A PROGRAMMED METHOD FOR THE COMPUTATION OF BRINE AND SOLID PHASE RESERVES OF EVAPORITE LAKE DEPOSITS

by

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ABSTRACT

This thesis presents a method for the computation of solid and brine phase reserves of evaporite lake deposits. The method takes advantage of the time-saving features of electronic data processing.

The anisotropism of evaporite lake deposits provides easily discoverable and meaningful criteria for the selection of zones for computation purposes. Such zones may be determined by lithology, mineralogy, chemical composition, and such physical properties as porosity and permeability.

Once zones are selected, maximum accuracy of computations is obtained by dividing the zones into blocks by means of a network of isopachs, isopleths, and isopors.

CHAPTER I

INTRODUCTION

In the most general case an evaporite lake deposit consists of two phases, a brine phase which is the original or modified "mother brine", and a solid phase which has resulted from evaporation of the brine. An inland lake containing high concentrations of the ions which form evaporite minerals may be considered a limiting case in one direction, while a brine-free deposit such as the Green River trona beds represents the opposite limiting case. Regardless of whether production is contemplated from only one or the other of the two phases, both must be taken into account in reserve estimates. For example, if only brine production is planned, porosity and permeability information is required for a preliminary reserve estimate; the same information plus data on the chemical composition of the solid phase will be required for production planning and subsequent reserve estimates due to brine-solids interactions.

This thesis, then, describes a method of computing the reserves of the most general type of evaporite lake deposit. Only those geologic features which may affect reserve computations are discussed.

Electronic data processing is indispensable in certain operations or stages of the estimates and may be very useful in other stages. This is discussed in Chapter III. Since this thesis is concerned only with reserve estimates, topics such as the use of operations research methods in the location of test wells for the optimum gain of information are not discussed.

CHAPTER II

FEATURES OF EVAPORITE LAKE DEPOSITS

A. Anisotropism Resulting from Depositional Processes

Evaporite lake deposits may be anisotropic to a much greater degree than is at first apparent. The most significant anisotropism usually results from the processes of formation of a deposit and consists of zonation of several components and physical properties. There may be several periods of influx and evaporation of brines, and several evaporite minerals may be sequentially precipitated during any one period. This results in stratification of both brine and solid phases. Searles Lake, California, provides an excellent example of stratification. As indicated by the U. S. Geological Survey and others (Gale 1915, Flint and Gale 1958), the upper salt body there consists of the precipitates and brines of two periods of inundation and evaporation. The resulting vertical zonation plays an important role in reserve calculations since it provides the basis for selecting for use in calculations natural and logical units such as hanksite ($9Na_2SO_4 \cdot 2Na_2CO_3 \cdot KCl$) layers, trona ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$) horizons, zones of greater-than-two percent KCl brine, and others.

Porosity and permeability of a deposit will also vary with depth since the evaporite minerals exhibit widely varying depositional textures and crystal shapes.

B. Post-Depositional Variations

In addition to anisotropic features resulting from depositional processes, there will be other such features induced by post-depositional geologic processes and by industrial production activities. Some of these features may also affect reserve calculations.

Tectonic activity and/or basin subsidence may result in many anisotropic features including permeability contrasts and barriers, faults, fracturing, and warping of salt horizons. The Trona Reef of Searles Lake, California, is believed to result from upward movement of brine along a fracture zone. Earthquake shocks may fracture impermeable mud seams, thus permitting mixing of high and low grade brines in salt horizons separated by the seams.

Production of brine with consequent influx of peripheral, and probably lower grade, brine and groundwaters probably upsets the chemical balance of the deposit. Brine-solids interactions may occur, and it is conceivable that porosity and permeability in a region could change. This could be extremely significant if undesirable and irreversible reactions are set in motion.

Most of the factors mentioned in this section are of consequence primarily in production planning and in reserve estimates after the deposit has been put in production. However, recoverable reserves will be affected to a degree by permeability barriers if such exist.

CHAPTER III

RESERVE CALCULATIONS

A. Data Requirements

The following data are required for a pre-production reserve estimate:

(1) solid phase chemical analyses
(2) brine phase chemical analyses
(3) total porosity
(4) effective porosity
(5) permeability
(6) specific gravity of solids and brine.

For purposes of production planning and post-production reserve estimates, the following data should also be gathered:

(7) hydrostatic head of brine in various salt horizons
(8) temperature of brine.

These factors will be discussed briefly in Chapter IV.

The total and effective porosity, permeability and solid phase analyses are, of course, obtained from core samples. Precautions must be taken in brine sampling to assure that the brine taken as representative of that occurring in a specified salt horizon actually is so representative.

