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METHODOLOGY FOR MODELING THE STANFORD HEAT EXTRACTION EXPERIMENT

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METHODOLOGY FOR MODELING THE STANFORD HEAT EXTRACTION EXPERIMENT

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Introductory Note

This report was written as a chapter for a report on "Analysis of the Stanford Geothermal Reservoir Model Experiments Using the LBL Reservoir Simulator," to be issued by the Stanford Geothermal Program. It summarizes the governing equations and solution method of the geothermal reservoir simulator MULKOM, and describes the discretization method employed in modeling the Stanford heat extraction experiments.

Description of LBL Reservoir Simulator

The simulations reported below were carried out on Lawrence Berkeley Laboratory's CDC-7600 computer, using the multi-purpose simulator "MULKOM". MULKOM was developed at LBL for simulating the flow of multi-component, multiphase fluids and heat in porous or naturally fractured media (Pruess, 1983a). The flow equations solved and the mathematical and numerical methods used in MULKOM are similar to the geothermal reservoir simulator SHAFT79 (Pruess and Schroeder, 1980).

Here we will briefly summarize the equations solved by the simulator, emphasizing the main assumptions and approximations made. Subsequently we shall outline the solution method, and discuss the discretization procedure employed for representing the various components of the Stanford geothermal reservoir model.

1. Governing Equations

The version of MULKOM used in the present study solves two coupled equations for each volume element of the flow domain, which express a mass balance for water, and a heat balance. In space - and time - discretized form the equations for volume element n are:

$$\left(\Phi_n^{k+1}\rho_n^{k+1} - \Phi_n^k\rho_n^k\right) - \frac{\Delta t}{V_n}\left\{\sum_m F_{nm}^{k+1}A_{nm} + V_n q_n^{k+1}\right\} = 0 \qquad (1)$$

$$\left(U_n^{k+1} - U_n^k\right) - \frac{\Delta t}{V_n}\left\{\sum_m G_{nm}^{k+1}A_{nm} + V_n Q_n^{k+1}\right\} = 0 \qquad (2)$$

Here n and m label the volume elements (n,m = 1, ..., N), and k is a time step counter. Φ_n^{k+1} is (average) porosity of volume element n at time level t^{k+1}, ρ is density, $\Delta t = t^{k+1} - t^k$ is time step size, V_n is the volume of element n, F_{nm}^{k+1} is the mass flux between elements n and m at time t^{k+1} (defined below), A_{nm} is the interface area between elements n and m, q_n^{k+1} is a mass sink or source term, U_n is the internal energy of volume element n (defined below), G_{nm}^{k+1} is the heat flux between elements n and m at time t^{k+1} (defined below), and Q_n^{k+1} is a heat sink or source term. The sums in equations (1), (2) extend over all elements m which share a surface segment with element n. To assure unconditional stability, we have used a fully implicit formulation, with all fluxes and variable sources evaluated at the new time level t^{k+1}.

We assume that mass flux is given by Darcy's law

$$F_{nm} = \sum_{\beta} \left(\frac{kk_\beta}{\mu_\beta}\right)_{nm} (\rho_\beta)_{nm} \left[\frac{P_m - P_n}{d_{nm}} - (\rho_\beta)_{nm} g_{nm}\right] \qquad (3)$$

The summation here extends over the phases present (β = liquid, vapor). k is absolute permeability, k_β is relative peremability to phase β ($0 < k_\beta < 1$), μ is viscosity, P is pressure, d_{nm} is the nodal distance between elements n and m, and g_{nm} is the normal component of gravitational acceleration between volumne elements n and m. The subscripts (nm) indicate that the respective quantities are to be evaluated at the interface between elements n and m. Different weighting procedures can be selected for this, e. g. harmonic weighting, spatial interpolation, or upstream weighting.

