations distort the flood-front locations, these maps are often adequate to indicate the probable zone causing breakthrough and the zones that require additional injection. This may provide an excellent guide as to where unswept oil may be present in the areal and vertical directions. Improving this parameter becomes a primary goal, because low sweep efficiencies are often responsible for the unacceptably low water-flood recovery efficiencies.

With the use of the isometric cross-section, it will be possible to center more attention on the producing well since a favorable completion ratio is required to provide adequate drainage of each zone.

A gas-injection project can be analyzed in a similar manner, providing information is available on the displaced oil saturation and a formation volume factor is used to convert injected gas volumes to the space the gas occupies in the reservoir.

FIELD EXAMPLES OF USING ISOMETRIC CROSS-SECTIONS

Practical applications of this work include selecting locations for the drilling of infill wells that are located directly offset to water-injection wells having large cumulative injection but where injection was not distributed over the effective pay. Also, in numerous cases, infill wells are required where a major bed is not continuous over the normal well spacing. With an infill drilling program, isometrics can be used to identify locations where wells are required to commence flooding discontinuous pay, re-establishing production of zones that are not continuous over the entire well spacing, and provide needed information for the effective completion of the newly drilled wells. There are cases where isometrics depict wells which require deepening to expose all effective oil pay. In many of these cases, wells are completed with liners and then perforated prior to being stimulated. While these are just some examples, the practical economic significance cannot be disputed since sizable reserves can be developed economically by improving the areal and vertical sweep efficiency.

With the even greater cost and complexity of tertiary recovery, it remains a challenge to properly use all information, including the greater geological input available from isometric cross-sections to minimize future operating costs and maximize the recovery of potentially economic reserves.

SUMMARY AND CONCLUSIONS

Flood performance can be no better than the geology. Injection-well performance and producing-well performance are obviously dependent and interrelated. Isometric work is absolutely essential to define and understand complex well and reservoir behavior. Yet, besides the basic planning and control aspects of reservoir isometrics, tangible reservoir and operational benefits appear. Here are a few of the important applications:

1. Permeability pinch-out areas may be located which may require a change in injection pattern or infill drilling of additional wells for adequate drainage.
2. The degree of geological continuity should be determined and assessed by specific beds or layers that would require multiple zone producers, injectors, or both.
3. Wells may have unperforated intervals or may require deepening to the oil-water contact or base of the pay to recover trapped oil, to improve areal and vertical sweep, or both in an injection program.
4. Injection and producing wells may have ineffective connection to oil pay in surrounding wells as determined from temperature logs, profile surveys, etc.
5. Zones that are fully depleted can be identified for temporary or permanent shut-off procedures. By this method, adverse counterflow in the producing wellbore may be reduced that would otherwise trap-off undepleted oil zones having lower pressure.
6. A number of perforation and stimulation prospects may become apparent to improve injection and producing well efficiency.

REFERENCES

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