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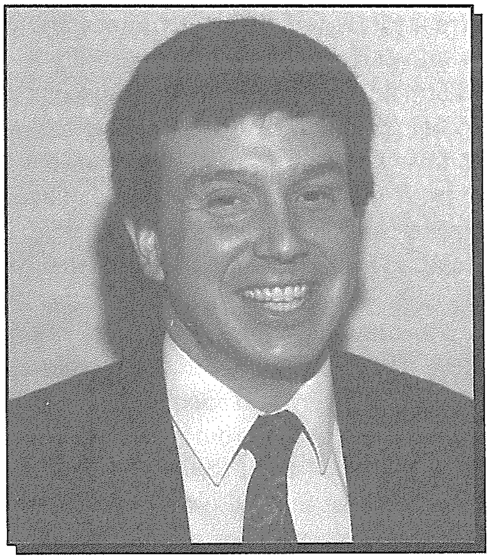

EXAMINING THE IMPACTS OF FAULTS ON AQUIFER FLOW SYSTEMS: IMPLICATIONS FOR REGIONAL GROUNDWATER FLOW MODELING

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INTRODUCTION

The importance of fault zones, a volume of geologic material significantly altered by faulting, is not solely relegated to seismic activities. Fault zones also can function as vital controls on groundwater flow through aquifers, either obstructing or channeling groundwater flow (Smith et al. 1990; Bredehoeft et al. 1992; Haneberg 1994). Two groups of fault-induced changes govern how the fault zone influences groundwater flow. The first group lumps together all the petrophysical alterations of the parent material attributable to fault slip and post-slip (digenesis) processes. The second group refers to structural alterations in the parent material's position, geometry or continuity within the aquifer. These two groups of alterations can significantly influence groundwater flow and possess particular significance in rift basins such as the Albuquerque Basin.

Structural or geometric alterations refer to fault-induced changes in the aquifer's shape, its orientation or the continuity of flow paths within the aquifer. Examples of geometric alteration include juxtaposition of the aquifer's high hydraulic conductivity stratigraphic unit against one or more units with differing hydraulic conductivities, tilting the beds or changing the thickness of an aquifer's most (or least) conductive unit. Bernard et al. (1989) investigated the latter example, concluding that the impact on flow is a function of the ratio between the most conductive unit's thickness at the fault and its overall thickness if petrophysical changes are assumed to be negligible.

Petrophysical alterations in sedimentary rocks typically influence native rock permeability in two ways: deformation via fault slip and subsequent diagenetic changes. Fault slip in crystalline rocks can create a low permeability gouge zone often surrounded by a much more permeable damaged or breccia zone in comparison with the parent rock (Smith et al. 1990). In less well consolidated rocks, however, slip events can decrease permeability through comminution, gouge formation, grain reorientation, and re-packing of clasts (Aydin 1978; Pittman 1981; Mozley and Goodwin 1994). It is possible that brecciation would increase the permeability of zones adjacent to the slip surface, but it is more likely that the relatively high friability of the parent materials will not permit formation of conduits. Diagenetic processes, such as cementation, decrease permeability, but other processes, like dissolution of earlier cements or grains, also can occur (Knipe 1993).

Hydraulic conductivity within fault zones can vary tremendously over very short distances. Davison and Kozak (1988) observed that the estimated fault hydraulic conductivity ranged over four orders of magnitude in less than five meters. Smith et al. (1990) show laboratory permeability measurement results for a variety of gouges range between 10^{-12} and 10^{-22} m^2. Field measurements of fault zone permeability in porous, well indurated sandstones indicate reductions between 10^{-3} and 10^{7} in the parent material's permeability (Antonellini and Aydin 1994). Published field measurements of fault permeabilities in poorly consolidated materials, such as those in the Albuquerque Basin's most productive aquifers, are less common. However, the author's unpublished data suggest that faults with less than 10 meters of slip have permeabilities one to two orders of magnitude less than the parent unconsolidated Upper Santa Fe Group sands.