The heat flux G_{nm} has a conductive and an advective component:

$$G_{nm} = K_{nm} \frac{T_m - T_n}{d_{nm}} + \sum_{\beta} (h_\beta)_{nm} (F_\beta)_{nm} \qquad (4)$$

K_{nm} is thermal conductivity at the interface between elements n and m, T is temperature, and h_β is the specific enthalpy of phase β.

Finally, the volumetric internal energy of the rock/fluid mixture is written

$$U_n = \phi_n \rho_n u_n + (1 - \phi_n) \rho_R C_R T_n \qquad (5)$$

Here ρ_n is the (average) fluid density in element n, u is specific internal energy, ρ_R is rock grain density and C_R is rock specific heat.

The main assumptions made in the above formulation are as follows: (1) Liquid, vapor, and rock are locally in thermodynamic equilibrium (i.e. at the same temperature and pressure at all times). (2) Kinetic energy and inertial force terms are neglected. (3) Capillary pressure and phase adsorption effects are neglected. The above equations need to be complemented with a description of the thermophysical properties of water in its liquid and vapor phases. In MULKOM the steam table equations as given by the International Formulation Committee are used (1967), which represent the needed parameters within experimental accuracy.

2. Solution Method

The governing equations as given above are in general highly non-linear, because of non-linear material properties and parameter changes during phase

transitions. Futhermore, mass and energy balance equations are strongly coupled, as in most geothermal applications mass flow is the dominant heat transfer mechanism. The flux terms also strongly couple the balance equations for different volume elements.

Because of these features of the equation system, MULKOM performs a completely simultaneous solution, taking all coupling terms into account. Newton-Raphson iteration is performed to handle the non-linearities. The linear equations arising at each iteration step are solved directly, using Gaussian elimination and sparse storage techniques. The linear algebra is performed with the Harwell subroutine package "MA28", which efficiently handles non-symmetric matrices with random sparsity structure (Duff, 1977). This feature is essential for the particular discretization technique used to represent the Stanford geothermal reservoir model (see below).

3. Discretization of the Flow System

In porous media, the variables of thermodynamic state are usually slowly varying functions of position. Under these conditions it is appropriate to discretize the flow domain for purpose of calculation into a number of "sufficiently" small simply-connected volume elements. Conceptually, this approach is straightforward, and it could also be applied to the Stanford geothermal reservoir model (SGRM). However, this is not very practical, as it would lead to a prohibitively large number of volume elements. The SGRM contains 30 rectangular and 24 triangular rock blocks, in which three-dimensional heat flow patterns evolve during heat extraction. Discretization needs to be rather

fine near the block surfaces, so that the steep temperature gradients at early times of the cold sweep experiment can be adequately represented. A rather coarse discretization would probably require of the order of 100 or more volume elements per rock block, and many additional elements to represent the water channels between the blocks, and the steel vessel. Clearly approximate methods are needed which permit a drastic reduction of geometric complexity.

The simulations performed in the present study used the method of "multiple interacting continua" ("MINC"; Pruess and Narasimhan, 1982). The MINC-method was developed as a simplified approach to calculating fluid and heat flow in fractured geothermal reservoirs. Part of the approximations made in this method had already been tested and validated against analytical solutions by C. H. Lai (personal communication, 1982). However, a more complete evaluation of the MINC-method by comparison with fluid flow and heat transfer experiments was considered desirable. The present simulation studies were in fact motivated by the hope to accomplish an experimental test of the MINC-method.

Before presenting specific details of the MINC-discretization employed in our simulations, it is appropriate to briefly review the basic ideas behind the methodology. A more complete discussion was given by Pruess and Narasimhan (1982) and Pruess (1983b).

