EVALUATION OF A PREDICTIVE GROUND-WATER SOLUTE-TRANSPORT MODEL AT THE IDAHO NATIONAL ENGINEERING LABORATORY IDAHO

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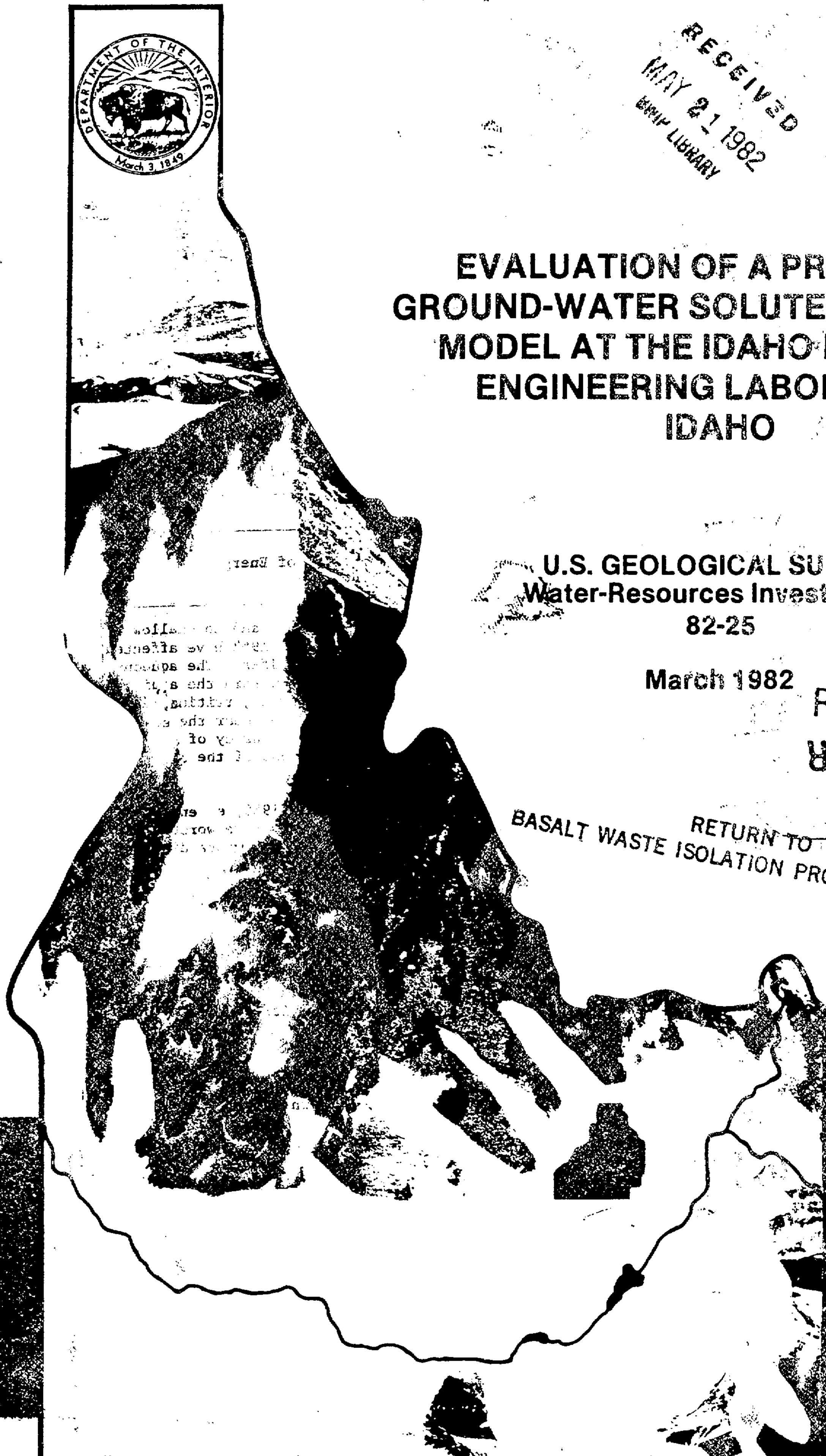

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Barney D. Lewis and Flora J. Goldstein

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16. Abstract (Limit: 200 words)

Aqueous chemical and radioactive wastes discharged to shallow ponds and to shallow or deep wells on the Idaho National Engineering Laboratory (INEL) since 1952 have affected the quality of the ground water in the underlying Snake River Plain aquifer. The aqueous wastes have created large and laterally dispersed concentration plumes within the aquifer. The waste plumes with the largest areal distribution are those of chloride, tritium, and with high specific conductance values. The data from eight wells drilled near the southern INEL boundary during the summer of 1980 were used to evaluate the accuracy of a predictive modeling study completed in 1973 that simulated 1980 positions of the chloride and tritium waste plumes.

As expected, the waste plumes projected by the computer model for 1980, extended somewhat further downgradient than indicated by well data due to conservative worst-case assumptions in the model input and inaccurate approximations of subsequent waste discharge and aquifer recharge conditions.

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*Snake River Plain aquifer, Idaho, *Hydrogeology, *Ground-water quality, Aqueous chemical and radioactive waste disposal, *Chloride and tritium waste plumes, and *Predictive solute-transport model

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(See ANSI-Z39.18) See Instructions on Reverse OPTIONAL FORM 272 (4-77) (Formerly NTIS-35) Department of Commerce *optimization* generally. The next section looks at a particular kind of discrete optimization problem.

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10.9 Combinatorial Minimization: Method of Simulated Annealing

The *method of simulated annealing* is a technique that has recently attracted significant attention as suitable for optimization problems of very large scale. For practical purposes, it has effectively "solved" the famous *traveling salesman problem* of finding the shortest cyclical itinerary for a traveling salesman who must visit each of N cities in turn. The method has also been used successfully for designing complex integrated circuits: The arrangement of several hundred thousand circuit elements on a tiny silicon substrate is optimized so as to minimize interference among their connecting wires. Amazingly, the implementation of the algorithm is quite simple.

Notice that the two applications cited are both examples of *combinatorial minimization*. There is an objective function to be minimized, as usual; but the space over which that function is defined is not simply the N-dimensional space of N continuously variable parameters. Rather, it is a discrete, but very large, configuration space, like the set of possible orders of cities, or the set of possible allocations of silicon "real estate" to circuit elements. The number of elements in the configuration space is factorially large, so that they cannot be explored exhaustively. Furthermore, since the set is discrete, we are deprived of any notion of "continuing downhill in a favorable direction." The concept of "direction" may not have any meaning in the configuration space.

At the heart of the method of simulated annealing is an analogy with thermodynamics, specifically with the way that liquids freeze and crystallize, or metals cool and anneal. At high temperatures, the molecules of a liquid move freely with respect to one another. If the liquid is cooled slowly, thermal mobility is lost. The atoms are often able to line themselves up and form a pure crystal that is completely ordered over a distance up to billions of times the size of an individual atom in all directions. This crystal is the state of minimum energy for this system. The amazing fact is that, for slowly cooled systems, nature is able to find this minimum energy state. In fact, if a liquid metal is cooled quickly or "quenched," it does not reach this state but rather ends up in a polycrystalline or amorphous state having somewhat higher energy.

So the essence of the process is *slow* cooling, allowing ample time for redistribution of the atoms as they lose mobility. This is the technical definition of ***annealing***, and it is essential for ensuring that a low energy state will be achieved.

Although the analogy is not perfect, there is a sense in which all of the minimization algorithms thus far in this chapter correspond to rapid cooling or quenching. In all cases, we have gone greedily for the quick, nearby solution: from the starting point, go immediately downhill as far as you can go. This, as often remarked above, leads to a local, but not necessarily a global, minimum. Nature's own minimization algorithm is based on quite a different procedure. The so-called Boltzmann probability distribution,

$$\text{Prob}(E) \sim \exp(-E/kT) \tag{10.9.1}$$

expresses the idea that a system in thermal equilibrium at temperature T has its energy probabilistically distributed among all different energy states E. Even at low temperature, there is a chance, albeit very small, of a system being in a high energy state. Therefore, there is a corresponding chance for the system to get out of a local energy minimum in favor of finding a better, more global, one. The quantity k (Boltzmann's constant) is a constant of nature which relates temperature to energy. In other words, the system sometimes goes *uphill* as well as downhill; but the lower the temperature, the less likely is any significant uphill excursion.

In 1953, Metropolis and coworkers first incorporated these kinds of principles into numerical calculations. Offered a succession of options, a simulated thermodynamic system was assumed to change its configuration from energy E_1 to energy E_2 with probability $p = \exp[-(E_2 - E_1)/kT]$. Notice that if $E_2 < E_1$, this probability is greater than unity; in such cases the change is arbitrarily assigned a probability $p = 1$, i.e. the system *always* took such an option. This general scheme, of always taking a downhill step while *sometimes* taking an uphill step, has come to be known as the Metropolis algorithm.

To make use of the Metropolis algorithm for other than thermodynamic systems, one must provide the following elements:

1. A description of possible system configurations.
2. A generator of random changes in the configuration; these changes are the "options" presented to the system.

3. An objective function E (analog of energy) whose minimization is the goal of the procedure.

4. A control parameter T (analog of temperature) and an *annealing schedule* which tells how it is lowered from high to low values, e.g., after how many random changes in configuration is each downward step in T taken, and how large is that step. The meaning of "high" and "low" in this context, and the assignment of a schedule, may require physical insight and/or trial-and-error experiments.

The Traveling Salesman Problem

A concrete illustration is provided by the traveling salesman problem. The salesperson visits N cities with given positions (x_i, y_i), returning finally to his or her city of origin. Each city is to be visited only once, and the route is to be made as short as possible. This problem belongs to a class known as *NP-complete* problems, whose computation time for an *exact* solution increases with N as exp(const. $\times N$), becoming rapidly prohibitive in cost as N increases. The traveling salesman problem also belongs to a class of minimization problems for which the objective function E has many local minima. In practical cases, it is often enough to be able to choose from these a minimum which, even if not absolute, cannot be significantly improved upon. The annealing method manages to achieve this, while limiting its calculations to scale as a small power of N.

As a problem in simulated annealing, the traveling salesman problem is handled as follows:

1. *Configuration.* The cities are numbered $i = 1 \ldots N$ and each has coordinates (x_i, y_i). A configuration is a permutation of the number $1 \ldots N$, interpreted as the order in which the cities are visited.

2. *Rearrangements.* An efficient set of moves has been suggested by Lin. The moves consist of two types: (a) A section of path is removed and then replaced with the same cities running in the opposite order; or (b) a section of path is removed and then replaced in between two cities on another, randomly chosen, part of the path.

3. *Objective Function.* In the simplest form of the problem, E is taken just as the total length of journey,

$$E = L \equiv \sum_{i=1}^{N} \sqrt{(x_i - x_{i+1})^2 + (y_i - y_{i+1})^2} \qquad (10.9.2)$$

with the convention that point $N + 1$ is identified with point 1. To illustrate the flexibility of the method, however, we can add the following additional wrinkle: suppose that the salesman has an irrational fear of flying over the Mississippi River. In that case, we would assign each city a parameter μ_i,

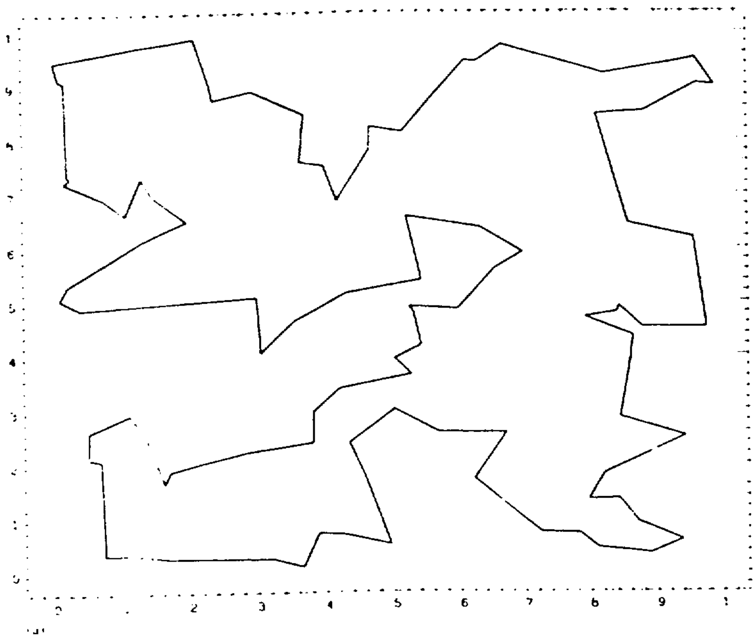

Figure 10.9.1 Traveling salesman problem solved by simulated annealing. The (nearly) shortest path among 100 randomly positioned cities is shown in (a). The dotted line is a river, but there is no penalty in crossing. In (b) the river-crossing penalty is made large, and the solution restricts itself to the minimum number of crossings, two. In (c) the penalty has been made negative: the salesman is actually a smuggler who crosses the river on the flimsiest excuse!

equal to +1 if it is east of the Mississippi, −1 if it is west, and take the objective function to be

$$E = \sum_{i=1}^{N} \sqrt{(x_i - x_{i+1})^2 + (y_i - y_{i+1})^2} + \lambda(\mu_i - \mu_{i+1})^2 \qquad (10.9.3)$$

A penalty 4λ is thereby assigned to any river crossing. The algorithm now finds the shortest path that avoids crossings. The relative importance that it assigns to length of path versus river crossings is determined by our choice of λ. Figure 10.9.1 shows the results obtained. Clearly, this technique can be generalized to include many conflicting goals in the minimization.

4. *Annealing schedule*. This requires experimentation. We first generate some random rearrangements, and use them to determine the range of values of ΔE that will be encountered from move to move. Choosing a starting value for the parameter T which is considerably larger than the largest ΔE normally encountered, we proceed downward in multiplicative steps each amounting to a 10 percent decrease in T. We hold each new value of T constant for, say, $100N$

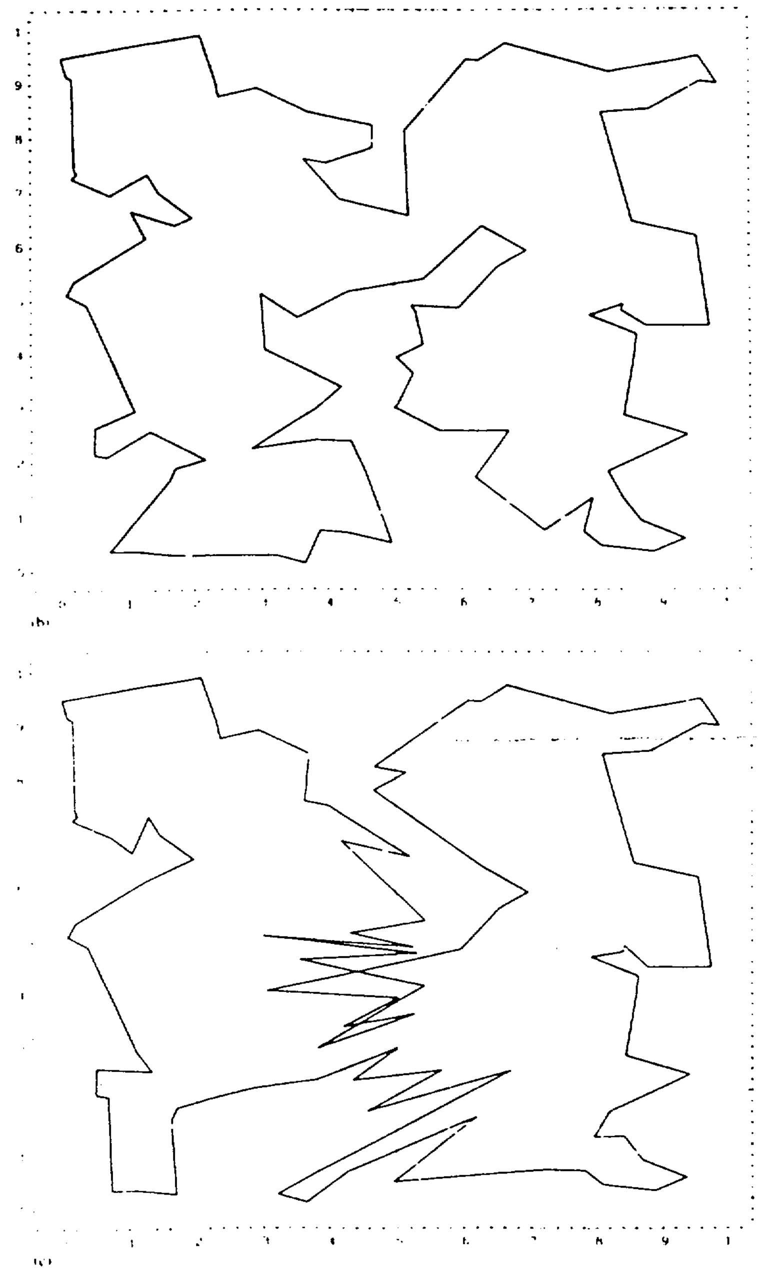

Figure 10.9.1. Traveling salesman problem solved by simulated annealing (see caption on previous page).

reconfigurations, or for $10N$ successful reconfigurations, whichever comes first. When efforts to reduce E further become sufficiently discouraging, we stop.