It is possible to relate petrophysical changes and specific fault zone structures to consistent alterations in permeability. Aydin (1978), Aydin and Johnson (1978), Aydin and Reches (1982), and Aydin and Johnson (1983) describe a hierarchy of slip-induced deformation structures in the porous, well-indurated Navajo and Entrada sandstones of Utah. Three types of fault deformation structures are defined. They are, in ascending order of scale, deformation bands, zones of deformation bands and slip surfaces. A summary of their most important characteristics is given below.

- Deformation bands:
  - formed by grain comminution, strain-hardening and crystal plasticity within a single "micro-faulting" event
  - typically possess widths ≈ 1 mm and lengths in the tens of meters
- Zones of deformation bands:
  - created by repeated "micro-faulting" events
  - form adjacent to pre-existing deformation bands or zones of deformation bands because the deformed rock is thought to be stronger (via strain hardening) than the adjacent parent material
  - have widths ≈ 0.1 meters and lengths ranging from the tens to hundreds of meters
- Slip surfaces:
  - form within complex zones of deformation bands
  - widths are on the order of a meter while lengths range between the hundreds and thousands of meters

Antonellini and Aydin (1994) present field permeability data for these deformation structures, suggesting that the reduction in parent material permeability is proportional to the amount of deformation which has occurred. The permeability of deformation bands was three orders of magnitude less than that of the parent material, while the reduction was seven orders of magnitude for slip surfaces.

Fault zones' complex structure and permeability heterogeneity pose a formidable challenge to hydrologists seeking to determine their impact on an aquifer's flow system. A typical question is whether a fault will obstruct or accelerate the movement of a groundwater contaminant off-site. The challenge is further complicated by the paucity of field measurements of the fault zone's permeability and information about its spatial expression below the surface. There may be few, if any, measurements of the parent material's hydraulic conductivity, leaving the hydrologist to solve the inverse problem using sparse head and hydraulic conductivity data. Stochastic or Monte Carlo methods are often best suited for tackling such data-poor problems (Benjamin and Cornell 1970; Freeze 1975; Gutjahr et al. 1994).

Finding a solution to the inverse problem first requires a measure of a fault zone's impact or influence on an aquifer system. Presented below are the first results from preliminary work in developing a set of tools for solving the forward problem and a first cut at identifying effective performance measures. The approach focuses on estimating the effects of the petrophysical changes within fault zones; structural alterations are not considered. Although the work is still too preliminary to support firm conclusions, the approach's initial results appear to indicate that fault zones exert a significant influence on an aquifer system, as measured by the mean and variance fields for heads.

APPROACH

An approach was devised to test two hypotheses:

- the ratio between the parent rock mean K and the fault zone's mean K is critical for determining the fault's impact on groundwater flow; and
- uncertainty about the true hydraulic conductivities for parent rock and fault can drown out the contribution of other data, such as information about the fault's location.

The approach consists of:

- constructing two idealized two-dimensional aquifer conceptual models, one with and one without a fault zone;
- developing a two-dimensional groundwater flow model which allows the heterogeneities in the hydraulic conductivity for both the parent aquifer material and the fault zone to be described stochastically, that is, by a distribution, mean, variance and covariance structure;
- estimating the head field for each of many equally likely hydraulic conductivity (K) fields;
- calculating the mean head and head variance fields for the entire set of equally likely realizations; and
- comparing the mean head and head variance fields for aquifers with and without fault zones for different ratios of mean Ks for the parent material and fault zone as well as different variances for the Ks.

The conceptual model comprises an aquifer with vertically averaged hydraulic conductivity described by a mean, variance and a variogram. The base 10 logarithm of hydraulic conductivity was simulated:

$$K_{aquifer} = 10^{Ya} \quad K_{fault} = 10^{Yf}$$

The mean, variance and variogram refer to the Y variables, not the Ks (Freeze 1975; Gutjahr et al. 1994). The exponential variogram adopted for this exercise, which determines how the Y values are correlated with each other in space, is of the form

$$\gamma(h) = c[1 - e^{(-\frac{h}{a})}]$$

where $\gamma(h)$ is the variogram value at separation distance (lag) h, c is the sill and a is the range or correlation length (Deutsch and Journel 1992).