The MINC - method is an extension of the familiar double-porosity concept for fractured reservoirs. A fractured reservoir is idealized as consisting of rock blocks separated by void spaces (see Figure 1). If such a system of hot rocks is swept by cold water, the water will flow rapidly through the fracture system, while heat will be conducted from the blocks to the water

on a much slower time scale. The MINC-method makes the approximation that the rock blocks are engulfed by cold water virtually instantaneously, so that heat flow within the blocks will occur in an essentially one-dimensional pattern, namely, outward towards the block faces. With this approximation, it is then possible to discretize the rock blocks into a one-dimensional string of nested volume elements, defined on the basis of distance from the block faces. This discretization is shown schematically in Figure 2 for a two-dimensional case. Note that this discretization correlates only approximately with the temperature distribution in the blocks, even if the assumption of an instantaneous temperature change at the block faces is valid, because near the block corners conduction effects of several block faces interfere. A more accurate discretization would employ curved interfaces, coinciding with the isotherms for the heat flow problem (e.g. Carslaw and Jaeger, 1959). However, for the problem of heat transfer between rock blocks and surrounding fluid, the detailed temperature distribution within the blocks is irrelevant, as long as the total rates of heat flow across the block faces are accurately predicted. Numerical and analytical studies by C. H. Lai for regularly shaped blocks have shown that the MINC approximation yields total heat flow rates at the block surface which are accurate to within a fraction of a percent (C. H. Lai, personal communication, 1982).

The other important approximation made in the MINC-method, namely, that temperature change at the block faces is sudden and instantaneous in comparison to the time needed for significant heat transfer from the blocks to the surrounding water, is not well justified for the conditions of the SGRM experiment. This is because of the small scale of the rock blocks and the large void spaces, which cause flow velocities to be rather small. The thermal diffusivity for the granite rocks is approximatley $\kappa = 10^{-6}\ m^2/s$, so that

the diffusion lengths $L_d = \sqrt{\kappa t_\ell / 2}$ corresponding to the time t_ℓ it takes to sweep past one layer of rock blocks are significant. Table 1 lists diffusion lengths and percentage of volume of the rectangular blocks affected by heat conduction for the times required to sweep one layer in the different experiments.

Experimental Run	t_ℓ	L_d	Percentage of affected block volume
1.5 hours	900 s	1.5 cm	37.2%
5 hours	3000 s	2.7 cm	60.0%
10 hours	6000 s	3.9 cm	75.7%

Table 1: Conduction effects as water sweeps one layer of rock blocks.

It should be noted that the "instantaneous sweep" assumption is sufficient to justify the discretization made in the MINC-method, but it may not be a necessary condition for its validity.

The basic MINC-discretization concept as illustrated in Figure 2 can be readily extended to rock blocks of arbitrary shape. In the general case it is convenient to define a "proximity function" PROX(x), which represents the total fraction of rock volume contained within a distance x from the block faces. The proximity function provides all the geometric information which is needed for obtaining a discretization of rock blocks into nested volume elements. Proximity functions for the rectangular and triangular blocks of

the SGRM, as well as average proximity functions for the individual layers, have been given by Pruess and Karasaki (1982). The computational grids for the simulations of the experiment were obtained from these proximity functions, using a preprocessor computer program "GMINC" (Pruess, 1983b).

A conceptual illustration of the computational grid is given in Figure 3. The water flow path from bottom to top is discretized into 30-60 layers. Each water volume element is represented by a solid circle in Figure 3. The water elements are connected to each other and to elements representing the vessel walls, which in turn are connected among each other, as well as with "infinite" volume elements representing the constant temperature ambient conditions ("surroundings"). Each water element is also connected to a one-dimensional string of nested volume elements in the rock blocks. For different runs, 4 - 11 nested volume elements were used.

The entire grid makes it possible to represent the following processes: (1) water flow up the void channels, (2) heat exchange between steel vessel and water, (3) heat loss from the vessel to the surroundings, (4) heat transfer from the rock blocks to the water, (5) heat conduction within the rock blocks, and (6) heat conduction along the walls of the vessel.