Chemical analyses of brine and core will be reported by laboratories in terms of components and ions. Percentages of compounds and ions must then be converted to equivalent percentages of desired constituents and to equivalent percentages of minerals. For example, in a potash deposit all potassium might be reported as K^+. It is desirable to know the distribution of the potassium in terms of minerals, as well as knowing the equivalent tons of K_2O or KCl.

Figure 1 (see pocket) is a flowchart for the conversion of ions and compounds as reported by laboratories to the five major minerals occurring in the upper and lower salt bodies, respectively, of Searles Lake, California. The flowchart also incorporates a method of removing the effect of "entrained brine" on solid phase reserve estimates and on studies of solid phase mineralogy. Not all the brine in a section of core will run out of the core prior to packing it for shipment. Some will remain in the core as "entrained brine"; it will evaporate during heating and its constituents will be reported as solid phase components. This effect can be taken into account if some element or compound, for example P_2O_5 or Br^-, is present only in the brine phase. Then the percentage of various constituents reported in the solid phase analyses, but actually due to entrained brine, can be calculated from the percentage of P_2O_5 or Br^- reported in the solid phase analysis. The flowchart, Figure 1 (see pocket), includes a method for taking into account entrained brine effects.

Figure 2 (see Appendix) is a Fortran Program for the conversion of ions to minerals in the case of Searles Lake.

B. Computation Method

The first step is to determine the vertical and lateral zonation of a deposit if such exists and to construct cross-sections. The purpose of this is to facilitate the selection of the most meaningful units for computation. For example, 95 percent of the brine containing economic concentrations of potash may lie within the boundaries of one solid phase zone. In reporting reserves in such a situation one would want to use two categories: (1) tons of KCl within the potash zone, and (2) tons of recoverable KCl lying outside the potash zone.

Zonation or stratigraphy can be established by constructing and interpreting cross-sections based on the composited results of core and brine analyses to appropriate intervals, ordinarily not more than five feet. A breakdown to smaller intervals may be necessary, for example to one- or two-foot intervals. The geologist logging the core is in the best position to determine the required interval. This should be kept in mind when making specifications for laboratory tests. The composited analyses of a number of test wells in a line across the deposit will be an accurate cross-section of the deposit. Two sets of sections, one set normal to the other, should be constructed. The zones selected for computation purposes will actually be delimited using these sections. Porosity and permeability should be composited to the same intervals as the chemical analyses.

The compositing is most speedily and economically done with the use of an electronic digital computer. The composited results for each of the several wells constituting a cross-section can be printed across a single output sheet. The zonation can then be depicted by drawing the appropriate vertical boundaries from well to well on the computer output sheet itself. The output format should call for proper spacing of the wells on the sheet, thus saving replotting.

Having drawn the cross-sections and selected the zones which will be used for computation, the next step is to construct two sets of isopach-isopor maps of these zones. While both sets will have the same isopachs, one set will have isopors of the total porosity and one set will have isopors of the effective porosity.

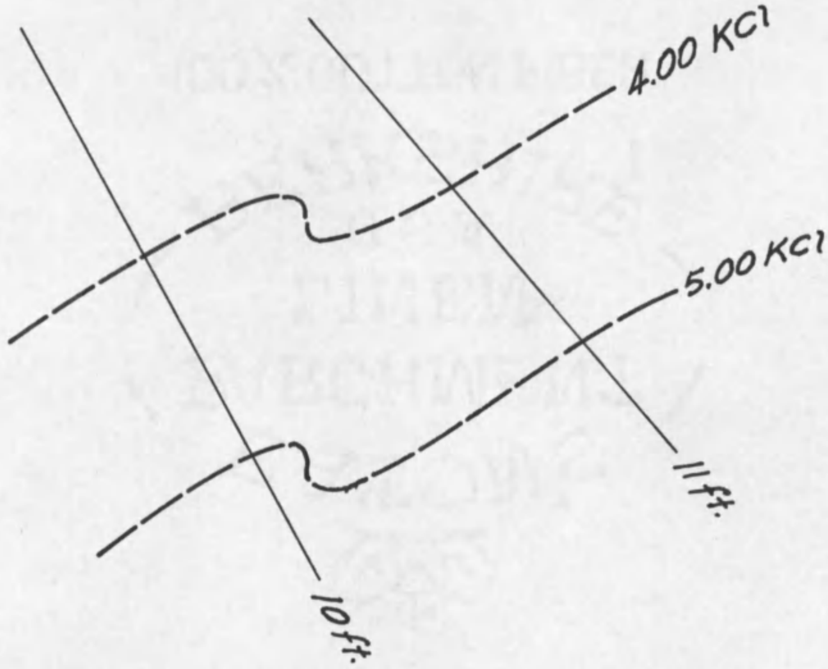

Figure 3. Isopach-Isopleth Net.