The following traveling salesman program, using the Metropolis algorithm, should illustrate for you the important aspects of the simulated annealing technique.

```
SUBROUTINE ANNEAL(X,Y,IORDER,NCITY)
   This algorithm finds the shortest round-trip path to NCITY cities whose coordinates are
   in the arrays X(I),Y(I). The array IORDER(I) specifies the order in which the cities are
   visited. On input, the elements of IORDER may be set to any permutation of the numbers
   1 to NCITY. This routine will return the best alternative path it can find.
DIMENSION X(NCITY),Y(NCITY),IORDER(NCITY),N(6)
LOGICAL ANS
ALEN(X1,X2,Y1,Y2)=SQRT((X2-X1)**2+(Y2-Y1)**2)
NOVER=100*NCITY              Maximum number of paths tried at any temperature
NLIMIT=10*NCITY              Maximum number of successful path changes before continuing
TFACTR=0.9                   Annealing schedule - T is reduced by this factor on each step
PATH=0.0
T=0.5
DO 11 I=1,NCITY-1            Calculate initial path length
   I1=IORDER(I)
   I2=IORDER(I+1)
   PATH=PATH+ALEN(X(I1),X(I2),Y(I1),Y(I2))
11 CONTINUE
I1=IORDER(NCITY)             Close the loop by tying path ends together
I2=IORDER(1)
PATH=PATH+ALEN(X(I1),X(I2),Y(I1),Y(I2))
IDUM=-1
ISEED=111
DO 13 J=1,100                Try up to 100 temperature steps
   NSUCC=0
   DO 12 K=1,NOVER
1     N(1)=1+INT(NCITY*RAN3(IDUM))         Choose beginning of segment
      N(2)=1+INT((NCITY-1)*RAN3(IDUM))     and end of segment
      IF (N(2).GE.N(1)) N(2)=N(2)+1
      NN=1+MOD((N(1)-N(2)+NCITY-1),NCITY)  NN is the number of cities not on the segment
      IF (NN.LT.3) GOTO 1
      IDEC=IRBIT1(ISEED)       Decide whether to do a segment reversal or transport
      IF (IDEC.EQ.0) THEN      Do a transport
         N(3)=N(2)+INT(ABS(NN-2)*RAN3(IDUM))+1
         N(3)=1+MOD(N(3)-1,NCITY)          Transport to a location not on the path
         CALL TRNCST(X,Y,IORDER,NCITY,N,DE)   Calculate cost
         CALL METROP(DE,T,ANS)     Consult the oracle
         IF (ANS) THEN
            NSUCC=NSUCC+1
            PATH=PATH+DE
            CALL TRNSPT(IORDER,NCITY,N)   Carry out the transport
         ENDIF
      ELSE                     Do a path reversal
         CALL REVCST(X,Y,IORDER,NCITY,N,DE)   Calculate cost
         CALL METROP(DE,T,ANS)     Consult the oracle
         IF (ANS) THEN
            NSUCC=NSUCC+1
            PATH=PATH+DE
            CALL REVERS(IORDER,NCITY,N)   Carry out the reversal
         ENDIF
      ENDIF
      IF (NSUCC.GE.NLIMIT) GOTO 2   Finish early if we have enough successful changes
12 CONTINUE
2  WRITE(*,*)
   WRITE(*,*) 'T =',T,' Path Length =',PATH
   WRITE(*,*) 'Successful Moves:  ',NSUCC
```

```
      T=T*TFACTR                 Annealing schedule
      IF (NSUCC.EQ.0) RETURN     If no success, we are done
13    CONTINUE
      RETURN
      END
```

```
      SUBROUTINE REVCST(X,Y,IORDER,NCITY,N,DE)
```

This subroutine returns the value of the cost function for a proposed path reversal. NCITY is the number of cities, and arrays X(I),Y(I) give the coordinates of these cities. IORDER(I) holds the present itinerary. The first two values N(1) and N(2) of array N give the starting and ending cities along the path segment which is to be reversed. On output, DE is the cost of making the reversal. The actual reversal is not performed by this routine.

```
      DIMENSION X(NCITY),Y(NCITY),IORDER(NCITY),N(6),XX(4),YY(4)
      ALEN(X1,X2,Y1,Y2)=SQRT((X2-X1)**2+(Y2-Y1)**2)
      N(3)=1+MOD((N(1)+NCITY-2),NCITY)    Find the city before N(1)
      N(4)=1+MOD(N(2),NCITY)                and the city after N(2)
      DO 11 J=1,4
        II=IORDER(N(J))            Find coordinates for the four cities involved
        XX(J)=X(II)
        YY(J)=Y(II)
11    CONTINUE
      DE=-ALEN(XX(1),XX(3),YY(1),YY(3))   Calculate cost of disconnecting the segment at both ends
     *    -ALEN(XX(2),XX(4),YY(2),YY(4))    and reconnecting in the opposite order
     *    +ALEN(XX(1),XX(4),YY(1),YY(4))
     *    +ALEN(XX(2),XX(3),YY(2),YY(3))
      RETURN
      END
```

```
      SUBROUTINE REVERS(IORDER,NCITY,N)
```

This routine performs a path segment reversal. IORDER(I) is an input array giving the present itinerary. The vector N has as its first four elements the first and last cities N(1),N(2) of the path segment to be reversed, and the two cities N(3) and N(4) which immediately precede and follow this segment. N(3) and N(4) are found by subroutine REVCST. On output, IORDER(I) contains the segment from N(1) to N(2) in reversed order.

```
      DIMENSION IORDER(NCITY),N(6)
      NN=(1+MOD(N(2)-N(1)+NCITY,NCITY))/2  This many cities must be swapped to effect the reversal
      DO 11 J=1,NN
        K=1+MOD((N(1)+J-2),NCITY)      Start at the ends of the segment and swap pairs of cities, moving
        L=1+MOD((N(2)-J+NCITY),NCITY)  toward the center
        ITMP=IORDER(K)
        IORDER(K)=IORDER(L)
        IORDER(L)=ITMP
11    CONTINUE
      RETURN
      END
```

```
      SUBROUTINE TRNCST(X,Y,IORDER,NCITY,N,DE)
```

This subroutine returns the value of the cost function for a proposed path segment transport. NCITY is the number of cities, and arrays X(I) and Y(I) give the city coordinates. IORDER is an array giving the present itinerary. The first three elements of array N give the starting and ending cities of the path to be transported, and the point among the remaining cities after which it is to be inserted. On output, DE is the cost of the change. The actual transport is not performed by this routine.

```
      DIMENSION X(NCITY),Y(NCITY),IORDER(NCITY),N(6),XX(6),YY(6)
      ALEN(X1,X2,Y1,Y2)=SQRT((X2-X1)**2+(Y2-Y1)**2)
      N(4)=1+MOD(N(3),NCITY)              Find the city following N(3)
      N(5)=1+MOD((N(1)+NCITY-2),NCITY)    and the one preceding N(1)
      N(6)=1+MOD(N(2),NCITY)              and the one following N(2)
      DO 11 J=1,6
        II=IORDER(N(J))            Determine coordinates for the six cities involved
        XX(J)=X(II)
```

```
   YY(J)=Y(II)
 11 CONTINUE
DE=-ALEN(XX(2),XX(6),YY(2),YY(6))      Calculate the cost of disconnecting the path segment from
•      -ALEN(XX(1),XX(5),YY(1),YY(5))     N(1) to N(2), opening a space between N(3) and N(4),
•      -ALEN(XX(3),XX(4),YY(3),YY(4))     connecting the segment in the space, and connecting
•      +ALEN(XX(1),XX(3),YY(1),YY(3))     N(5) to N(6)
•      +ALEN(XX(2),XX(4),YY(2),YY(4))
•      +ALEN(XX(5),XX(6),YY(5),YY(6))
RETURN
END
```

```
SUBROUTINE TRNSPT(IORDER,NCITY,N)
```

This routine does the actual path transport, once METROP has approved. IORDER is an input array of length NCITY giving the present itinerary. The array N has as its six elements the beginning N(1) and end N(2) of the path to be transported, the adjacent cities N(3) and N(4) between which the path is to be placed, and the cities N(5) and N(6) which precede and follow the path. N(4), N(5) and N(6) are calculated by subroutine TRNCST. On output, IORDER is modified to reflect the movement of the path segment.

```
PARAMETER(MXCITY=1000)                  Maximum number of cities anticipated
DIMENSION IORDER(NCITY),JORDER(MXCITY),N(6)
M1=1+MOD((N(2)-N(1)+NCITY),NCITY)       Find the number of cities from N(1) to N(2)
M2=1+MOD((N(5)-N(4)+NCITY),NCITY)         and the number from N(4) to N(5)
M3=1+MOD((N(3)-N(6)+NCITY),NCITY)         and the number from N(6) to N(3)
NN=1
DO 11 J=1,M1
   JJ=1+MOD((J+N(1)-2),NCITY)   Copy the chosen segment
   JORDER(NN)=IORDER(JJ)
   NN=NN+1
 11 CONTINUE
IF (M2.GT.0) THEN
   DO 12 J=1,M2                          Then copy the segment from N(4) to N(5)
      JJ=1+MOD((J+N(4)-2),NCITY)
      JORDER(NN)=IORDER(JJ)
      NN=NN+1
 12   CONTINUE
ENDIF
IF (M3.GT.0) THEN
   DO 13 J=1,M3                          Finally, the segment from N(6) to N(3)
      JJ=1+MOD((J+N(6)-2),NCITY)
      JORDER(NN)=IORDER(JJ)
      NN=NN+1
 13   CONTINUE
ENDIF
DO 14 J=1,NCITY
   IORDER(J)=JORDER(J)        Copy JORDER back into IORDER
 14 CONTINUE
RETURN
END
```

```
SUBROUTINE METROP(DE,T,ANS)
```

Metropolis algorithm. ANS is a logical variable which issues a verdict on whether to accept a reconfiguration which leads to a change DE in the objective function E. If DE<0, ANS=.TRUE., while if DE>0, ANS is only .TRUE. with probability exp(-DE/T), where T is a temperature determined by the annealing schedule.

```
PARAMETER(JDUM=1)
LOGICAL ANS
ANS=(DE.LT.0.0).OR.(RAN3(JDUM).LT.EXP(-DE/T))
RE.URN
END
```

Assessing the Promise of Simulated Annealing

There is not yet enough practical experience with the method of simulated annealing to say definitively that it will realize its current promise. The method has several extremely attractive features, rather unique when compared with other optimization techniques.

First, it is not "greedy", in the sense that it is not easily fooled by the quick payoff achieved by falling into unfavorable local minima. Provided that sufficiently general reconfigurations are given, it wanders freely among local minima of depth less than about T. As T is lowered, the number of such minima qualifying for frequent visits is gradually reduced.

Second, configuration decisions tend to proceed in a logical order. Changes which cause the greatest energy differences are sifted over when the control parameter T is large. These decisions become more permanent as T is lowered, and attention then shifts more to smaller refinements in the solution. For example, in the traveling salesman problem with the Mississippi River twist, if λ is large, a decision to cross the Mississippi only twice is made at high T, while the specific routes on each side of the river are determined only at later stages.

The analogies to thermodynamics may be pursued to a greater extent than we have done here. Quantities analogous to specific heat and entropy may be defined, and these can be useful in monitoring the progress of the algorithm toward an acceptable solution. Information on this subject is found in the references by Kirkpatrick et al.

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At the heart of the method of simulated annealing is an analogy with thermodynamics, specifically with the way that liquids freeze and crystallize, or metals cool and anneal. At high temperatures, the molecules of a liquid move freely with respect to one another. If the liquid is cooled slowly, thermal mobility is lost. The atoms are often able to line themselves up and form a pure crystal that is completely ordered over a distance up to billions of times the size of an individual atom in all directions. This crystal is the state of minimum energy for this system. The amazing fact is that, for slowly cooled systems, nature is able to find this minimum energy state. In fact, if a liquid metal is cooled quickly or "quenched," it does not reach this state but rather ends up in a polycrystalline or amorphous state having somewhat higher energy.

So the essence of the process is *slow* cooling, allowing ample time for redistribution of the atoms as they lose mobility. This is the technical definition of ***annealing***, and it is essential for ensuring that a low energy state will be achieved.

Although the analogy is not perfect, there is a sense in which all of the minimization algorithms thus far in this chapter correspond to rapid cooling or quenching. In all cases, we have gone greedily for the quick, nearby solution: from the starting point, go immediately downhill as far as you can go. This, as often remarked above, leads to a local, but not necessarily a global, minimum. Nature's own minimization algorithm is based on quite a different procedure. The so-called Boltzmann probability distribution,

$$\text{Prob}(E) \sim \exp(-E/kT) \tag{10.9.1}$$

expresses the idea that a system in thermal equilibrium at temperature T has its energy probabilistically distributed among all different energy states E. Even at low temperature, there is a chance, albeit very small, of a system being in a high energy state. Therefore, there is a corresponding chance for the system to get out of a local energy minimum in favor of finding a better, more global, one. The quantity k (Boltzmann's constant) is a constant of nature which relates temperature to energy. In other words, the system sometimes goes *uphill* as well as downhill; but the lower the temperature, the less likely is any significant uphill excursion.

In 1953, Metropolis and coworkers first incorporated these kinds of principles into numerical calculations. Offered a succession of options, a simulated thermodynamic system was assumed to change its configuration from energy E_1 to energy E_2 with probability $p = \exp[-(E_2 - E_1)/kT]$. Notice that if $E_2 < E_1$, this probability is greater than unity; in such cases the change is arbitrarily assigned a probability $p = 1$, i.e., the system *always* took such an option. This general scheme, of always taking a downhill step while *sometimes* taking an uphill step, has come to be known as the Metropolis algorithm.

To make use of the Metropolis algorithm for other than thermodynamic systems, one must provide the following elements:

1. A description of possible system configurations.
2. A generator of random changes in the configuration; these changes are the "options" presented to the system.

3. An objective function E (analog of energy) whose minimization is the goal of the procedure.

4. A control parameter T (analog of temperature) and an ***annealing schedule*** which tells how it is lowered from high to low values, e.g., after how many random changes in configuration is each downward step in T taken, and how large is that step. The meaning of "high" and "low" in this context, and the assignment of a schedule, may require physical insight and/or trial-and-error experiments.

The Traveling Salesman Problem

A concrete illustration is provided by the traveling salesman problem. The salesperson visits N cities with given positions (x_i, y_i), returning finally to his or her city of origin. Each city is to be visited only once, and the route is to be made as short as possible. This problem belongs to a class known as ***NP-complete*** problems, whose computation time for an ***exact*** solution increases with N as $\exp(\text{const.} \times N)$, becoming rapidly prohibitive in cost as N increases. The traveling salesman problem also belongs to a class of minimization problems for which the objective function E has many local minima. In practical cases, it is often enough to be able to choose from these a minimum which, even if not absolute, cannot be significantly improved upon. The annealing method manages to achieve this, while limiting its calculations to scale as a small power of N.

As a problem in simulated annealing, the traveling salesman problem is handled as follows:

1. *Configuration.* The cities are numbered $i = 1 \dots N$ and each has coordinates (x_i, y_i). A configuration is a permutation of the number $1 \dots N$, interpreted as the order in which the cities are visited.

2. *Rearrangements.* An efficient set of moves has been suggested by Lin. The moves consist of two types: (a) A section of path is removed and then replaced with the same cities running in the opposite order; or (b) a section of path is removed and then replaced in between two cities on another, randomly chosen, part of the path.

3. *Objective Function.* In the simplest form of the problem, E is taken just as the total length of journey,

$$E = L \equiv \sum_{i=1}^{N} \sqrt{(x_i - x_{i+1})^2 + (y_i - y_{i+1})^2} \qquad (10.9.2)$$

with the convention that point $N + 1$ is identified with point 1. To illustrate the flexibility of the method, however, we can add the following additional wrinkle: suppose that the salesman has an irrational fear of flying over the Mississippi River. In that case, we would assign each city a parameter μ_i,

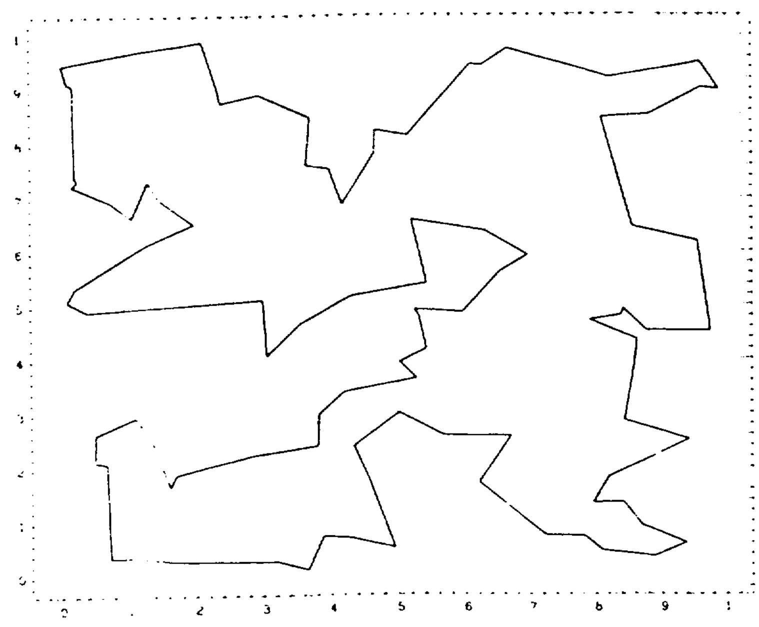

Figure 10.9.1 Traveling salesman problem solved by simulated annealing. The (nearly) shortest path among 100 randomly positioned cities is shown in (a). The dotted line is a river, but there is no penalty in crossing. In (b) the river-crossing penalty is made large, and the solution restricts itself to the minimum number of crossings, two. In (c) the penalty has been made negative: the salesman is actually a smuggler who crosses the river on the flimsiest excuse!

equal to +1 if it is east of the Mississippi, −1 if it is west, and take the objective function to be

$$E = \sum_{i=1}^{N} \sqrt{(x_i - x_{i+1})^2 + (y_i - y_{i+1})^2} + \lambda(\mu_i - \mu_{i+1})^2 \qquad (10.9.3)$$

A penalty 4λ is thereby assigned to any river crossing. The algorithm now finds the shortest path that avoids crossings. The relative importance that it assigns to length of path versus river crossings is determined by our choice of λ. Figure 10.9.1 shows the results obtained. Clearly, this technique can be generalized to include many conflicting goals in the minimization.