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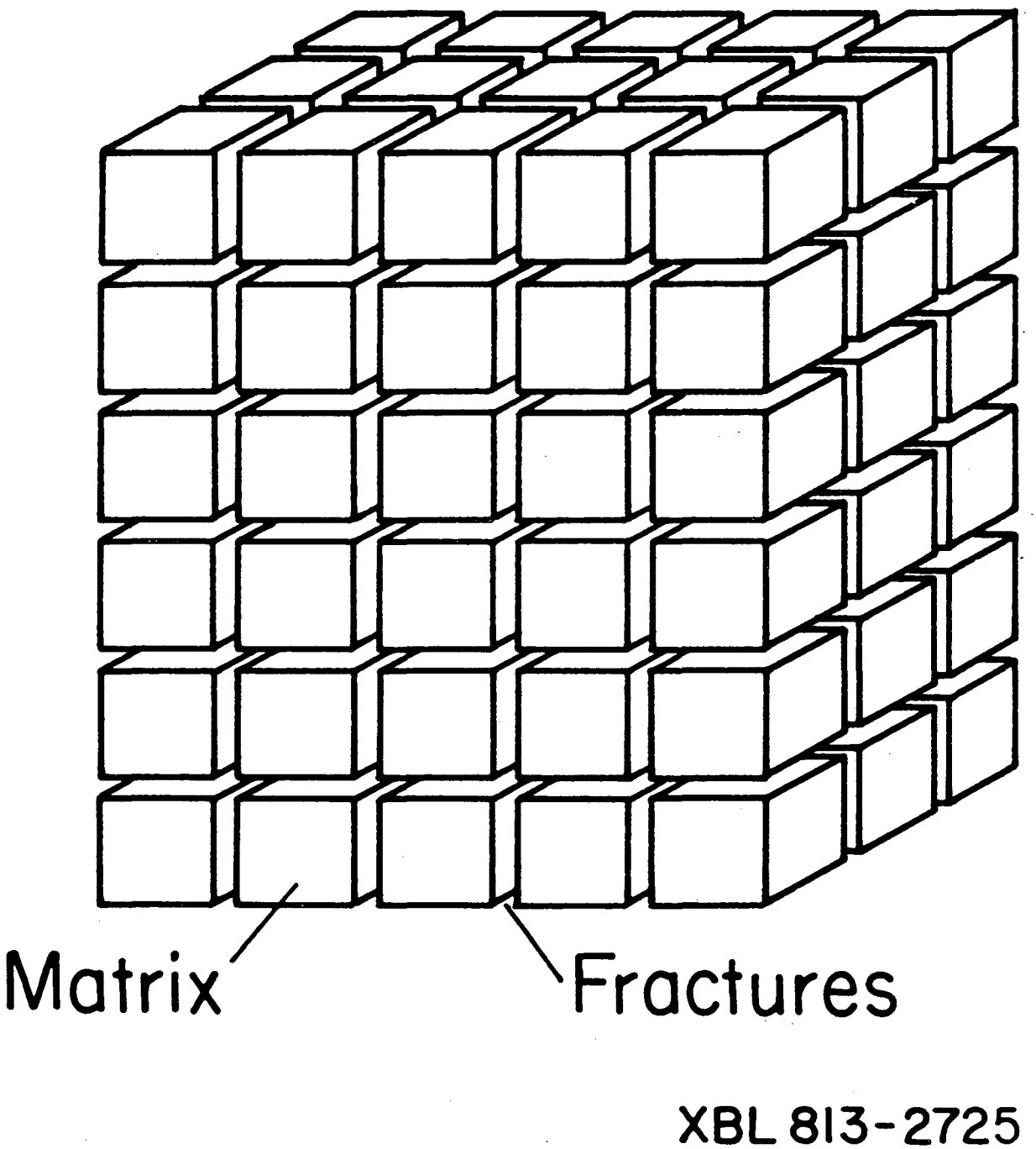

Figure 1. Idealized model of a fractured porous medium.