Next, overlays of isopleths of each component of interest in the zone are drawn to the same scale as the isopach-isopor maps. The values of porosity and percent of desired constituent used to draw the isopors and isopleths, respectively, are determined by summing and averaging the values of each five-foot interval in the zone for each data point (well). Thus, these values are actually weighted averages.

The amount of any desired constituent in the zone, either in brine or solid phase, is then obtained in the following manner:

(1) The proper isopleth overlay is placed on the isopach-isopor map. The intersections of the three sets of lines, isopachs, isopors and isopleths, break the zone into a number of segments. The area of each segment is obtained by planimeter.

(2) The area of each segment is multiplied by its thickness as determined by visual inspection of the isopachs to obtain the volume of each segment.

The methods of calculation for solids and brine diverge at this point. Brine is considered first.

(3a) The volume of each segment is multiplied by its effective porosity as determined by inspection of the isopors. This operation gives the volume of recoverable brine in the segment. If total brine, recoverable and non-recoverable, is desired, then the isopach-isopor map with isopors of total porosity must be used.

For the solid phase:

(3b) The volume of each segment is multiplied by its total porosity as determined by inspection of the isopors, and the resulting value is subtracted from the volume of the segment. The remainder is the volume of solids in the segment.

From this point on the computations for brine and solids are again similar.

(4) The result of (3) is multiplied by the appropriate tonnage factor as determined by the specific gravity of the brine or solid phase. This gives the tons of brine or solids in each segment.

(5) The tonnage of solids or brine is multiplied by the percentage of the desired constituent

in the segment. This step gives the tons of the desired constituent in each segment.

(6) The results of step (5) for all the segments are summed to obtain the total tonnage of the desired constituents in the zone.

Having obtained the areas of the segments by planimeter and the corresponding thicknesses, porosities and grades by visual inspection, these values can be punched on data cards and the calculations carried out by computer. This could result in some saving of time if computer facilities were readily available. The program for such a procedure involves nothing more complicated than multiplication and is therefore not appended.

The areas of the small segments bounded by the isopach, isopor and isopleth lines could be calculated by computer. A statistical method could also be programmed for the assignment of values of thickness, porosity and grade to the segments rather than selecting these values by visual inspection. Neither of these steps is recommended, however, for reasons discussed in the following section.

Other computation methods could be used such as construction of polygons or numerical integration over surfaces defined by functions representing distributions of values of chemical analyses, thicknesses, etc. The isopach-isopleth-isopor method is believed to be more accurate than the polygon method and is believed to present a clearer geologic picture.

The writer has not studied the applications of distribution function - numerical integration techniques in detail. It seems, however, that the boundaries of evaporite zones studied by the writer to date should lend themselves to representation by mathematical functions without excessive difficulties.

C. Applicability of Electronic Data Processing Methods

The anisotropism of evaporite lake deposits and the large amount of data required for accurate reserve estimates require a great deal of time and money to be spent carrying out laborious computations unless advantage is taken of electronic data processing methods. In one case, six man-months were required to compute the reserves of one constituent of a large, but very anisotropic evaporite lake deposit using desk calculators. The same job could have been done in one man-month by taking advantage of electronic data processing methods. Thus the applicability of the electronic digital computer to the conversion of chemical analyses to valuable constituents and minerals, to the compositing of well data, and to the final volume and tonnage calculations have been mentioned above.

Of course, the entire process of reserve estimation could be accomplished by computer. This would involve writing a very complex program which would include instructions defining values for the delimitation of economic zones, instructions as to the number of points required to accurately define the curved lines between isopleth-isopach-isopor intersections, a statistical method for assigning thicknesses, etc., to segments of zones, and other features. This is believed to be an inadvisable undertaking. In the first place the accuracy would in all probability be no greater than that obtained by visual inspection of isopach-isopleth-isopor maps. The area calculations by computer could be less accurate than the calculations obtained by planimetering. The most dangerous aspect is that such a method may cause a geologist to overlook important features of a deposit that he would notice in visual inspection of cross-sections, isopachs, etc. The computer cannot discriminate between significant relationships unless programmed to do so (and if a geologist knew every variation he would encounter in a deposit prior to his study of it, there would be no need to drill exploratory wells to begin with). Thus the computer should be used to assist the geologist and not to do his work for him. If anything, use of a computer requires better geologic insight than might otherwise be required.