4. *Annealing schedule*. This requires experimentation. We first generate some random rearrangements, and use them to determine the range of values of ΔE that will be encountered from move to move. Choosing a starting value for the parameter T which is considerably larger than the largest ΔE normally encountered, we proceed downward in multiplicative steps each amounting to a 10 percent decrease in T. We hold each new value of T constant for, say, $100N$

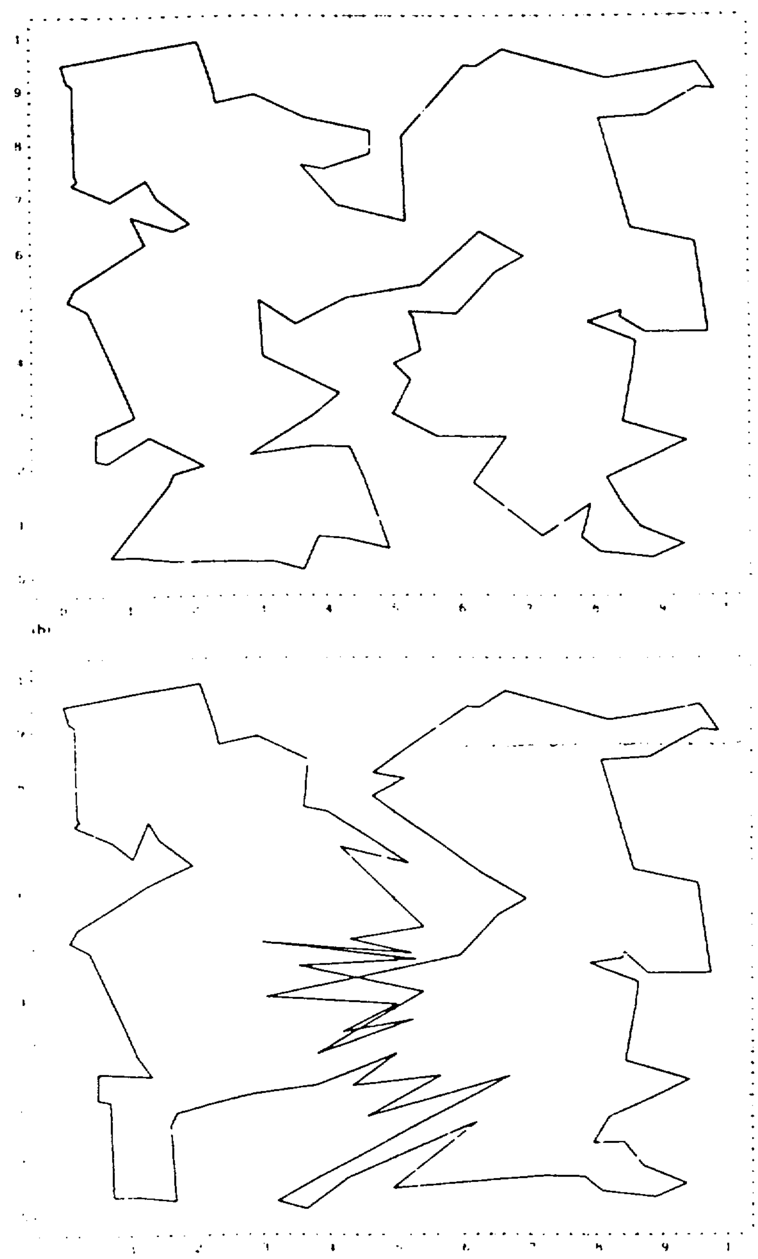

Figure 10.9.1. Traveling salesman problem solved by simulated annealing (see caption on previous page).

reconfigurations, or for $10N$ successful reconfigurations, whichever comes first. When efforts to reduce E further become sufficiently discouraging, we stop.

The following traveling salesman program, using the Metropolis algorithm, should illustrate for you the important aspects of the simulated annealing technique.

```
      SUBROUTINE ANNEAL(X,Y,IORDER,NCITY)
         This algorithm finds the shortest round-trip path to NCITY cities whose coordinates are
         in the arrays X(I),Y(I). The array IORDER(I) specifies the order in which the cities are
         visited. On input, the elements of IORDER may be set to any permutation of the numbers
         1 to NCITY. This routine will return the best alternative path it can find.
      DIMENSION X(NCITY),Y(NCITY),IORDER(NCITY),N(6)
      LOGICAL ANS
      ALEN(X1,X2,Y1,Y2)=SQRT((X2-X1)**2+(Y2-Y1)**2)
      NOVER=100*NCITY                 Maximum number of paths tried at any temperature
      NLIMIT=10*NCITY                 Maximum number of successful path changes before continuing.
      TFACTR=0.9                      Annealing schedule - T is reduced by this factor on each step
      PATH=0.0
      T=0.5
      DO 11 I=1,NCITY-1               Calculate initial path length
          I1=IORDER(I)
          I2=IORDER(I+1)
          PATH=PATH+ALEN(X(I1),X(I2),Y(I1),Y(I2))
11    CONTINUE
      I1=IORDER(NCITY)                Close the loop by tying path ends together
      I2=IORDER(1)
      PATH=PATH+ALEN(X(I1),X(I2),Y(I1),Y(I2))
      IDUM=-1
      ISEED=111
      DO 13 J=1,100                   Try up to 100 temperature steps
          NSUCC=0
          DO 12 K=1,NOVER
1             N(1)=1+INT(NCITY*RAN3(IDUM))        Choose beginning of segment
              N(2)=1+INT((NCITY-1)*RAN3(IDUM))  and end of segment
              IF (N(2).GE.N(1)) N(2)=N(2)+1
              NN=1+MOD((N(1)-N(2)+NCITY-1),NCITY)  NN is the number of cities not on the segment
              IF (NN.LT.3) GOTO 1
              IDEC=IRBIT1(ISEED)      Decide whether to do a segment reversal or transport
              IF (IDEC.EQ.0) THEN     Do a transport
                  N(3)=N(2)+INT(ABS(NN-2)*RAN3(IDUM))+1
                  N(3)=1+MOD(N(3)-1,NCITY)        Transport to a location not on the path
                  CALL TRNCST(X,Y,IORDER,NCITY,N,DE)  Calculate cost
                  CALL METROP(DE,T,ANS)     Consult the oracle
                  IF (ANS) THEN
                      NSUCC=NSUCC+1
                      PATH=PATH+DE
                      CALL TRNSPT(IORDER,NCITY,N)  Carry out the transport
                  ENDIF
              ELSE                    Do a path reversal
                  CALL REVCST(X,Y,IORDER,NCITY,N,DE)  Calculate cost
                  CALL METROP(DE,T,ANS)     Consult the oracle
                  IF (ANS) THEN
                      NSUCC=NSUCC+1
                      PATH=PATH+DE
                      CALL REVERS(IORDER,NCITY,N)  Carry out the reversal
                  ENDIF
              ENDIF
              IF (NSUCC.GE.NLIMIT) GOTO 2  Finish early if we have enough successful changes
12        CONTINUE
2         WRITE(*,*)
          WRITE(*,*) 'T =',T,' Path Length =',PATH
          WRITE(*,*) 'Successful Moves:  ',NSUCC
```

```
      T=T*TFACTR                    Annealing schedule
      IF (NSUCC.EQ.0) RETURN        If no success, we are done
13    CONTINUE
      RETURN
      END
```

```
      SUBROUTINE REVCST(X,Y,IORDER,NCITY,N,DE)
```

This subroutine returns the value of the cost function for a proposed path reversal. NCITY is the number of cities, and arrays X(I),Y(I) give the coordinates of these cities. IORDER(I) holds the present itinerary. The first two values N(1) and N(2) of array N give the starting and ending cities along the path segment which is to be reversed. On output, DE is the cost of making the reversal. The actual reversal is not performed by this routine.

```
      DIMENSION X(NCITY),Y(NCITY),IORDER(NCITY),N(6),XX(4),YY(4)
      ALEN(X1,X2,Y1,Y2)=SQRT((X2-X1)**2+(Y2-Y1)**2)
      N(3)=1+MOD((N(1)+NCITY-2),NCITY)     Find the city before N(1)
      N(4)=1+MOD(N(2),NCITY)                 and the city after N(2)
      DO 11 J=1,4
        II=IORDER(N(J))                 Find coordinates for the four cities involved
        XX(J)=X(II)
        YY(J)=Y(II)
11    CONTINUE
      DE=-ALEN(XX(1),XX(3),YY(1),YY(3))    Calculate cost of disconnecting the segment at both ends
     *   -ALEN(XX(2),XX(4),YY(2),YY(4))      and reconnecting in the opposite order
     *   +ALEN(XX(1),XX(4),YY(1),YY(4))
     *   +ALEN(XX(2),XX(3),YY(2),YY(3))
      RETURN
      END
```

```
      SUBROUTINE REVERS(IORDER,NCITY,N)
```

This routine performs a path segment reversal. IORDER(I) is an input array giving the present itinerary. The vector N has as its first four elements the first and last cities N(1),N(2) of the path segment to be reversed, and the two cities N(3) and N(4) which immediately precede and follow this segment. N(3) and N(4) are found by subroutine REVCST. On output, IORDER(I) contains the segment from N(1) to N(2) in reversed order.

```
      DIMENSION IORDER(NCITY),N(6)
      NN=(1+MOD(N(2)-N(1)+NCITY,NCITY))/2  This many cities must be swapped to effect the reversal
      DO 11 J=1,NN
        K=1+MOD((N(1)+J-2),NCITY)      Start at the ends of the segment and swap pairs of cities, moving
        L=1+MOD((N(2)-J+NCITY),NCITY)  toward the center
        ITMP=IORDER(K)
        IORDER(K)=IORDER(L)
        IORDER(L)=ITMP
11    CONTINUE
      RETURN
      END
```

```
      SUBROUTINE TRNCST(X,Y,IORDER,NCITY,N,DE)
```

This subroutine returns the value of the cost function for a proposed path segment transport. NCITY is the number of cities, and arrays X(I) and Y(I) give the city coordinates. IORDER is an array giving the present itinerary. The first three elements of array N give the starting and ending cities of the path to be transported, and the point among the remaining cities after which it is to be inserted. On output, DE is the cost of the change. The actual transport is not performed by this routine.

```
      DIMENSION X(NCITY),Y(NCITY),IORDER(NCITY),N(6),XX(6),YY(6)
      ALEN(X1,X2,Y1,Y2)=SQRT((X2-X1)**2+(Y2-Y1)**2)
      N(4)=1+MOD(N(3),NCITY)             Find the city following N(3)
      N(5)=1+MOD((N(1)+NCITY-2),NCITY)   and the one preceding N(1)
      N(6)=1+MOD(N(2),NCITY)             and the one following N(2)
      DO 11 J=1,6
        II=IORDER(N(J))                  Determine coordinates for the six cities involved
        XX(J)=X(II)
```

```
      YY(J)=Y(II)
11    CONTINUE
      DE=-ALEN(XX(2),XX(6),YY(2),YY(6))     Calculate the cost of disconnecting the path segment from
     *    -ALEN(XX(1),XX(5),YY(1),YY(5))      N(1) to N(2), opening a space between N(3) and N(4),
     *    -ALEN(XX(3),XX(4),YY(3),YY(4))      connecting the segment in the space, and connecting
     *    +ALEN(XX(1),XX(3),YY(1),YY(3))      N(5) to N(6)
     *    +ALEN(XX(2),XX(4),YY(2),YY(4))
     *    +ALEN(XX(5),XX(6),YY(5),YY(6))
      RETURN
      END

      SUBROUTINE TRNSPT(IORDER,NCITY,N)
```

This routine does the actual path transport, once METROP has approved. IORDER is an input array of length NCITY giving the present itinerary. The array N has as its six elements the beginning N(1) and end N(2) of the path to be transported, the adjacent cities N(3) and N(4) between which the path is to be placed, and the cities N(5) and N(6) which precede and follow the path. N(4), N(5) and N(6) are calculated by subroutine TRNCST. On output, IORDER is modified to reflect the movement of the path segment.

```
      PARAMETER(MXCITY=1000)               Maximum number of cities anticipated
      DIMENSION IORDER(NCITY),JORDER(MXCITY),N(6)
      M1=1+MOD((N(2)-N(1)+NCITY),NCITY)    Find the number of cities from N(1) to N(2)
      M2=1+MOD((N(5)-N(4)+NCITY),NCITY)      and the number from N(4) to N(5)
      M3=1+MOD((N(3)-N(6)+NCITY),NCITY)      and the number from N(6) to N(3)
      NN=1
      DO 11 J=1,M1
        JJ=1+MOD((J+N(1)-2),NCITY)         Copy the chosen segment
        JORDER(NN)=IORDER(JJ)
        NN=NN+1
11    CONTINUE
      IF (M2.GT.0) THEN
        DO 12 J=1,M2                       Then copy the segment from N(4) to N(5)
          JJ=1+MOD((J+N(4)-2),NCITY)
          JORDER(NN)=IORDER(JJ)
          NN=NN+1
12      CONTINUE
      ENDIF
      IF (M3.GT.0) THEN
        DO 13 J=1,M3                       Finally, the segment from N(6) to N(3)
          JJ=1+MOD((J+N(6)-2),NCITY)
          JORDER(NN)=IORDER(JJ)
          NN=NN+1
13      CONTINUE
      ENDIF
      DO 14 J=1,NCITY
        IORDER(J)=JORDER(J)                Copy JORDER back into IORDER
14    CONTINUE
      RETURN
      END

      SUBROUTINE METROP(DE,T,ANS)
```

Metropolis algorithm. ANS is a logical variable which issues a verdict on whether to accept a reconfiguration which leads to a change DE in the objective function E. If DE<0, ANS=.TRUE., while if DE>0, ANS is only .TRUE. with probability exp(-DE/T), where T is a temperature determined by the annealing schedule.

```
      PARAMETER(JDUM=1)
      LOGICAL ANS
      ANS=(DE.LT.0.0).OR.(RAN3(JDUM).LT.EXP(-DE/T))
      RETURN
      END
```

Assessing the Promise of Simulated Annealing

There is not yet enough practical experience with the method of simulated annealing to say definitively that it will realize its current promise. The method has several extremely attractive features, rather unique when compared with other optimization techniques.

First, it is not "greedy", in the sense that it is not easily fooled by the quick payoff achieved by falling into unfavorable local minima. Provided that sufficiently general reconfigurations are given, it wanders freely among local minima of depth less than about T. As T is lowered, the number of such minima qualifying for frequent visits is gradually reduced.

Second, configuration decisions tend to proceed in a logical order. Changes which cause the greatest energy differences are sifted over when the control parameter T is large. These decisions become more permanent as T is lowered, and attention then shifts more to smaller refinements in the solution. For example, in the traveling salesman problem with the Mississippi River twist, if λ is large, a decision to cross the Mississippi only twice is made at high T, while the specific routes on each side of the river are determined only at later stages.

The analogies to thermodynamics may be pursued to a greater extent than we have done here. Quantities analogous to specific heat and entropy may be defined, and these can be useful in monitoring the progress of the algorithm toward an acceptable solution. Information on this subject is found in the references by Kirkpatrick et al.

REFERENCES AND FURTHER READING:

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UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

JUN 23 10 52 AM '00

JUN 16 1993

Mr. Dwight Shelor, Associate Director for
Systems and Compliance
Office of Civilian Radioactive Waste Management
U.S. Department of Energy, RW 30
Washington, DC 20585

Dear Mr. Shelor:

SUBJECT: REVIEW OF U.S. DEPARTMENT OF ENERGY (DOE) STUDY PLAN "SITE SATURATED-ZONE HYDROLOGIC SYSTEM SYNTHESIS AND MODELING"

On January 28, 1993, DOE transmitted the study plan, "Site Saturated-Zone Hydrologic System Synthesis and Modeling" (Study Plan 8.3.1.2.3.3) to the U.S. Nuclear Regulatory Commission for review and comment. NRC has completed its review of this document using the Review Plan for NRC Staff Review of DOE Study Plans, Revision 2 (March 10, 1993). The material submitted in the study plan was considered to be consistent, to the extent possible at this time, with the revised NRC-DOE "Level of Detail Agreement and Review Process for Study Plans" (Shelor to Holonich, March 22, 1993).

A major purpose of the review is to identify concerns with studies, tests, or analyses that, if started, could cause significant and irreparable adverse effects on the site, the site characterization program, or the eventual usability of the data for licensing. Such concerns would constitute objections, as that term has been used in earlier NRC staff reviews of DOE's documents related to site characterization (Consultation Draft Site Characterization Plan and the Site Characterization Plan for the Yucca Mountain site). It does not appear that the conduct of the activities described in this study plan will have adverse impacts on repository performance and the review of this study plan identified no objections with any of the activities proposed.