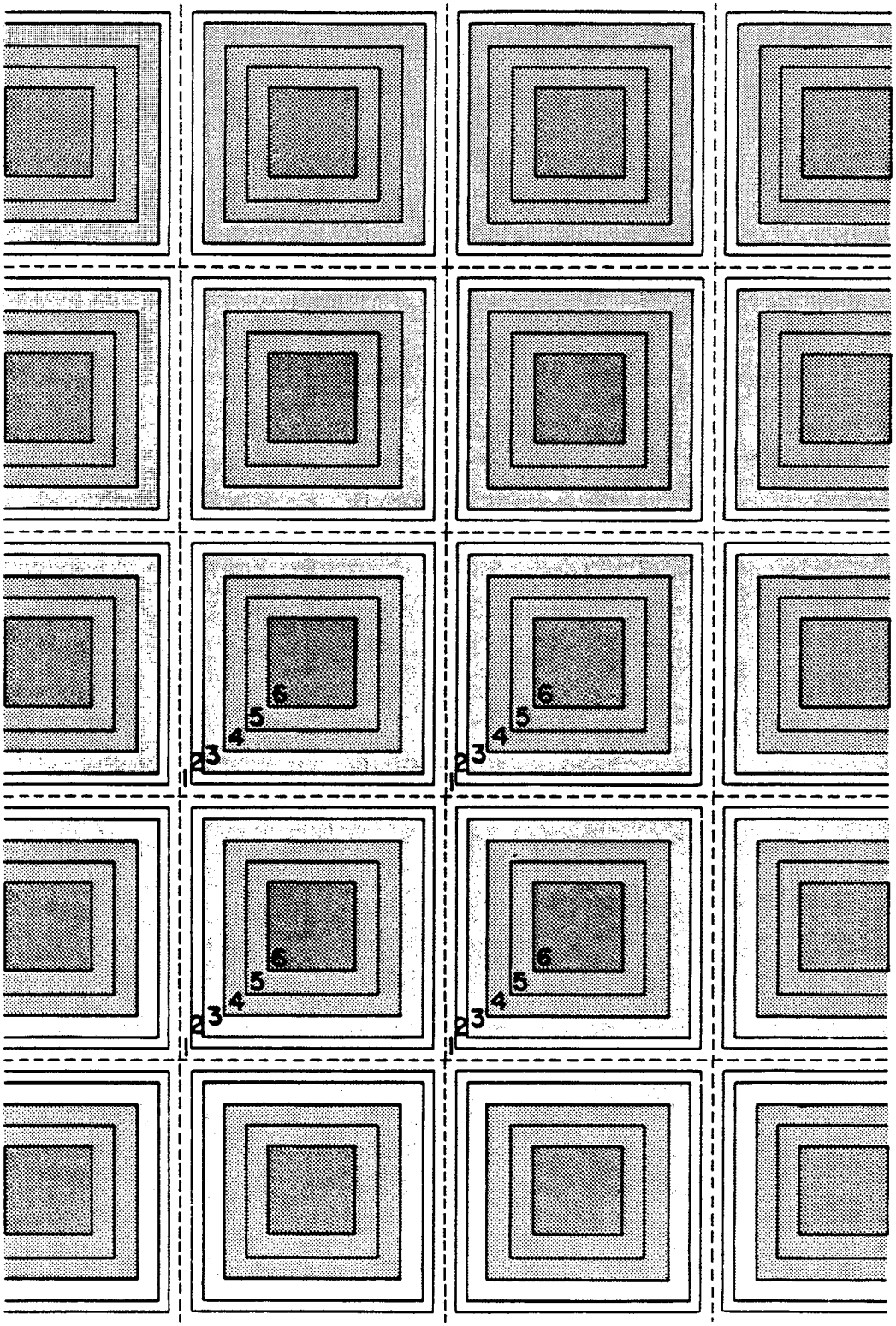

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Figure 2. Basic computational mesh for a fractured porous medium.