The aquifer has a constant mean gradient applied across its north and south boundaries while no flow is permitted out of or in through the east and west boundaries. Only steady-state, confined groundwater flow is considered. No recharge, extraction wells, injection wells, or other sources/ sinks are used. The computational domain is a 64 by 64 block-centered grid of equally spaced blocks with constant thickness.

The aquifer's hydraulic conductivity fields are simulated using a non-conditional algorithm employing a spectral (Fast Fourier Transform) approach (Gutjahr et al. 1994). Each K field is statistically indistinguishable from the others. A second K field is generated using the mean, variance and variogram for the fault zone K. A random, arbitrary algorithm is used to determine which blocks are assigned to the fault zone. After the head field is estimated for the aquifer without a fault, the fault zone K values are overlaid onto the initial K field and a solution for the faulted aquifer head field is found.

The flow code uses a multigrid equation solver, which offers extremely fast solution times. The flow code was verified using MODFLOW (McDonald and Harbaugh 1988). Running the code for 100 realizations produces 100 head fields for the faulted aquifer and 100 non-faulted head fields. The means and variances of the two sets of 100 heads in each block are estimated and plotted for comparison. Two different values of the ratio, K_r, of parent aquifer material hydraulic conductivity to the fault zone hydraulic conductivity were examined:

$$K_r = K_{aquifer} / K_{fault} = 10^2 \text{ and } K_r = 10^4$$

The values of K_r were limited to these two values based on the author's unpublished field measurements of fault zone permeability. Two variances were also examined: a moderate variance of 0.5 and a high variance of 1.5. The variograms and correlation lengths were held constant throughout the study.

RESULTS

Figure 1 compares the head fields for a pair of hydraulic conductivity field realizations for an aquifer with and an aquifer without a fault zone for the moderate variance and $K_r = 100$. Note the variation in head contours for the no fault aquifer, the contour lines would be perfectly horizontal for a homogeneous field. Even more striking is the difference in the head contours for the faulted aquifer.

Figure 2 compares the head fields from two realizations in which $K_r = 10{,}000$. Neither of the two contour plots appears significantly different from those presented in Figure 1. The next figure (Figure 3) demonstrates that the mean head field is not terribly sensitive to the ratio K_r for the two values examined.

Figure 4 presents the results for the high variance, low K_r case. There is much less difference between the faulted and no fault mean head fields because there is a much greater variability in both the parent material and fault zone hydraulic conductivities.

The head variances are presented in figures 5 and 6. Note the clear difference between the no fault and faulted aquifers in Figure 5, the structure of the head variance follows the fault trace. However, as the variance increases, the difference between the no fault and faulted aquifers becomes much less clear.