Among the references listed for this study are several which have not been provided to the NRC and are not readily available in the public domain. We therefore request that DOE provide the NRC with the documents which are listed in the Enclosure. Following receipt of the requested references, NRC plans to provide DOE with detailed comments on this study plan. Those comments and/or questions will be transmitted to DOE as a separate package at a later date, following receipt of the requested references.

ENCLOSURE 1

If you have any questions concerning this letter, please contact Charlotte Abrams (301) 504-3403 of my staff.

Sincerely,

Joseph J. Holonich, Director
Repository Licensing and Quality Assurance
Project Directorate
Division of High-Level Waste Management
Office of Nuclear Material Safety
and Safeguards

Enclosure: As stated

cc: R. Loux, State of Nevada
T. J. Hickey, Nevada Legislative Committee
C. Gertz, DOE/NV
M. Murphy, Nye County, NV
M. Baughman, Lincoln County, NV
D. Bechtel, Clark County, NV
D. Weigel, GAO
P. Niedzielski-Eichner, Nye County, NV
B. Mettam, Inyo County, CA
V. Poe, Mineral County, NV
F. Sperry, White Pine County, NV
R. Williams, Lander County, NV
L. Fiorenzi, Eureka County, NV
L. Vaughan II, Esmeralda County, NV
C. Shank, Churchill County, NV
L. Bradshaw, Nye County, NV

ENCLOSURE

NOT-READILY-AVAILABLE REFERENCES FOR STUDY PLAN 8.3.1.2.3.3

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EVALUATION OF A PREDICTIVE GROUND-WATER

SOLUTE-TRANSPORT MODEL AT THE

IDAHO NATIONAL ENGINEERING LABORATORY, IDAHO

By Barney D. Lewis and Flora J. Goldstein

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 82-25

Prepared in cooperation with the

U.S. Department of Energy

March 1982

UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

U.S. Geological Survey
Water Resources Division
Project Office
Idaho National Engineering Laboratory
CF-690, Room 164, P.O. Box 2230
Idaho Falls, Idaho 83401

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ILLUSTRATIONS

ILLUSTRATIONS

TABLES

FACTORS FOR CONVERTING INCH-POUND UNITS TO METRIC (SI) UNITS

The following factors can be used to convert inch-pound units published herein to the International System (SI) of metric units.

Multiply inch-pound units	By	To obtain metric units
inches (in)	2.54	centimeters (cm)
feet (ft)	0.3048	meters (m)
miles (mi)	1.609	kilometers (km)
square feet (ft^2)	0.0929	square meters (m^2)
acres	0.4047	hectares (ha)
square miles (mi^2)	2.590	square kilometers (km^2)
gallons (gal)	3.785	liters (L)
gallons (gal)	3.785×10^{-3}	cubic meters (m^3)
million gallons (10^6 gal)	3,785	cubic meters (m^3)
acre-feet (acre-ft)	1,233	cubic meters (m^3)
pounds (lb)	0.4536	kilograms (kg)
feet per mile (ft/mi)	0.1894	meters per kilometer (m/km)
curies (Ci)	3.70×10^{10}	becquerel (Bq)
micromhos (μmho)	1.00	microsiemens (μS)

EVALUATION OF A PREDICTIVE GROUND-WATER SOLUTE-TRANSPORT MODEL AT THE IDAHO NATIONAL ENGINEERING LABORATORY, IDAHO

By

Barney D. Lewis and Flora J. Goldstein

ABSTRACT

In 1973, a digital chemical solute-transport modeling study at the Idaho National Engineering Laboratory (INEL) had been used to project chloride and tritium waste plumes for 1980. The model indicated that for the conditions assumed, the wastes would be at or near the INEL southern boundary by 1980. Eight wells were drilled during the summer of 1980 near the southern boundary to fill existing gaps in the INEL hydrogeological data base, to delineate the leading edge of the waste plumes, and to monitor for first arrivals of aqueous wastes at the exiting boundary of the INEL. The data from the eight wells were used to evaluate the accuracy of the predictive model, and the assumptions used.

Data interpretation from the drilling program indicates that the subsurface geology in the southwestern INEL vicinity is dominated by thin basalt flows interbedded with layers of sediment and silicic rocks are penetrated only in those wells near the INEL's southern boundary. The Arco volcanic rift zone was found to have a marked effect on the regional ground-water flow regimen, and perhaps, on water quality. This same subsurface geologic structure appears to have lower water-yielding and transmitting capabilities than the surrounding aquifer matrix and retards the movement of aqueous wastes.

Interpretation of data also indicates that the leading edges of the chloride and tritium waste plumes are 2 to 3 miles upgradient from the southern boundary of the INEL, and higher-than-background specific conductance values are measurable at about the same upgradient distance. As expected, the waste plumes projected by the computer model for 1980 extended somewhat further downgradient than indicated by well data due to conservative worst-case assumptions in the model input and inaccurate approximations of subsequent waste discharge and aquifer recharge conditions.

Future programs at the INEL are needed to determine more accurately the hydrologic properties of the Snake River Plain aquifer, for inclusion into and recalibration of the digital model, and to delineate more accurately the subsurface hydrogeologic characteristics and their effects on the regional aquifer system.

INTRODUCTION

The Idaho National Engineering Laboratory (INEL), formerly the National Reactor Testing Station, was established in 1949 by the Atomic Energy Commission (AEC) and is now operated by the U.S. Department of Energy (DOE) to build, operate, and test various types of nuclear reactors. Fifty-two reactors have been constructed to date, of which 17 are still operable.

The INEL site covers 890 square miles of the eastern Snake River Plain (fig. 1) in southeastern Idaho. The Plain is a structural and topographic basin about 200 miles long and 50 to 70 miles wide. Thin basaltic lava flows, rhyolite deposits, and interbedded sediments fill the basin to its present level (land surface) from depths of approximately 2,000 to 10,000 feet. A more detailed description of the geology is found in Robertson, Schoen, and Barraclough (1974). Underlying the plain, and contained in the upper part of this stratigraphic sequence, is a vast body of ground water contained in the Snake River Plain aquifer--the major aquifer in Idaho. The INEL obtains its entire water supply from from this aquifer. Aqueous chemical and radioactive wastes are discharged to shallow ponds and to shallow or deep wells on the INEL site. Many of these waste constituents enter the aquifer either directly or indirectly following percolation through the unsaturated zone.

The study of the effects of subsurface waste disposal on the regional hydrology requires a knowledge of the hydrogeology of the Snake River Plain aquifer, the locations and quantities of aqueous waste disposal, the methods of disposal, and the geochemistry of the waste solutions and of the ground water in the aquifer. During recent years, the prime concern has been to trace the movement of dilute chemical and low-level radioactive wastes in the subsurface, and to explain the chemical and radiochemical changes that accompany such movement in terms of the geologic, hydrologic, and geochemical properties. Many project studies and resultant publications have been completed during these past years concerning these chemical and physical factors, but there are still areas with insufficient data. Public concern about waste disposal and migration prompted the initiation of a drilling program that was completed during the summer of 1980. This program bolstered knowledge of the aforementioned factors and provided additional monitoring points for possible waste migration in the Snake River Plain aquifer near the southern boundary of the INEL.

PURPOSE AND SCOPE

In 1949, the AEC requested that the U.S. Geological Survey (USGS) investigate and describe the water resources of the INEL and adjacent areas. Information was collected that depicted hydrogeologic conditions prior to reactor operations and waste disposal programs at the Laboratory. A continuing investigative program serves to increase an understanding of

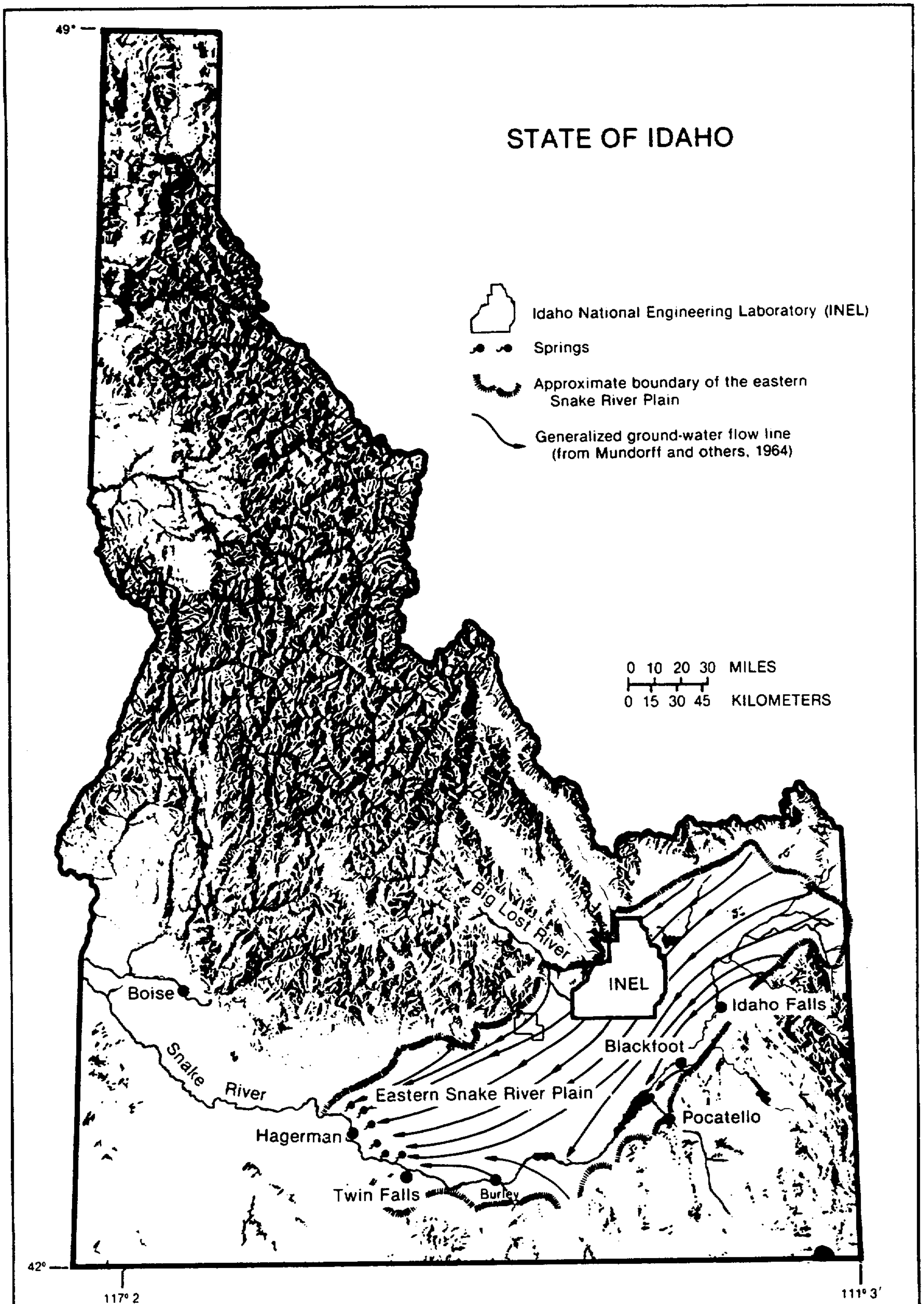


Figure 1.--Relief map of Idaho showing the location of the INEL, Snake River Plain, and generalized ground-water flow lines of the Snake River Plain aquifer (from Barraclough, Lewis, and Jensen, 1981).

the hydrogeologic system and to determine changes in that system resulting from activities at the INEL. The effects on the aquifer, and the extent of migration therein, of low-level radioactive and nonradioactive chemical wastes, have caused increasing public concern. With this public awareness in mind, eight new monitoring wells were drilled in the summer of 1980 to supplement the existing INEL monitoring network. Geologic information from this drilling program and analyses of ground-water samples from the wells, along with those from monitoring wells, were used to compare the extent of the actual chloride and tritium plumes with those projected for 1980 by Robertson's (1974) predictive digital model of waste-solute transport. The information was also used for updating and calibrating the digital model and to understand further the subsurface geology and hydrology near the INEL's southern boundary.

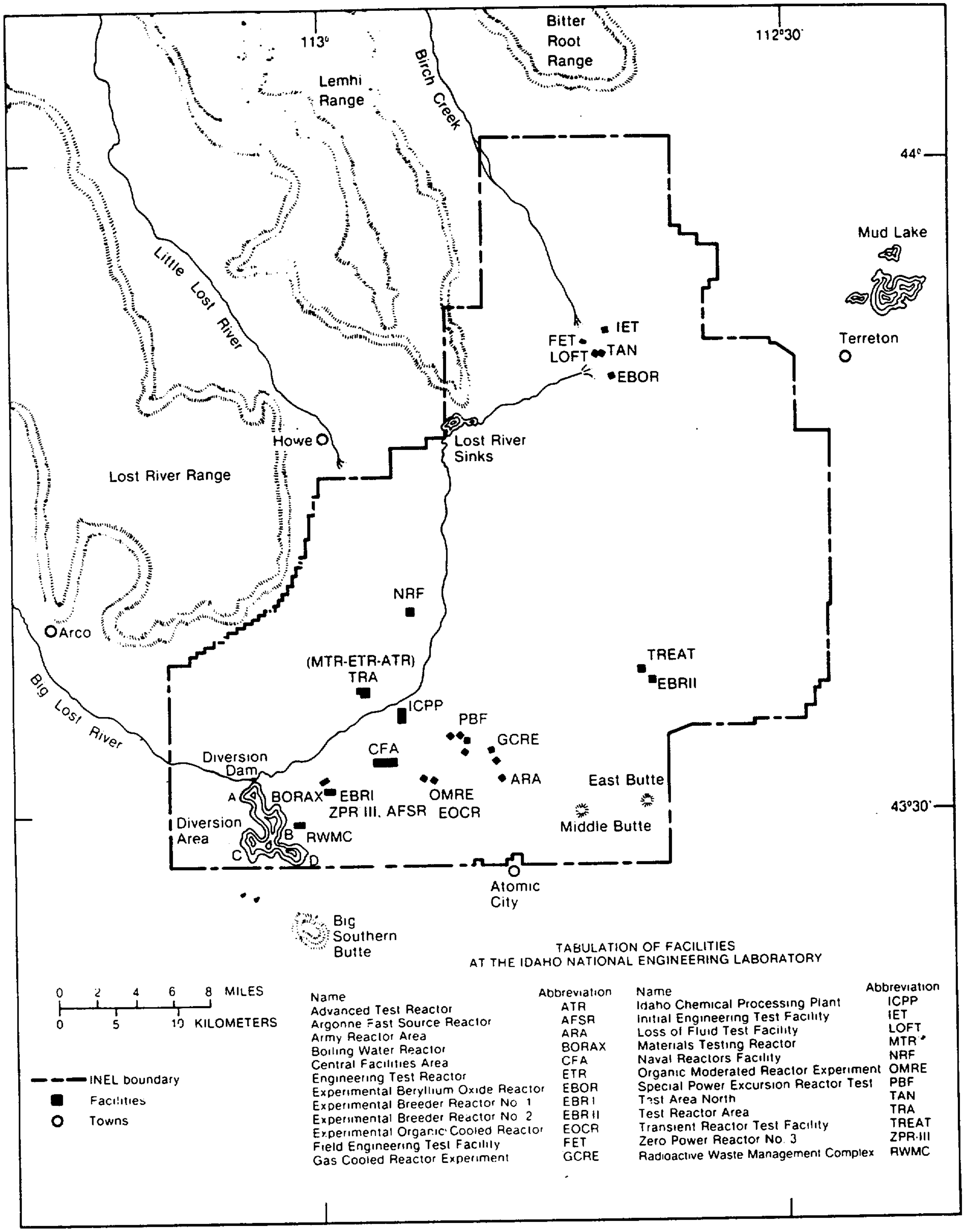
This report presents the information obtained by drilling the eight new wells and the interpretations made from the data collected. Subsurface geologic interpretations were made from geophysical logs recorded in each well and these aided in the construction of three hydrogeologic sections. Pumping tests were run on five of the wells to help determine aquifer properties and to collect pumped well-water samples for chemical analyses. The results of the sample analyses helped to delineate the southernmost extent of the chloride and tritium waste plumes, and delineate an aquifer area with higher-than-background specific conductance values. The water level was measured in each well to refine delineation of the configuration of the regional water table.

Reports on previous USGS investigations describing geologic and hydrologic studies of the INEL and the surrounding area, and related reports by the DOE staff, are listed in the Selected References and may be examined in the offices of the USGS at the Central Facilities Area (CFA) (fig. 2) or the INEL Library.

ACKNOWLEDGMENTS

This study has been sponsored and funded by the Department of Energy. Funds were made available by the INEL to finance the well drilling. The U.S. Geological Survey project at the INEL is coordinated through the following personnel of the DOE-Idaho Operations Office (IDO): J. P. Hamric, Director, Nuclear Fuel Cycle and Waste Management Division; J. B. Whitsett, Chief, Radioactive Waste Programs Branch; and M. M. Williamson, Director, Radiological and Environmental Sciences Laboratory. Considerable assistance was also obtained from the following DOE-IDO personnel: the staff of the Analytical Chemistry Branch, L. Z. Bodnar, Chief, who provided most of the chemical and radiometric analyses of ground-water samples; and E. W. Chew, Chief, Environmental Sciences Branch.