A computer could be used to calculate the areas of the segments of the zones, but this would involve the selection of a very large number of points for each constituent in each zone, writing and running a program. It is believed that this process would not be any faster than planimetering.

In the computation of reserves in evaporite lake deposits the computer is best used where it can save time and money, or where it can assist the geologist to obtain a clearer picture of a deposit.

The applicability of computers to production planning and post-production reserve estimates is discussed in Chapter IV, below.

CHAPTER IV

PRODUCTION PLANNING AND POST-PRODUCTION RESERVE ESTIMATES

Production planning and related post-production reserve estimates are outside of the subject of this thesis. They are, however, related and thus deserve brief comment.

The essence of production planning is the determination of that combination of wells and pumping rates which will maximize profits over the desired life of the deposit. This requires more information than the original reserve estimates. Pumping tests must be carried out to determine draw down rates, to locate possible permeability barriers, and to determine the effect of pumping on grade. These pumping tests may also provide information on solids-brine interactions when studied in conjunction with the zonation of the minerals. Careful and systematic sampling of brine from all wells, not just those being pumped, should be carried out. Operations research techniques may be employed to locate further wells for either maximum profits or maximum gain of information on the deposit.

The amount of computation that is involved in such a program would require months to carry out and would involve many technicians. Electronic data processing is an indispensable tool in such an undertaking. Savings in time and money due to the speed of data processing would be very considerable and in addition, the deposit could be put into production under optimum conditions months sooner than if computer techniques were not used.

Post-production reserve estimates must take into account the effects of production on the grades of the remaining components. These effects may considerably alter previously held notions of recoverable reserves.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The reserves of evaporite lake deposits should be calculated in a manner that takes advantage of their anisotropism and points out limitations imposed by their anisotropism. Selection of zones for computation based on composited drill core analyses followed by computation by means of an isopach-isopleth-isopor net is believed to be the best method. Electronic data processing can be used to advantage in the reserve computations in reducing the time needed for calculations and in arranging data in such forms as may bring important geologic features of the deposit to the geologist's attention.

The methods discussed in this thesis may be extended to any stratiform ore deposit.

APPENDIX

Figure 2

Fortran Program

```
***     HARRY WINTERS
*       COMPILE FORTRAN,EXECUTE FORTRAN

C         THIS PROGRAM CONVERTS IONS TO MINERALS.
C         READ A CARD CONTAINING ION CONTENTS.
        5 READ 10,100,HOLE,XK,CL,HCO3,CO3,SO4,B4O7,XNA,ORG
       10 FORMAT(9F6.2)
C         ORG=ORGANIC CONTENT.
          TOTNA = XNA
C         HANKS=HANKSITE
          HANKS=(1.955*SO4)-(3.202*XK)
          HKCL = HANKS*0.0227
          HKCO3 = HANKS*0.0767
          HKNA = HANKS*0.3233
          HKK = HANKS*0.0250
          HKSO4 = HANKS*0.5524
C         GLAS=GLASERITE
          GLAS = (3.060*XK)-(0.138*SO4)
          GLNA = GLAS*0.0692
```

Figure 2--*Continued*

```
      GLSO4 = GLAS*0.5780
      GLK = GLAS*0.3528
C     ANBOR=ANHYDROUS BORAX
      ANBOR = 1.296*B407
C     HALIT=HALITE
      HALIT = 1.649*(CL-HKCL)
      HLNA = HALIT*0.3934
      HLCL = HALIT*0.6066
C     ANTRO=ANHYDROUS TRONA
      ANTRO = 1.5832*(CO3-HKCO3+(0.9834*HCO3))
      ATHCO = ANTRO*0.3211
      ATCO3 = ANTRO*0.3158
      TOTMN=GLAS+HANKS+ANBOR+HALIT+ANTRO+ORG
C     PRINT MINERALS.
      PRINT 50, HOLE,HANKS,GLAS,ANBOR,HALIT,ANTRO,ORG
   50 FORMAT(7F6.2)
      GO TO 5
  100 STOP
      END
```

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Gale, Hoyt S. (1915), Salines in the Owens, Searles, and Panamint Basins, Southeastern California: U. S. Geol. Survey Bull. 580-L, pp. 251-323.

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Figure 1
SEARLES LAKE DEPOSIT

FLOW CHART OF
CONVERSION OF IONS TO UPPER STRUCTURE SOLID PHASE MINERALS

Drawn by: H. Winters

Date: January 1966