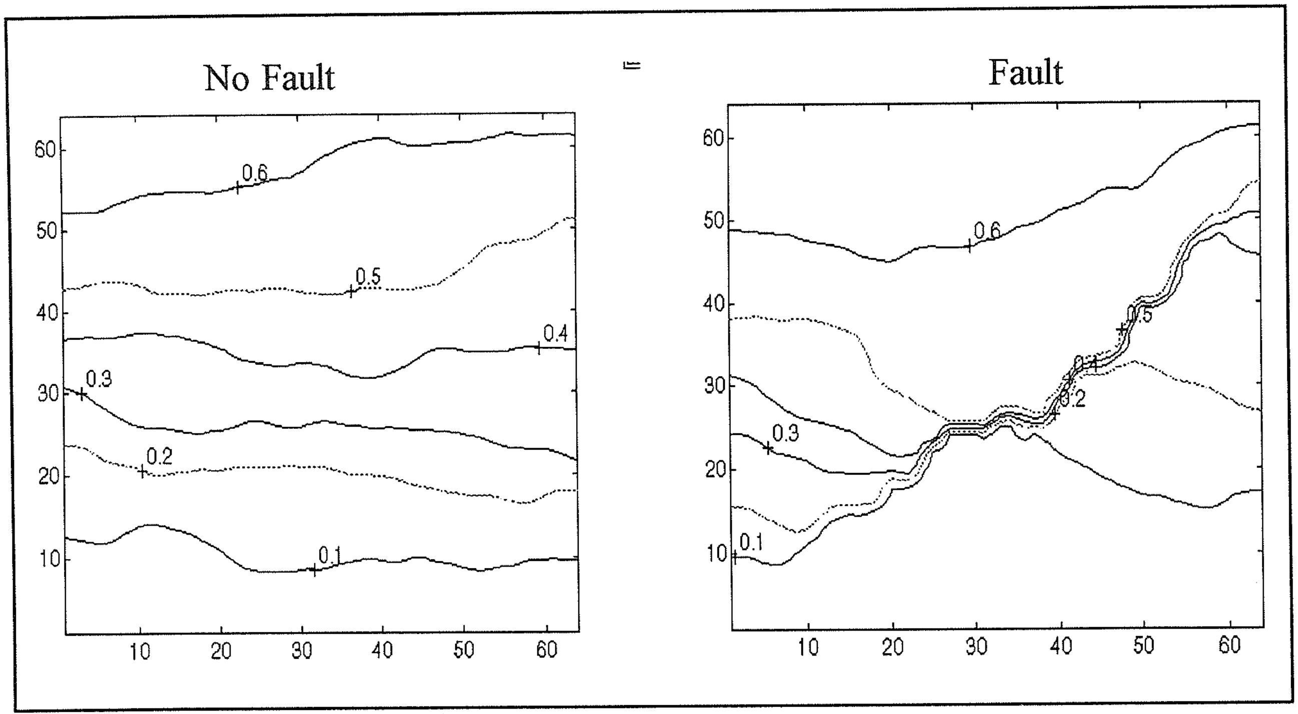

Figure 1. Head fields for $K_r = 10^2$, $\sigma^2 = 0.5$

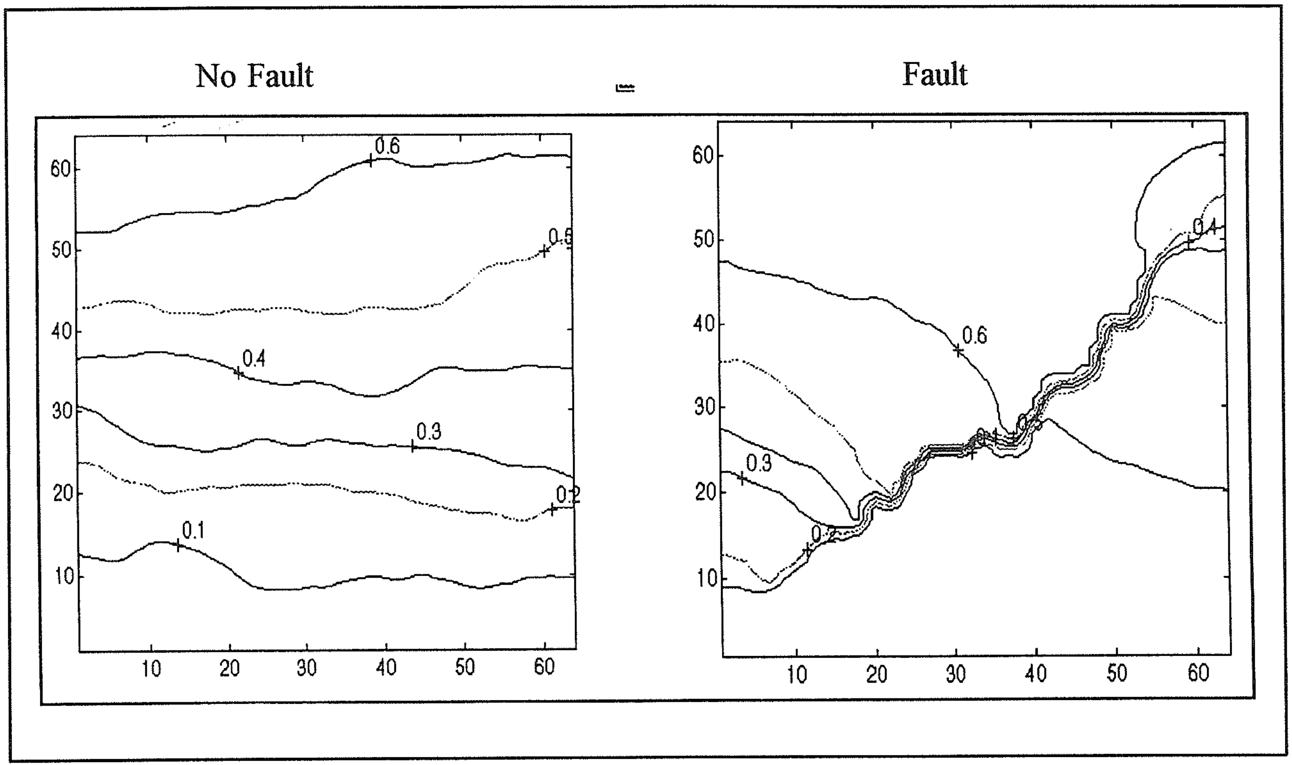

Figure 2. Head fields for $K_r = 10^4$, $\sigma^2 = 0.5$

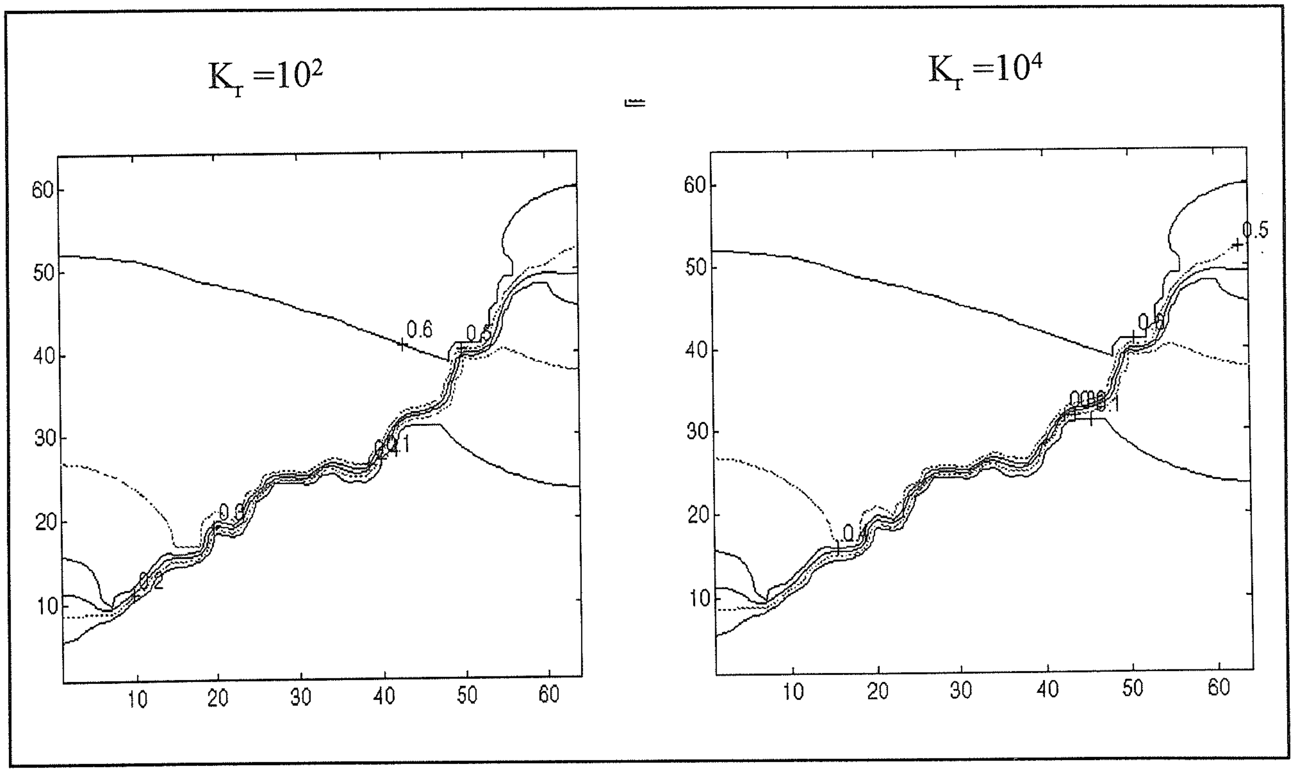

Figure 3. Mean head fields, $\sigma^2 = 0.5$