Personnel of Morrison-Knudsen Company (M-K), the prime construction contractor at the INEL, were responsible for all contracting duties connected with the drilling project. These duties included but were not limited to drafting and administering of the contract, providing technical support, providing on-site safety inspections of the drill rig and drilling procedures, and maintaining a day-to-day schedule of drilling progress.



TABULATION OF FACILITIES AT THE IDAHO NATIONAL ENGINEERING LABORATORY

Name	Abbreviation	Name	Abbreviation
Advanced Test Reactor	ATR	Idaho Chemical Processing Plant	ICPP
Argonne Fast Source Reactor	AFSR	Initial Engineering Test Facility	IET
Army Reactor Area	ARA	Loss of Fluid Test Facility	LOFT
Boiling Water Reactor	BORAX	Materials Testing Reactor	MTR
Central Facilities Area	CFA	Naval Reactors Facility	NRF
Engineering Test Reactor	ETR	Organic Moderated Reactor Experiment	OMRE
Experimental Beryllium Oxide Reactor	EBOR	Special Power Excursion Reactor Test	PBF
Experimental Breeder Reactor No 1	EBR I	Test Area North	TAN
Experimental Breeder Reactor No 2	EBR II	Test Reactor Area	TRA
Experimental Organic Cooled Reactor	EOCR	Transient Reactor Test Facility	TREAT
Field Engineering Test Facility	FET	Zero Power Reactor No. 3	ZPR-III
Gas Cooled Reactor Experiment	GCRE	Radioactive Waste Management Complex	RWMC

Figure 2.--Location of the INEL facilities (from Barraclough, Lewis, and Jensen, 1981).

REGIONAL HYDROLOGY

INTRODUCTION

The eastern Snake River Plain is underlain by a vast ground-water reservoir known as the Snake River Plain aquifer, which may contain more than 1 billion acre-feet of water (Barraclough, Lewis, and Jensen, 1981). The flow of ground water in the aquifer is principally to the south-southwest (fig. 1) at relatively high velocities of 5-20 feet per day. The transmissivity of the aquifer generally ranges from 1 million to 100 million gallons per day per foot or 134,000 to 13,400,000 feet squared per day (Robertson, Schoen, and Barraclough, 1974).

The basaltic volcanic rocks and interbedded sediments composing the aquifer are all included in the Snake River Group of Quaternary age. The basement rocks are probably comprised of older volcanic and sedimentary rocks, in addition to underlying crystalline rocks. The basalt is the principal aquifer. Water-bearing openings in the basalt are distributed throughout the rock system in the form of intercrystalline and intergranular porespace, fractures, cavities, interstitial voids, interflow zones, and lava tubes. The variety and degree of interconnection of these openings complicates the direction of ground-water movement locally throughout the aquifer.

Ground-water recharge to the INEL is primarily by underflow from the northeastern part of the plain and also from adjacent drainages on the west and north. Most of the ground water flowing under the INEL entered the ground in the uplands to the north, northeast, and northwest of the site, moves south or southwestward through the aquifer, and discharges at springs along the Snake River valley near Hagerman (fig. 1). Lesser amounts of recharge are derived from local precipitation on the plain. Most of the precipitation evaporates but part infiltrates the ground surface and percolates through the unsaturated zone to the regional water table. Some recharge is also derived from occasional flow in the Big Lost River.

CONFIGURATION OF THE REGIONAL WATER TABLE

Figure 3 is a map of the southwestern part of the INEL site and adjacent areas showing altitude contours on the water table of the Snake River Plain aquifer for July to October 1980. The altitude of the water table ranges from 4,494 feet above the National Geodetic Vertical Datum of 1929 in the central part of the site (top of figure 3) to 4,415 feet near the southwestern boundary of the site. The general direction of the regional ground-water movement is to the south and southwest. The average slope of the water table is about 4 feet per mile. In the southwestern part of the INEL, near Big Southern Butte, the water-table gradient is low, sloping southwestward less than 2 feet per mile (fig. 3).

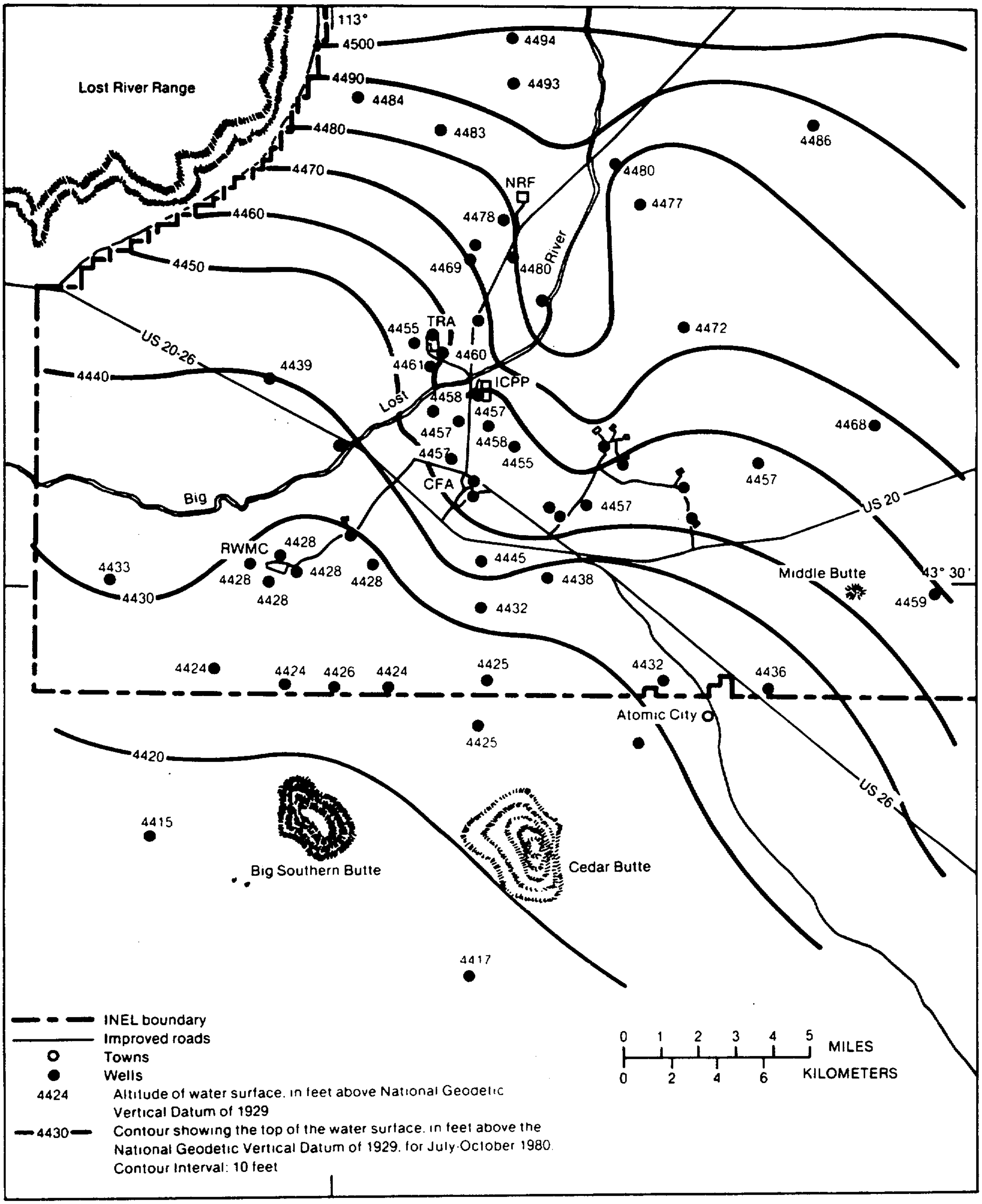


Figure 3.--Generalized altitude contours of the water table, Snake River Plain aquifer, southwestern INEL and vicinity, July-October 1980.

Data indicate that the altitude of the water table (shown by figure 3) has declined by less than 2 feet to as much as 6 feet compared to similar data for July 1978 (Barraclough, Lewis, and Jensen, 1981). The largest declines were measured in areas where the water table position is sensitive to changes in recharge from the Big Lost River, whose discharge was abnormally low during the years 1977 and 1979.

SURFACE WATER

Surface water is mainly that in streams draining the mountains and valleys to the west and north of the INEL (see fig. 1). On the INEL locally, snowmelt and rain also contribute to surface water, especially in the spring. The Big Lost River is the INEL's most important source of surface water. Recharge to the Snake River Plain aquifer from streamflow during wet years has been significant. All streamflow that enters the Snake River Plain is recharged to the subsurface, except for evaporation and transpiration losses. During dry periods, streamflow does not reach the INEL.

The Big Lost River flows southeastward down the Big Lost River valley past Arco, onto the Snake River Plain, and then turns northeastward through the INEL to its termination in playas, the Lost River Sinks (fig. 2). The river loses water by infiltration through the channel bottom as it flows on the plain. As flow approaches the terminal playas, the channel branches into many distributaries and the flow spreads over several flooding and ponding areas (Barraclough and others, 1967).

Two major artificial controls affect the river, in addition to irrigation diversions. These are the Mackay Dam, 30 miles upstream from Arco, and the INEL flood-diversion system in the southwestern part of the site (fig. 2). The INEL flood-control diversion system was constructed in 1958 to reduce the threat of floods from the Big Lost River on that part of the site. The diversion dam can divert flow out of the main channel to diversion areas A, B, C, and D (see Lamke, 1969, for discussion of flood control). During winter months nearly all flow is diverted to avoid accumulation of ice in the main channel and reduce the possibility of flooding INEL facilities.

The period of highest average flow of the Big Lost River below Mackay Reservoir for the entire historical record (fig. 4) was from 1965 through 1976, with 1965, 1969, 1967, 1974, 1975, and 1971 recording the six highest flows of record in order of decreasing magnitude. The total discharge decreased during 1977 to 160,300 acre-feet, much lower than normal. During the 1978 water year the discharge was measured at 225,900 acre-feet, slightly above average. In 1979, the discharge declined to an average of 202,400 acre-feet. In 1980 the discharge rose to an above average 249,500 acre-feet.

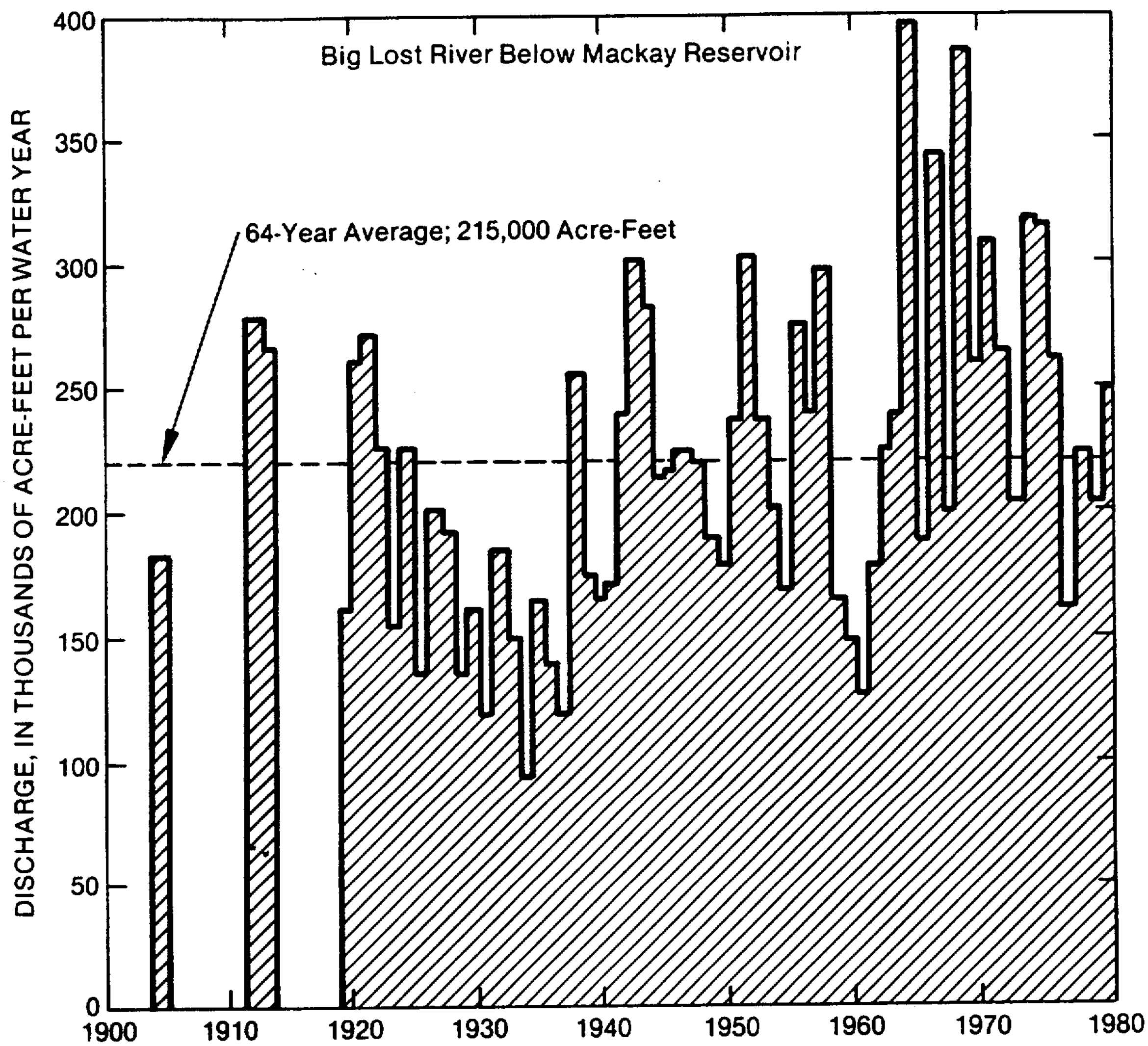


Figure 4.--Discharge of the Big Lost River below the Mackay Reservoir.

Continuous flow of the Big Lost River was recorded at the INEL diversion gaging station for at least three years prior to 1977 (Barraclough, Lewis, and Jense, 1981). However, since 1977 very little or no water has flowed past the diversion, reflecting the dry period that began in 1977. The above-average flow of the Big Lost River below Mackay Reservoir for 1980 (fig. 4) was diverted for irrigation purposes in the Big Lost River valley (see fig. 1) and only a very small amount reached the diversion area.

GROUND WATER

Water infiltrates from the Big Lost River during periods of flow and percolates to the Snake River Plain aquifer. Significant amounts of this recharge have caused a regional rise of the ground-water level over much of the INEL following several flow events. The water levels in some wells have risen as much as 6 feet in a few months following high flows in the river (Barraclough, Lewis, and Jensen, 1981). Water-level changes in four regional aquifer wells (fig. 5) in the southwestern part of the INEL illustrate the influence of recharge from the Big Lost River. In wells 17, 23, and 12 (see fig. 6 for well locations), the lowest water levels on record occurred in 1964 following four years of below average discharge in the river. The highest water levels occurred in 1972 following the wet period from 1965 to 1971.

The water level in well 12, which taps the Snake River Plain aquifer, rose 21.5 feet in 8 years from 1964 to 1972. This is the largest measured fluctuation of the water level in an INEL well. The water level in well 23 rose about 18 feet during this same period, which is the second largest water-level rise that has been measured.

The water level in well 20 rose only about 6 feet from 1964 to 1972 and had declined by nearly 8 feet to a record low by the end of 1980 (fig. 5). The more stable position of this water level may indicate that well 20 is not influenced by recharge from the Big Lost River and represents the changes in water level for the Snake River Plain aquifer on a more regional basis.

The Snake River Plain aquifer is the only source of water utilized at the INEL. Twenty-five of the 28 production wells on the INEL are generally in use. The combined pumpage of these wells has been about 2.4 billion gallons of water per year for the past several years. This averages about 6.6 million gallons per day or 7,370 acre-feet per year.