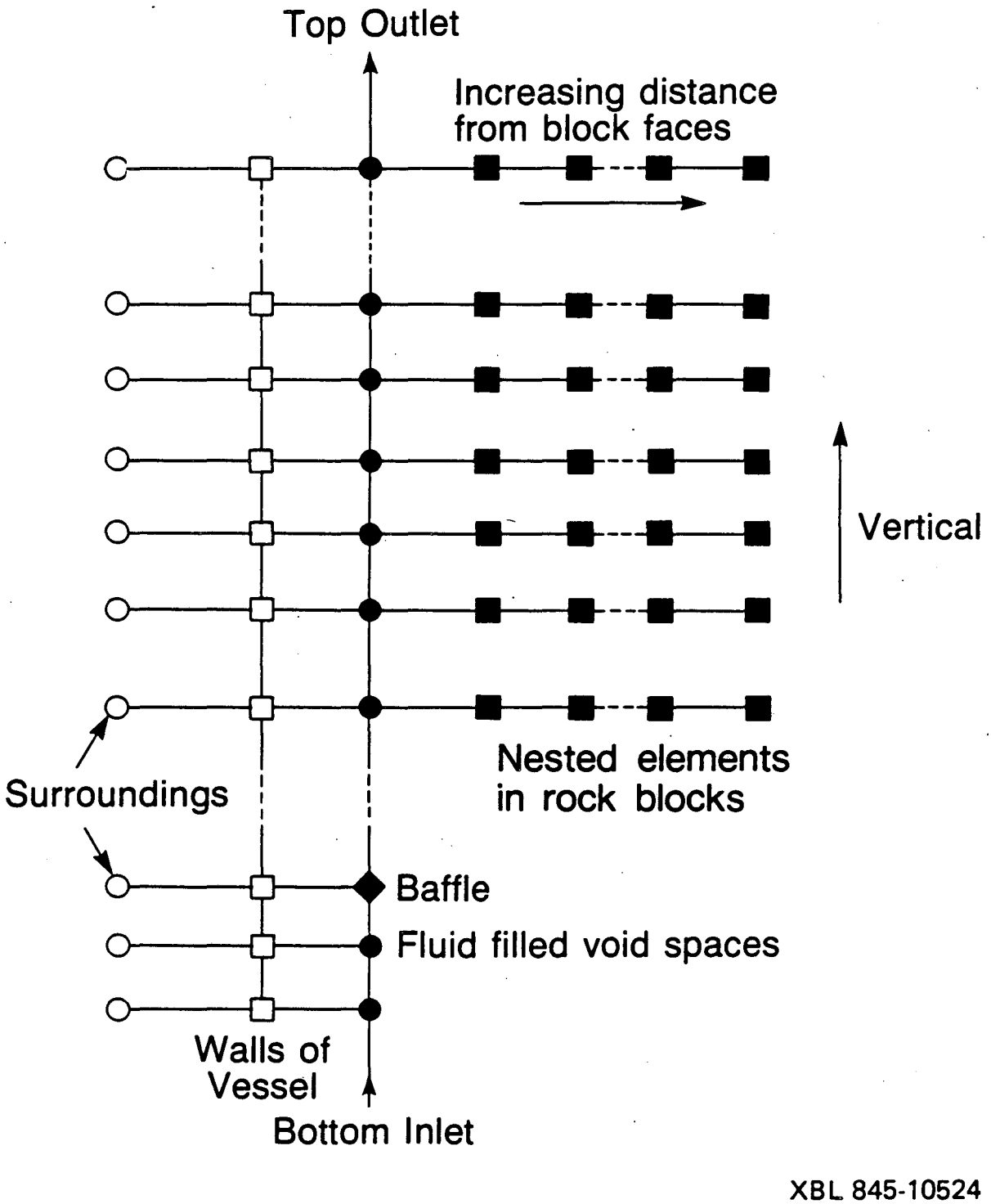

Figure 3. Conceptual illustration of the computational grid used for the Stanford Geothermal Reservoir Model.

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