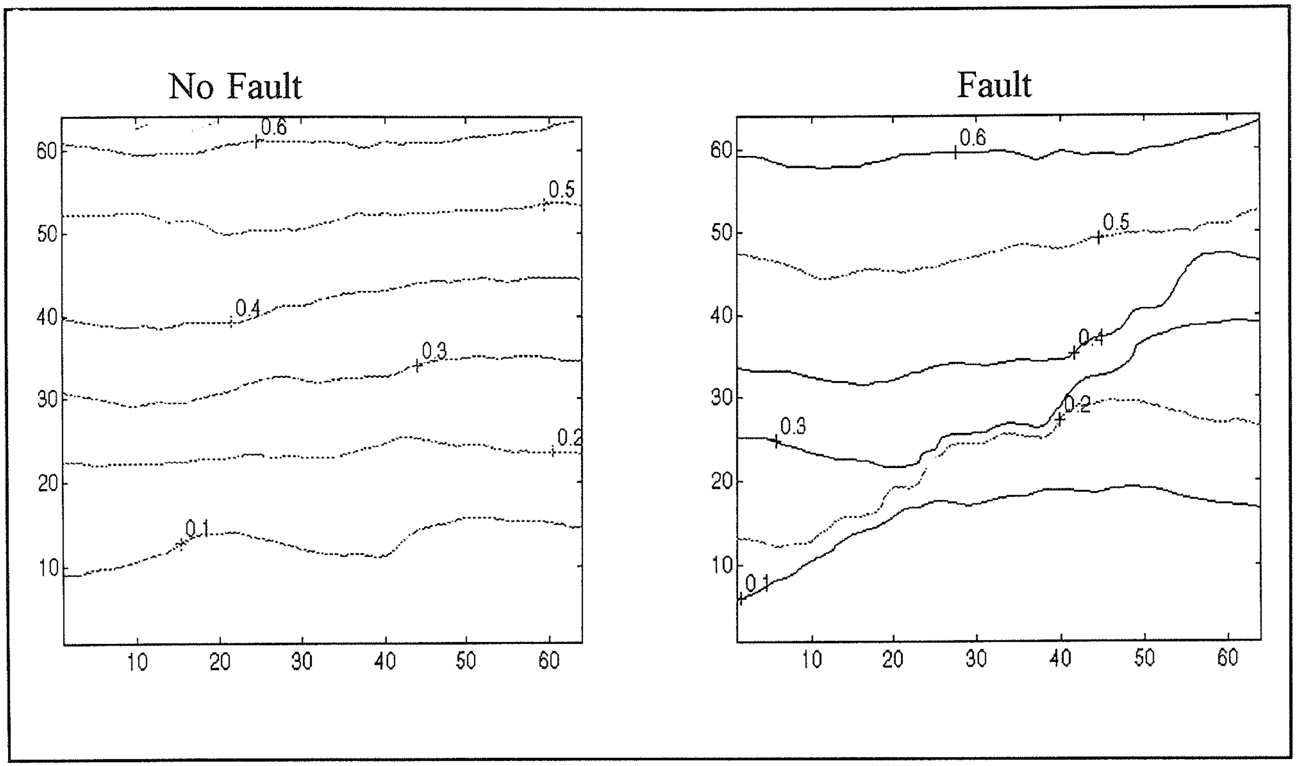

Figure 4. Mean head fields for $K_r = 10^2$, $\sigma^2 = 1.5$

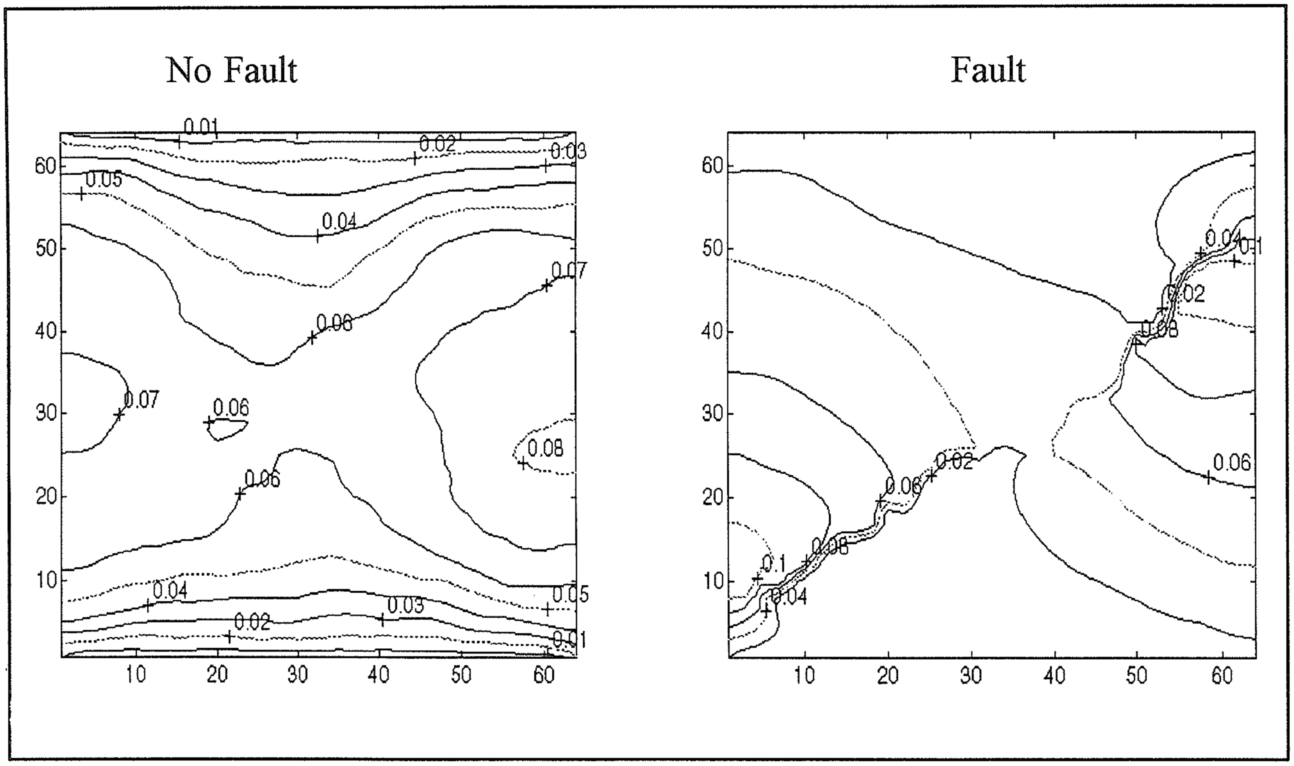

Figure 5. Head variance fields for $K_r = 10^4$, $\sigma^2 = 0.5$

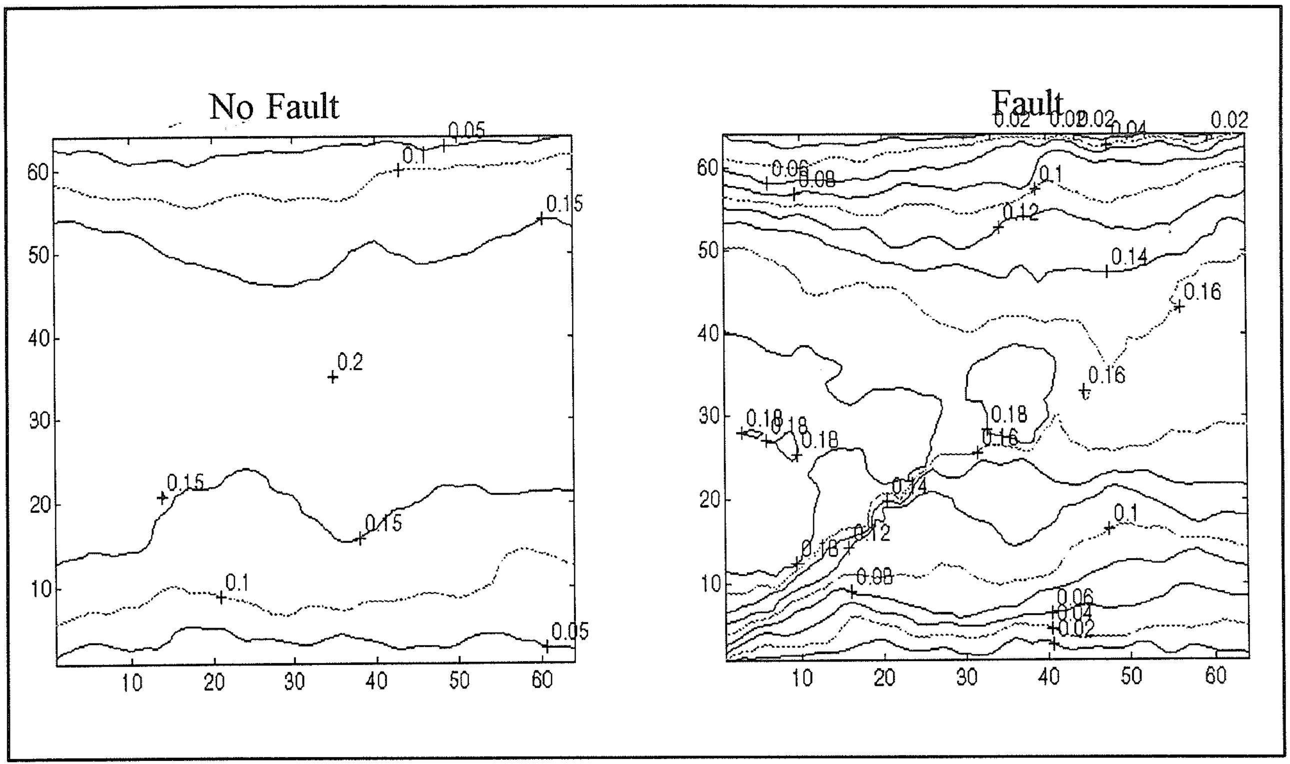

Figure 6. Head variance fields for $K_r = 10^2$, $\sigma^2 = 1.5$

CONCLUSIONS

Monte Carlo simulation is a potentially effective tool for examining the impact of a fault zone on an idealized aquifer system (Benjamin and Cornell 1970; Gutjahr et al. 1994).

The preliminary performance measures for the forward problem, head mean and variance plots, appear to provide some qualitative measure of the influence a fault exerts on an aquifer flow system. However, the head fields are probably very sensitive to the gap between the boundaries and the fault tips. As the gap increases, the head mean and variance fields will most likely not differ significantly between the fault and no fault cases. Further work is required to explore the approach's sensitivity to the distance between the fault tips and the boundaries. Other performance measures, however, will be required for the inverse problem.

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