Not all the water pumped out of the aquifer is actually consumed. Some of the waste water is discharged directly back into the Snake River Plain aquifer through deep disposal wells. Other aqueous wastes (radioactive, chemical, and sewage) are discharged into ponds. Both methods of waste disposal contribute recharge to the aquifer. Nearly 60 percent of

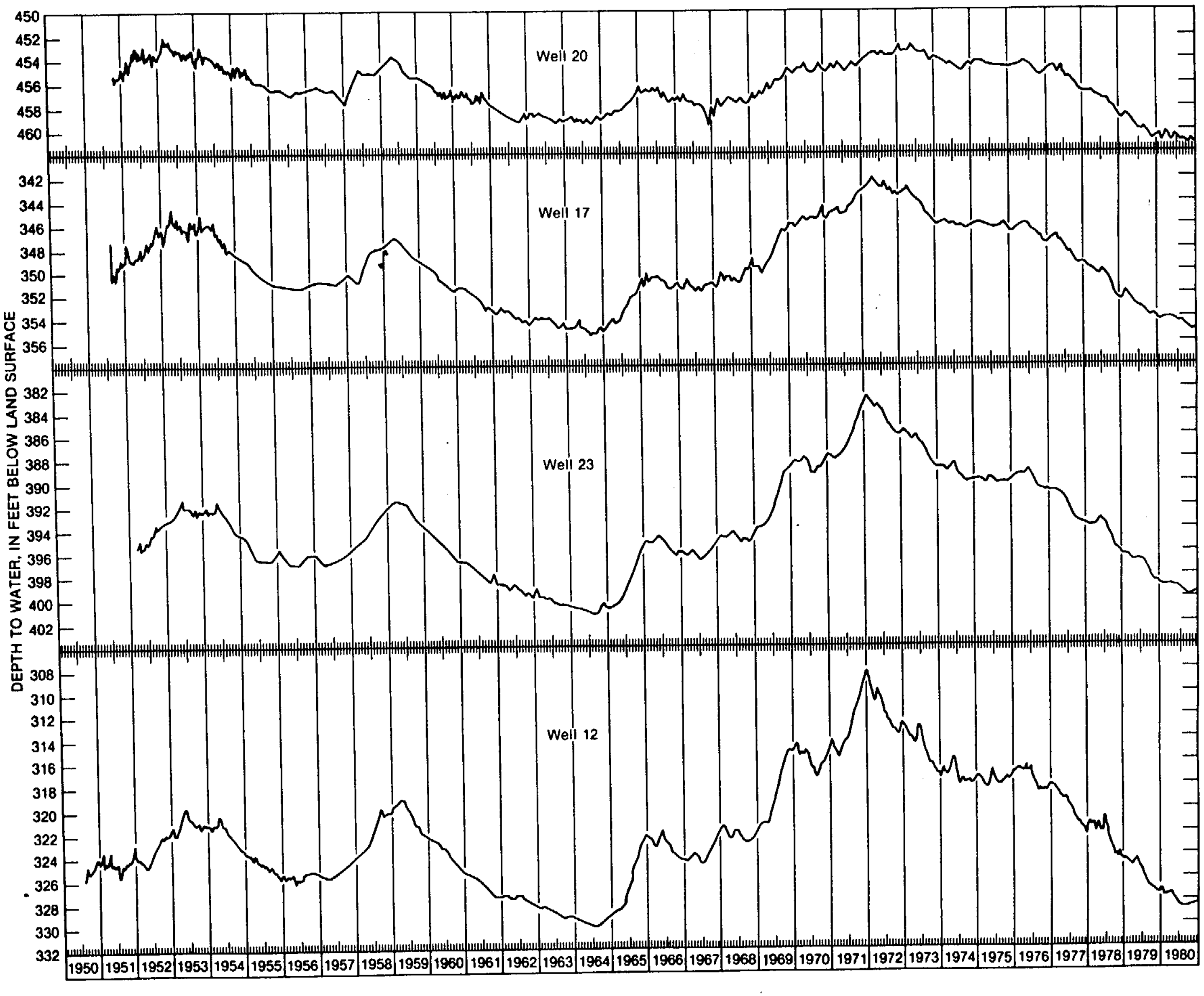


Figure 5.--Hydrographs of four wells in the southwestern part of the INEL.

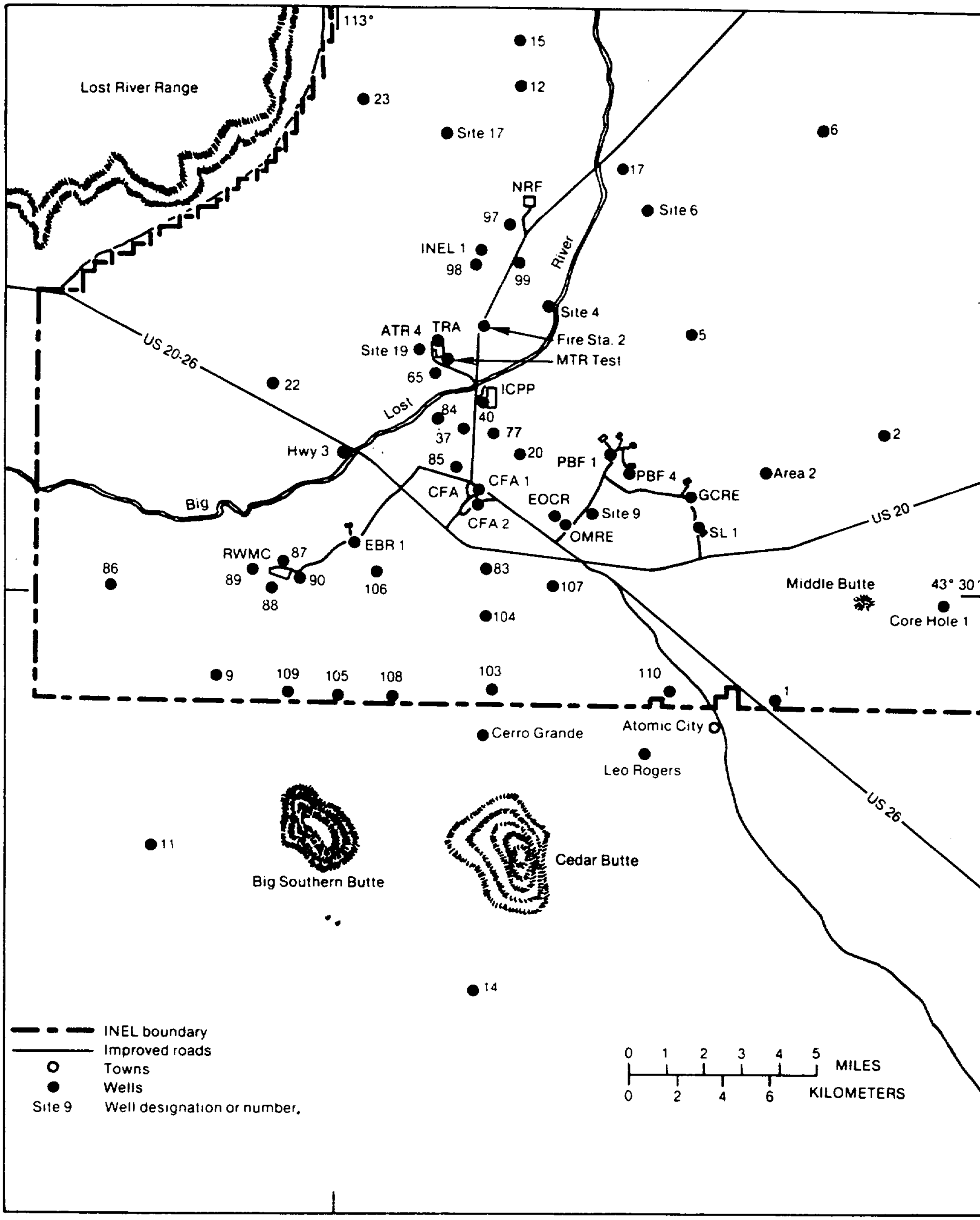


Figure 6.--Location of observation wells completed in the Snake River Plain aquifer, selected facilities, and geographic features in the southwestern INEL and vicinity.

the water pumped is disposed of to the surface or subsurface (Barraclough, Lewis, and Jensen, 1981). Pumping has little or no effect on annual water-level changes in the aquifer in the vicinity of the INEL because the amount pumped is a very small part of the total ground-water storage and recharge.

WASTE DISPOSAL SITES

Liquid low-level radioactive and dilute chemical wastes have been discharged to the subsurface at the Test Reactor Area since 1952, through a deep disposal well and through ponds; and at the Idaho Chemical Processing Plant since 1953 through a deep disposal well.

TEST REACTOR AREA

The TRA (see fig. 2) utilizes four disposal systems to dispose of nearly 470 million gallons of waste water annually (Barraclough, Lewis, and Jensen, 1981). Low-level radioactive wastes are discharged to three seepage ponds. These ponds receive more than 40 percent of the total TRA liquid waste. A part of the waste percolates to the Snake River Plain aquifer, 450 feet below the land surface. Chemical wastes are discharged to another seepage pond. Two seepage ponds are used to dispose of sanitary wastes. Cooling-tower blowdown wastes are discharged to the aquifer through a deep disposal well.

The average annual discharge to the TRA radioactive waste ponds has been about 190 million gallons for the past 10 years, but this rate was reduced by more than 60 percent during 1979 and 1980. Barraclough, Lewis, and Jensen (1981) showed that water discharged to the radioactive waste ponds during 1974 to 1978 contained an average of about 2,400 Ci (curies) per year of activation and fission products. During 1977 and 1978 this average was reduced to about 1,300 Ci per year as the yearly volume of discharged waste water was reduced. By 1980, the average curie discharge was reduced to less than 260 Ci as the yearly volume of discharged waste water was again reduced. In recent years, the average amount of tritium discharged to the ponds has also decreased from about 212 Ci per year to 120 Ci per year, but now represents a greater percentage of the total discharged radioactivity. It should be noted that, on the average, about 70 percent of these products have a short half-life (less than several weeks) and probably move only a short distance during their half-lives.

A pond has been utilized at the TRA since 1962 to dispose of chemical (non-radioactive) wastes from ion-exchange system. Sulfate and sodium are the major chemical constituents in the waste water and are disposed of in approximately 22 million gallons of water yearly, in annual amounts of about 1.2 million lbs and 114,000 lbs, respectively. These discharge amounts yield sulfate and sodium discharge concentrations of about 0.05 and 0.01 lbs per gallon, respectively.

A disposal well (1,275-feet deep) has been used at the TRA since 1964 to dispose of about 306 million gallons per year of non-radioactive waste water. The well discharges directly into the Snake River Plain aquifer. The water level is generally about 450 feet below the land surface. Most of the injected water is from cooling-tower blowdown; it contains a yearly average of 521,000 lbs of sulfate and 61,000 lbs of various other chemicals.

IDAHO CHEMICAL PROCESSING PLANT

The ICPP currently discharges low-level radioactive waste and dilute chemical waste directly to the Snake River Plain aquifer through a disposal well 600 feet deep. The natural water level is about 450 feet below the land surface. The average yearly discharge to the well has been about 319 million gallons since disposal began in 1953.

Most of the radioactivity of this waste, except for tritium, is removed by distillation and ion exchange before it is discharged into the well. In terms of radioactivity, more tritium is discharged than any other waste isotope.

During the past seven years, 1974 through 1980, the average curie discharge rate (all isotopes) to the ICPP well was 290 Ci per year, and the average volume of water discharge was 377 million gallons per year; resulting in an average radioactivity concentration of about 200 picocuries per milliliter (pCi/mL) in the discharge water. The amount of radioactivity discharged to the well from year to year is variable and depends on plant operations. For example, 223 Ci was discharged in 1979 and 112 Ci in 1980, below the overall discharge average. About 98 percent of the total activity was tritium, approximately 221 Ci and 109 Ci for 1979 and 1980 respectively, and nearly one percent (about 2 Ci yearly) was strontium-90. The remainder was made up of low quantities of various other radioisotopes.

WELL SITE SELECTION

The hydrologic data base used by the USGS at the INEL is comprehensive. There is a need, however, to improve and expand the data base to refine and quantify hydrogeologic concepts. Gaining additional knowledge about the subsurface hydrogeology at the INEL could enhance the understanding of ground-water flow directions, flow velocity, and chemical quality; waste product movement longitudinally and laterally from points of discharge at the TRA and ICPP (see fig. 2 for facility locations); waste concentrations in the aquifer downgradient from the discharge points, particularly near the INEL's southern boundary; and the existing geologic controls on the ground-water flow system and waste migration.

Figure 6 shows the expanded data base following the completion of the 1980 drilling program. Wells numbered 103 through 110 were completed during the summer of 1980. The figure includes only those wells in the southwestern part of the INEL, which is the part most affected by aqueous waste disposal (Barraclough, Lewis, and Jensen, 1981). It should be noted that many observation wells near and immediately south of the TRA and ICPP have been omitted as their inclusion would unduly congest figure 6.

Well sites 103 through 110 were selected by evaluating several criteria:

1) to fill existing gaps in the INEL hydrogeologic data base by drilling in areas not previously penetrated by wells;

2) to specifically determine the subsurface geology near the INEL's southern boundary and the Big Southern Butte, and to depict the hydrological and geochemical effects of this geologic setting on the ground-water flow system and waste migration;

3) to determine the southernmost extents of chloride and tritium waste plumes in the aquifer, and define an aquifer area with higher-than-background specific conductance values; and

4) to compare the tritium and waste chloride plumes with those simulated for 1980 by Robertson's (1974) model.

Additional siting criteria were used for the placement of three wells in particular. Well 109 (fig. 6) was located near the eastern edge of the Big Lost River diversion area (fig. 2) to evaluate the effects of recharge from the diversion ponds on the Snake River Plain aquifer during years of high flow. Wells 107 and 110 (fig. 6) were placed in stratigic locations to monitor the possible migration of waste products toward Atomic City, the only inhabited community downgradient and in the general vicinity of waste disposal sites.

DRILLING AND AQUIFER-TESTING DOCUMENTATION

WELL 103

The drilling of well 103 began on July 29 and was completed on August 20, 1980. Total depth of the well is 760 feet (fig. 7), of which 600 feet are cased with an 8-inch casing. The remainder of the well is an 8-inch open hole from 600 feet to total depth. The measured water level in the well is about 582 feet below land surface.

The geophysical logs shown in figure 7 indicate that the subsurface geology is dominated by numerous basalt flows. A sedimentary sequence, approximately 90 feet thick, was encountered at a depth of about 175 feet. Silicic rocks, probably rhyolite, exist at a depth of about 400 feet below land surface and are nearly 90 feet thick. A zone of fractured basalt exists at depths from about 650 feet to 710 feet, which is below water level, and it could yield significant quantities of water.

A pump was set in the well at a depth of about 630 feet for development and testing purposes. A test was run on well 103 from December 22 to December 24, 1980. The duration of the test was about two days with a pumping rate of 85 gallons per minute (gpm) for the first 20 minutes and an average rate of 96 gpm thereafter. No measurable water-level decline occurred in the well during the test.

A total of seven water samples was taken at various times during the test for selected radiochemical and standard chemical analyses (see table 1 and table 2 for selected representative analyses). No waste products were detectable in these samples (table 1). The ground-water chemistry is dominated by calcium, magnesium, and bicarbonate with minor concentrations of sodium, silica, sulfate, and chloride (table 2). This water chemistry type is consistent with that determined by Olmsted (1962) to be representative of ground water in the Snake River Plain aquifer prior to aqueous waste disposal.

WELL 104

The drilling of well 104 started on July 30 and was completed on August 22, 1980. The total depth of the well is 700 feet (fig. 8) with an 8-inch casing set to a depth of 550 feet. The remainder of the well, 550 to 700 feet, is an 8-inch open borehole. The measured water level is about 557 feet below land surface.

The geophysical logs recorded in the borehole (fig. 8) indicate a predominance of basalt in the subsurface with two sedimentary layers being present at a depth approximately 135 feet and 340 feet below land surface. These sedimentary deposits are both about 25 feet thick. The logs also show a basalt with few openings near to and below the water level in the uncased portion of the borehole.

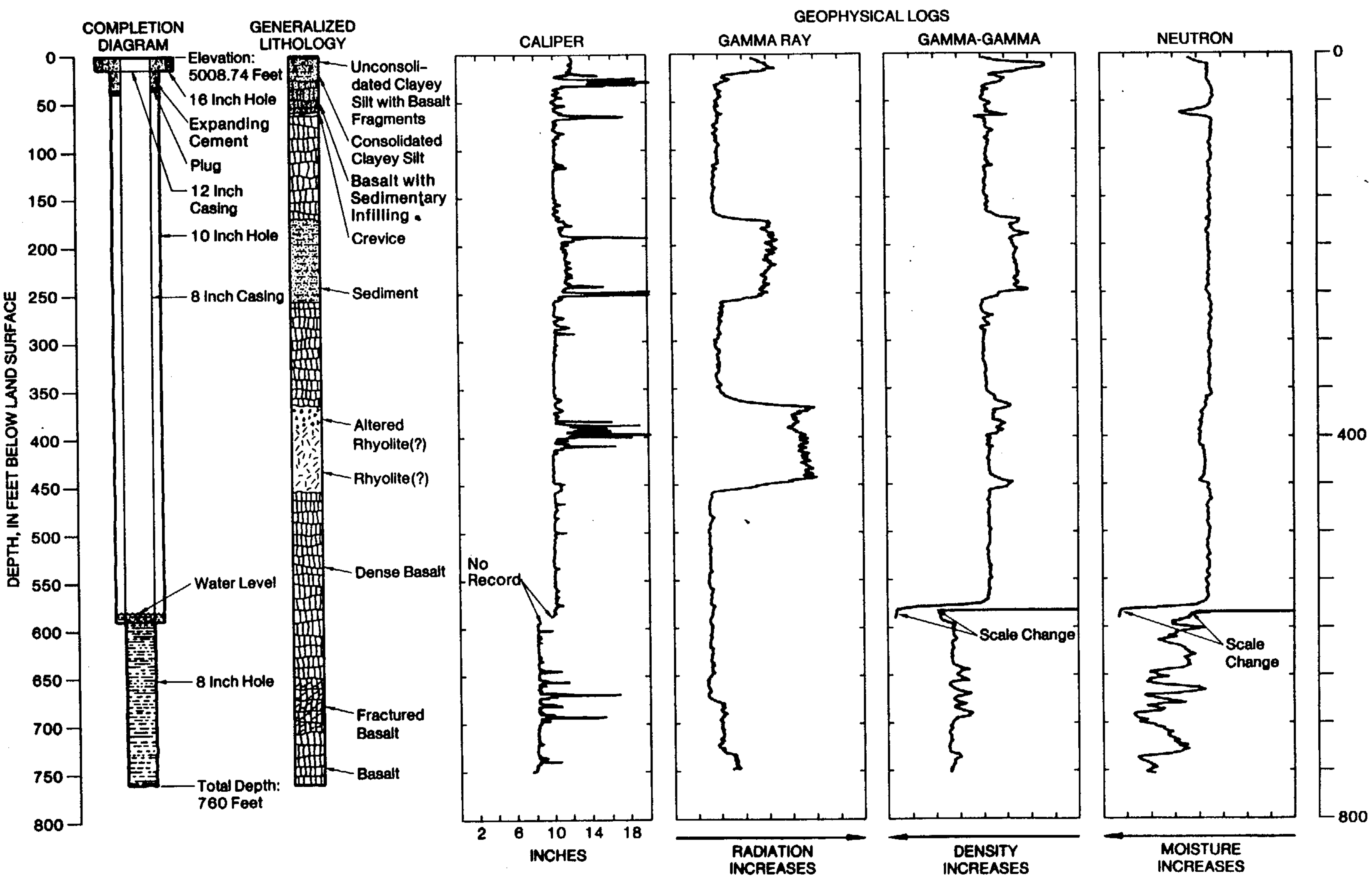


Figure 7.--Diagrams showing well completion, geology, and geophysical logs for well 103.

Table 1.--Tritium and chloride analyses, and the specific conductance of water from wells drilled during the summer of 1980[1]

Well number	Date of collection	Time of collection (hours after pumping started)	Tritium (pCi/mL)	Chloride (mg/L)	Specific conductance (µmhos/cm at 25°C)
103	10-06-80	---[2]	<0.4	20	260
-Do-	12-22-80	0.23	<0.4	14	300
-Do-	12-22-80	5.25	<0.4	15	300
-Do-	12-23-80	20.17	<0.4	14	320
-Do-	12-23-80	27.67	<0.4	12	310
-Do-	12-23-80	33.92	<0.4	13	310
-Do-	12-24-80	45.58	<0.4	13	300
104	10-06-80	---[2]	<0.4	13	230
-Do-	11-26-80	0.13	<0.4	12	270
-Do-	12-05-80	7.33	0.6	12	280
-Do-	12-06-80	17.22	0.8	11	270
-Do-	12-07-80	33.80	1.0	11	280
-Do-	12-07-80	44.80	0.8	11	270
105	10-06-80	---[2]	<0.4	19	320
-Do-	01-05-81	0.25	<0.4	26	370
-Do-	01-05-81	3.83	<0.4	27	370
-Do-	01-06-81	20.08	<0.4	26	370
-Do-	01-06-81	23.58	<0.4	26	370
-Do-	01-07-81	38.92	<0.4	27	370
-Do-	01-07-81	45.08	<0.4	28	370
106	10-06-80	---[2]	3.2	18	270
-Do-	01-09-81	0.25	3.1	27	340
-Do-	01-12-81	65.58	3.4	27	340
-Do-	01-12-81	69.92	2.9	27	330
-Do-	01-13-81	88.25	2.5	27	330
-Do-	01-13-81	97.75	3.1	27	330
-Do-	01-14-81	114.58	3.1	27	330
107	10-06-80	---[2]	<0.4	18	270
-Do-	06-11-81	0.04	<0.3	21	310
-Do-	06-11-81	0.17	<0.3	22	320
-Do-	06-11-81	0.50	<0.3	22	320
-Do-	06-11-81	1.00	<0.3	21	320
-Do-	06-11-81	4.00	<0.3	22	300
-Do-	06-12-81	19.00	<0.3	22	290
108	10-06-80	---[2]	<0.4	16	250
-Do-	12-29-80	0.25	<0.4	17	310
-Do-	12-29-80	3.25	<0.4	18	300
-Do-	12-30-80	17.83	<0.4	17	290
-Do-	12-30-80	26.08	<0.4	18	310
-Do-	12-31-80	45.25	<0.4	18	320
-Do-	12-31-80	51.50	<0.4	17	310
109	10-08-80	---[3]	<0.4	26	310
-Do-	04-02-81	---[3]	<0.4	21	310
110	10-08-80	---[2]	<0.4	27	290
-Do-	06-16-81	0.04	<0.4	22	310
-Do-	06-16-81	4.83	<0.4	21	290
-Do-	06-17-81	17.83	<0.4	23	300
-Do-	06-25-81	2.00	<0.4	23	300

[1] Laboratory measurements made by the Research Environmental Sciences Laboratory at the INEL.
[2] Thief sampler used to collect water sample.
[3] Bailer used to collect water sample.

Table 2.--Chemical analyses of water from selected wells drilled during the summer of 1980
(Constituents are dissolved and in milligrams per liter unless indicated otherwise[1])

Well number	Date of collection[2]	Specific conductance (µmhos/cm at 25°)	pH	Field water temperature (°C)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Sodium adsorption ratio (SAR)	Potassium (K)	Total alkalinity ($CaCO_3$)	Silica (SiO_2)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)
103	12-24-80	353	7.9	14.0	35	15	13.	0.5	2.7	130	30	24	11.	0.3
104	12-18-80	316	7.9	13.0	35	12	7.6	0.3	2.3	130	29	20	9.4	0.2
105	01-07-81	413	8.0	14.0	43	16	14.	0.5	4.9	140	27	34	20.	0.3
106	01-14-81	380	7.9	14.0	40	17	7.4	0.2	2.1	150	20	25	12.	0.2
107	06-14-81	333	7.9	14.9	36	15	16.	0.6	3.2	131	32	26	17.	0.3
108	12-31-80	347	7.7	13.0	35	15	11.	0.4	2.7	130	29	22	11.	0.3
110	06-25-81	361	7.4	14.5	35	14	16.	0.6	3.5	130	33	20	20.	0.5

[1] Laboratory measurements, except for water temperature, made at the U.S. Geological Survey's Central Laboratory, Denver, Colorado.
[2] Sample collected following many hours of pumping.

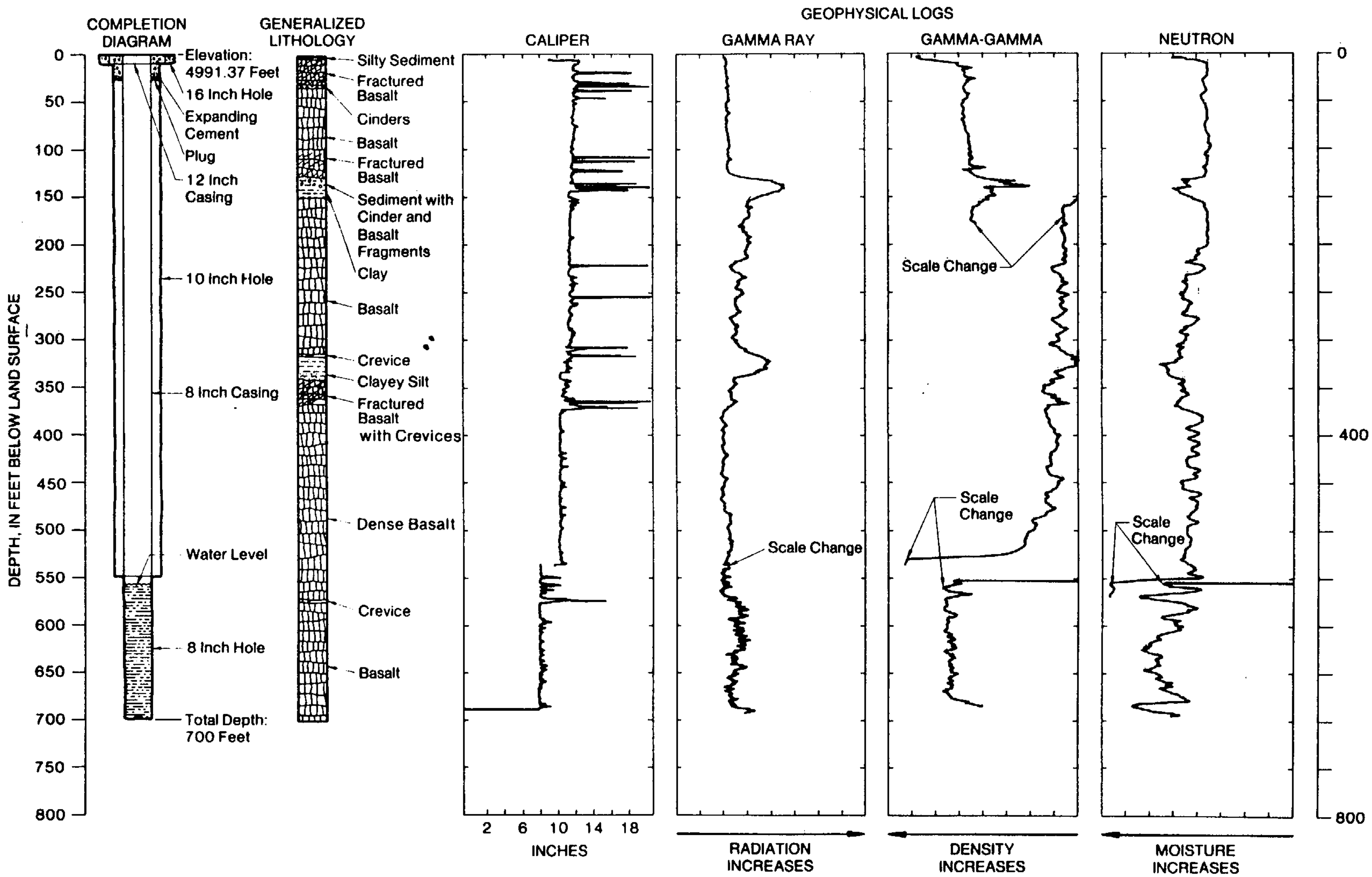


Figure 8.--Diagrams showing well completion, geology, and geophysical logs for well 104.

An aquifer test was run from December 6 to December 7, 1980 with a pump set at a depth of about 610 feet. The well was pumped at 21 gpm with a resultant water-level decline of 51 feet. The computed aquifer transmissivity for this test (using the semi-log, single-cycle, slope-intercept method described by Freeze and Cherry, 1979) was about 50 feet squared per day, with a computed specific capacity of about 0.4 gpm per foot of drawdown. As indicated by the geophysical logs, the aquifer water yield in the immediate vicinity of well 104 is much lower than those generally associated with the Snake River Plain aquifer (for example see Mundorff, Crosthwaite, and Kilburn, 1964; or Robertson, Schoen, and Barraclough, 1974).

Six water samples were collected during the aquifer test and analysed for various chemical and radiochemical constituents (see table 1 and table 2). Chloride concentrations were low, which indicates that chloride wastes have not reached this well; however, tritium concentrations were found to be above the background levels of 0.05 to 0.1 pCi/mL as depicted by Barraclough and others (1966). The average concentration of tritium in the water samples was 0.6 pCi/mL and indicates that this particular waste constituent has traveled downgradient at least 6 miles from the nearest point of discharge. The ground-water chemistry is dominated by calcium, magnesium, and bicarbonate with minor concentrations of sodium, silica, sulfate, and chloride (table 2); it is closely similar to the chemistry of the water pumped from well 103.

WELL 105

The drilling of well 105 began on August 25 and was completed on September 9, 1980. The total depth of the well is 800 feet with an 8-inch casing set from land surface to a depth of about 400 feet (fig. 9). The remaining 400 feet of the well is uncased and exists as an open borehole. The water level in the well was measured at a depth of about 670 feet below land surface.

The geophysical logs shown in figure 9 indicate that basalt is the predominant rock type in the subsurface. A silicic rock layer, probably rhyolite, was encountered at a depth of approximately 245 feet and is nearly 85 feet thick. Underlying this rhyolite zone is a thin clay layer. The basalt near and below the well's water level is severely fractured and contains many openings and crevices.

A pump was set in the well at a depth of about 720 feet and a test was run on the well from January 5 to January 7, 1981. The duration of the test was two complete days and the pumping rate averaged 63 gpm. No appreciable water-level decline was measured during the test.

Seven pumped-water samples were collected during the test, and the results of their analyses are listed in table 1 and table 2. The results do not indicate the presence of tritium in appreciable concentrations in any of the water samples (table 1). The chloride concentrations,

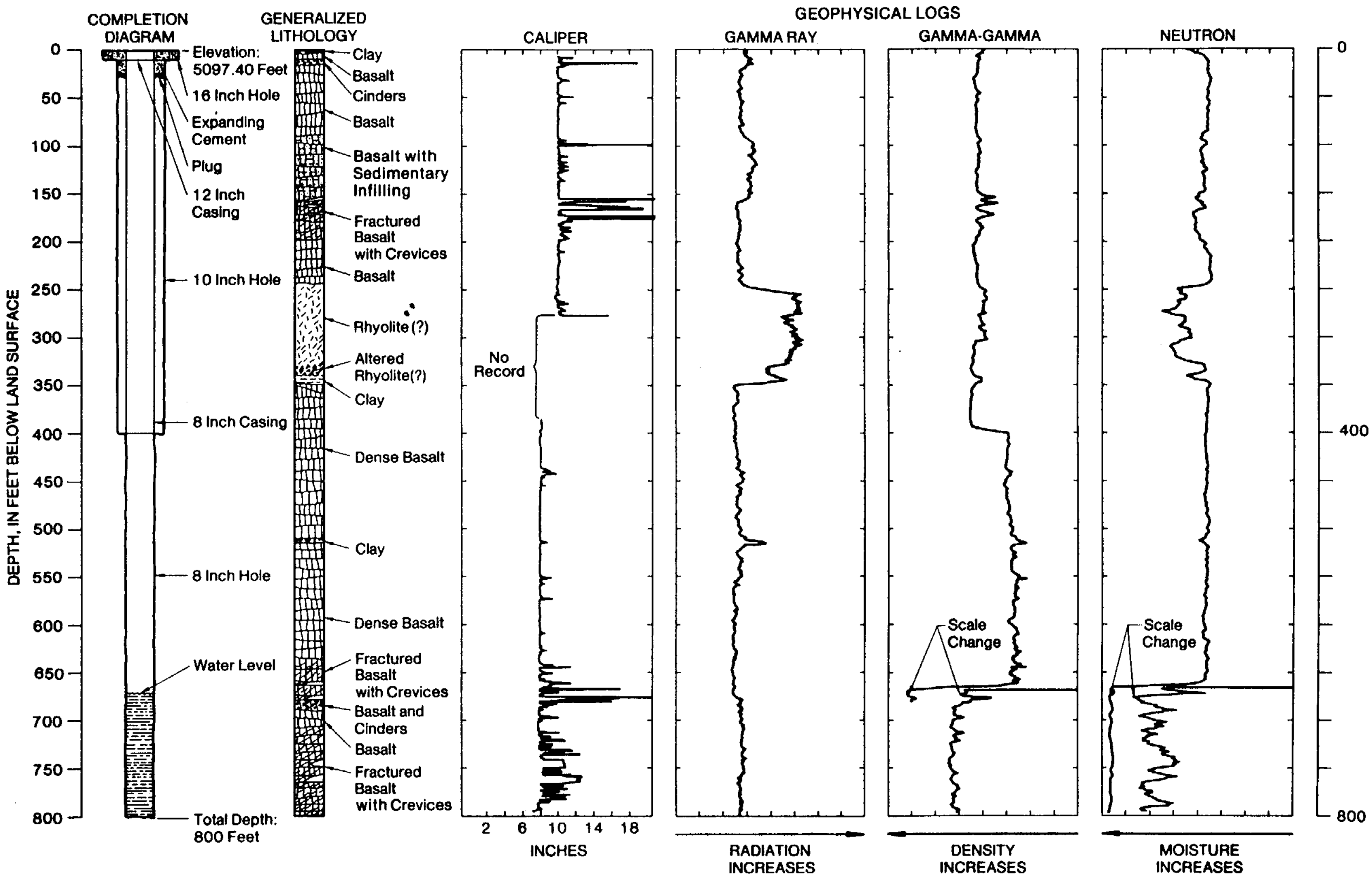


Figure 9.--Diagrams showing well completion, geology, and geophysical logs for well 105.

however, average 27 milligrams per liter (mg/L), and this is higher than the 10 to 20 mg/L range normally considered to be background levels for the regional aquifer (Robertson and Barraclough, 1973). This higher-than-background chloride concentration may not be associated with waste migration as other anomalously high chloride concentrations have been noted in the Snake River Plain aquifer that are not attributable to waste disposal (Robertson, Schoen, and Barraclough, 1974). Unknown hydrogeologic controls, such as varying rock types, could be contributing to the anomalous chloride values. Table 2 shows that the chemistry of the ground water in well 105 is dominated by calcium, magnesium, and bicarbonate with minor concentrations of sodium, silica, chloride, and sulfate.

WELL 106

The drilling of well 106 started on August 18 and was completed on August 28, 1980. The total depth of the well is 760 feet. An 8-inch casing was set from the surface to a depth of about 400 feet (fig. 10). The remainder of the well was completed as 200 feet of 10-inch open hole to a depth of 600 feet and another 160 feet of 8-inch open hole to the total depth of 760 feet. The measured water level in the well is at a depth of about 587 feet below land surface.

Figure 10 shows the geophysical logs recorded in well 106. The logs indicate that basalt flows and interbeds of clay and silt, are the predominant lithologic features in the subsurface. A prominent sedimentary zone is present at a depth of about 130 feet below land surface and is approximately 80 feet thick. A zone of fractured basalt is present at a depth of about 680 feet. This 80-foot thick fractured zone is below the well's water level and is in the uncased 8-inch open hole.

A test was run on well 106 for two days from January 12 to January 13, 1981. The pump was set at a depth of 640 feet and discharged 95 gpm. No measurable water-level decline occurred during the test.

During the test, six samples of the pumped ground water were collected for waste constituent analysis (table 1); and one sample was collected for standard chemical analyses (table 2). The analyses listed in table 1 indicate that tritium is present in the well water in an average concentration of 3.1 pCi/mL, which is above background levels. Chloride concentrations are also above background levels with an average concentration of 27 mg/L. These results show that both waste chloride and tritium have migrated at least six miles from their discharge points at the TRA and ICPP. The chloride concentration is not markedly above the background levels of 10 to 20 mg/L and, as in the case of well 105, may represent an anomalously high chloride concentration in the Snake River Plain aquifer. However, in the TRA-ICPP-CFA vicinity (see fig. 6), the background chloride concentration is about 12 mg/L (Robertson and Barraclough, 1973) and a part of the dissolved chloride in the water sampled from well 106 is likely supplemented by waste chloride. The analyses listed in table 2 show that the other constituents present are indicative of those normally found in the regional aquifer and the water chemistry is similar to that of previously discussed wells.

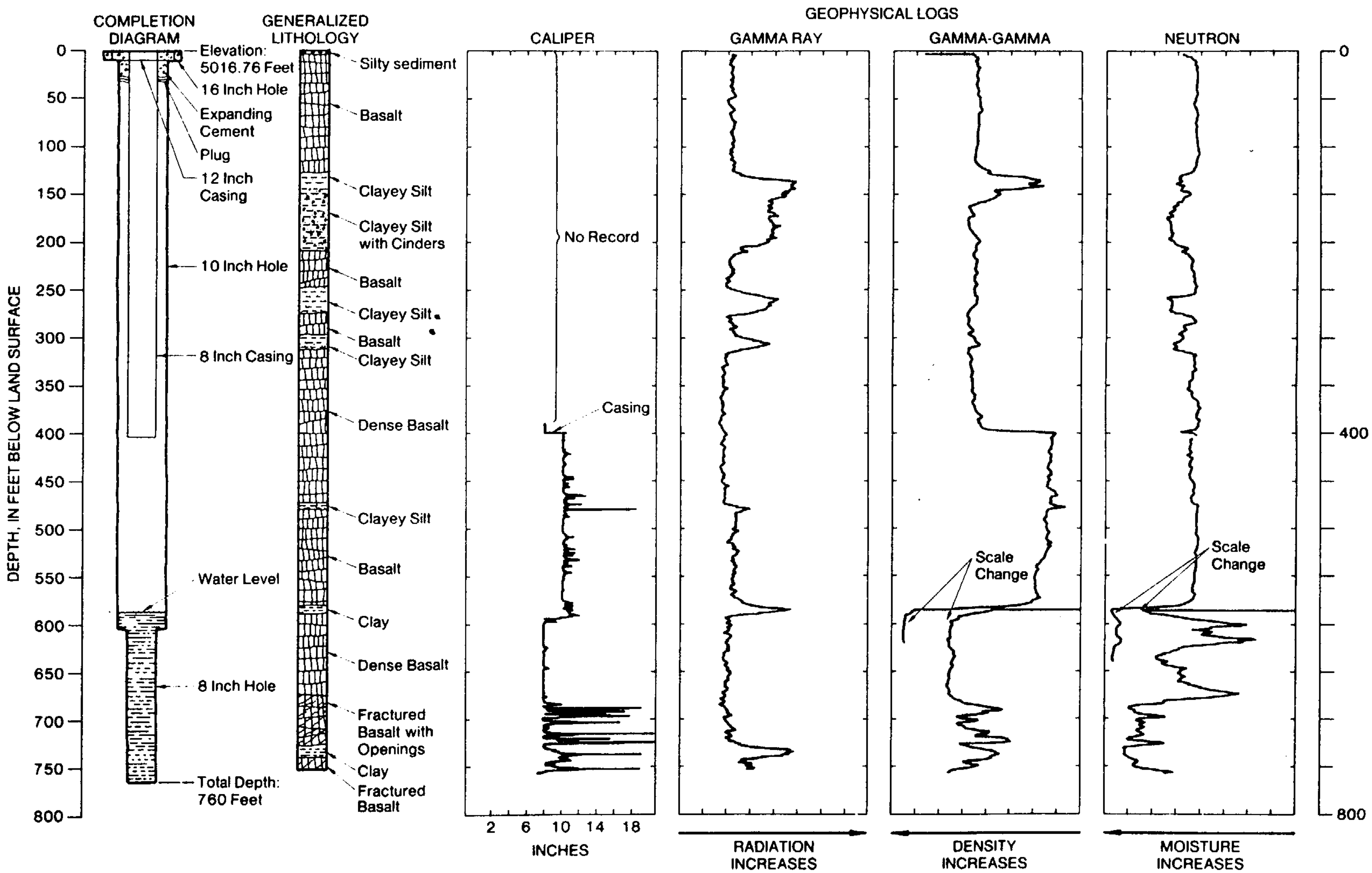


Figure 10.--Diagrams showing well completion, geology, and geophysical logs for well 106.

WELL 107

The drilling of well 107 began on September 2 and was completed on September 8, 1980. The total depth of the well is 690 feet with an 8-inch casing set to a depth of 195 feet below land surface (fig. 11). The remainder of the well is an 8-inch open hole from the termination of the casing at 195 feet to the total depth of 690 feet. The measured water level in the well is at a depth of about 480 feet.

The geophysical logs illustrated in figure 11 indicate that basalt is the dominant rock type in the subsurface. Two thin sedimentary deposits were encountered during drilling, one at about 50 feet and the other at about 450 feet below land surface. The logs also indicate that extensive fracture zones are present in the uncased part of the well; one at about 190 to 250 feet below land surface, which contains several crevices, and another at a depth of about 340 to 440 feet. Following completion of the well, the borehole contained two partly bridged areas, one at a depth of about 500 feet and the other at 550 feet. The detrital material that created these obstructions could have originated in either of the fractured zones. Another zone of fractured basalt exists below the well's water level from a depth of about 500 to 530 feet.

Well 107 was re-entered on May 7, 1981, to remove the obstructions in the borehole. Following this cleaning procedure, a 6-inch casing was suspended from land surface to a depth of 270 feet (fig. 11). The severely fractured zone at a depth of about 190 to 250 feet was therefore cased out. A caliper tool was then run to the bottom of the borehole, and indicated that this cleaning and casing procedure had stabilized the caving and bridging problem. The "recompletion" process was completed on May 12, 1981.

A test was made on well 107 from June 11 to June 12, 1981. The pump for this test was set at a depth of about 530 feet. The duration of the test was 19 hours with a pumping rate of 125 gpm. No measurable water-level decline occurred in the well during the test. Six water samples were taken at various times during the test for selected radiochemical and standard chemical analyses. No waste products were detectable in these samples (table 1). The ground water is also dominanted by calcium, magnesium, and bicarbonate, with minor concentrations of sodium, silica, sulfate, and chloride (table 2).

WELL 108

The drilling of well 108 started on September 11 and was completed on September 18, 1980. The total depth of the well is 760 feet with an 8-inch casing set from land surface to a depth of 400 feet (fig. 12). An 8-inch open hole makes up the remaining part of the well, from the end of the casing to the well's total depth at 760 feet. The measured water level is at 607 feet below land surface.

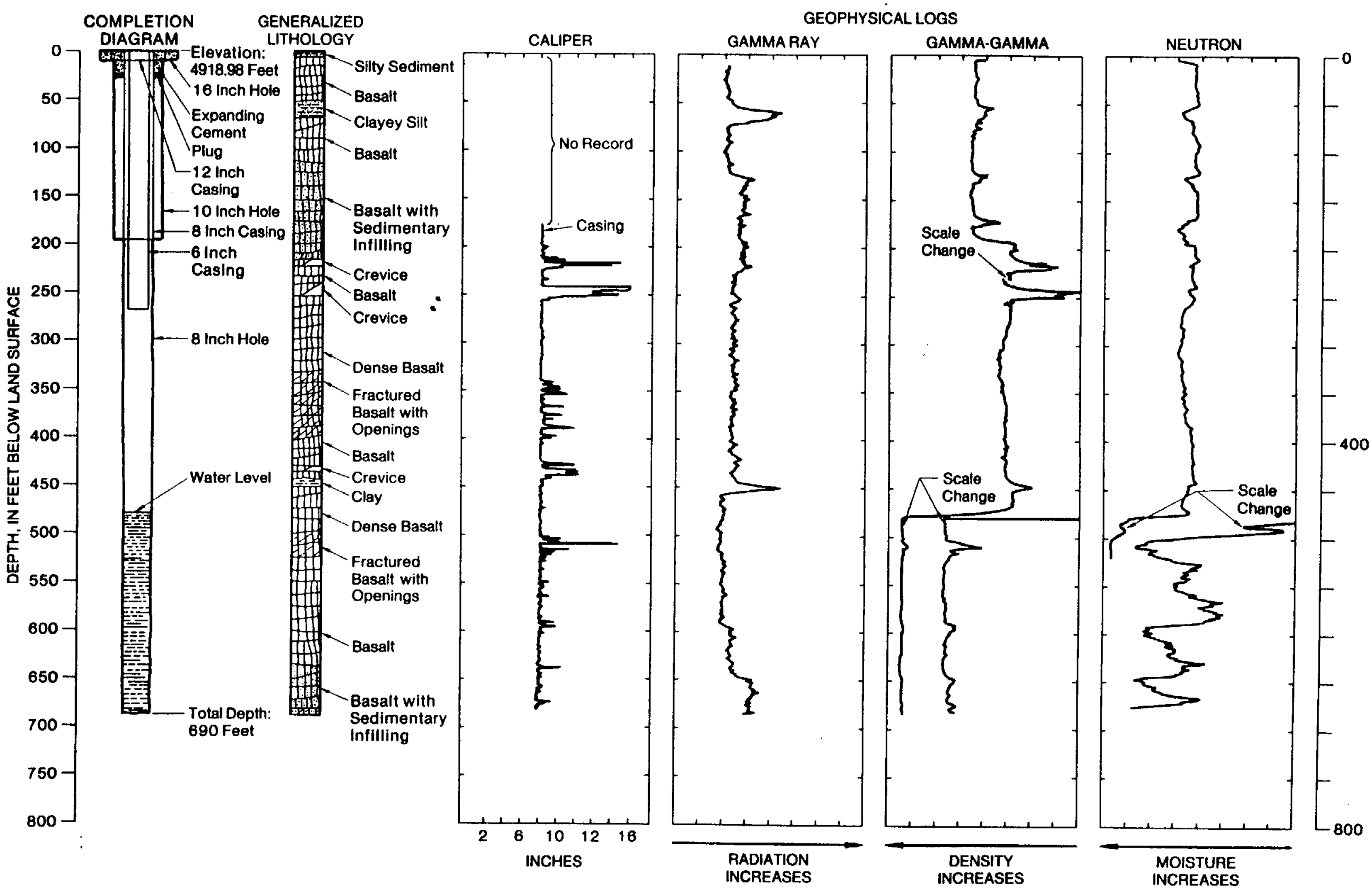


Figure 11.--Diagrams showing well completion, geology, and geophysical logs for well 107.

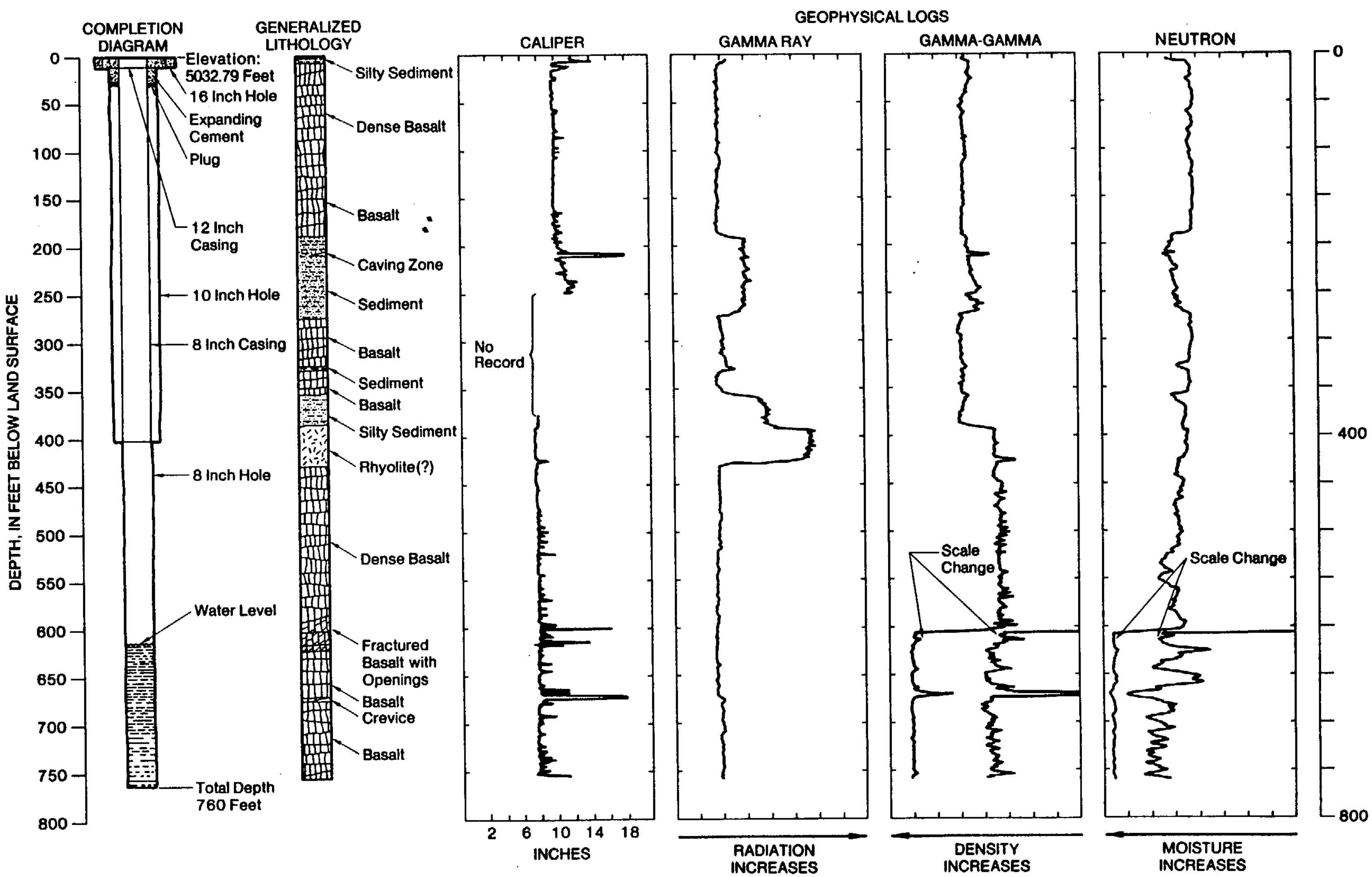


Figure 12.--Diagrams showing well completion, geology, and geophysical logs for well 108.

The geophysical logs recorded in the borehole (fig. 12) indicate that basalt dominates the subsurface geology. Two thick sedimentary deposits occur in the well at depths of about 180 to 280 feet and 360 to 390 feet. The deeper layer of sediment overlies a silicic rock zone, probably rhyolite, that extends to a depth of about 430 feet. A zone of fractured basalt with numerous openings occurs near and just below the well's water level, and a crevice zone is located about 60 feet below this static water level.

A test was run on well 108 from December 29 to December 31, 1980. The pumping rate was 88 gpm and the pump was set at a depth of about 660 feet. The duration of the test was 42 hours, during which no appreciable water-level decline was measured.

The selected waste constituent analyses of six water samples collected during the test (table 1) give no indication that waste products are present in well 108. As shown by the analyses in table 2, the water is dominanted by calcium, magnesium, and bicarbonate with minor concentrations of sodium, silica, sulfate, and chloride. As in the cases of wells 103, 104, 105, 106, and 107 analyses, this ground-water chemical characterization is similar to that normally found in the Snake River Plain aquifer not affected by aqueous waste disposal (Olmsted, 1962).

WELL 109

The drilling of well 109 began on September 13 and was completed on September 26, 1980. The total depth of the well is 800 feet below land surface with an 8-inch casing extending to a depth of 180 feet and a 6-inch casing extending from a depth of about 180 to 345 feet (fig. 13). The remainder of the well is a 6-inch open hole from a depth of 345 feet to the total depth of 800 feet. The measured water level in the well is at a depth of about 620 feet.

The geophysical logs shown in figure 13 indicate that various basalt flows dominate the subsurface geology. Several thin sedimentary layers and zones of fractured basalt are located throughout the sequence of rock units penetrated by the well. The upper surface of an 80-foot thick silicic rock zone, probably rhyolite, is located about 230 feet below land surface. Immediately overlying this silicic rock unit is a sedimentary deposit of clayey silt approximately 20-feet thick. The caliper log (fig. 13) depicts many zones of fractured basalt with crevices occurring in the borehole below the well's water level.

Following well completion, an obstruction existed in the well at about 635 feet below land surface. To correct this problem the well was cleaned, the obstruction removed, and a 4-inch casing set in the borehole. The 4-inch casing was set from the land surface to the well's total depth of 800 feet (fig. 13). The lower 200 feet of the casing was perforated for well development and pumping purposes. This cleaning and additional casing process began on May 12 and was completed on May 20, 1981.

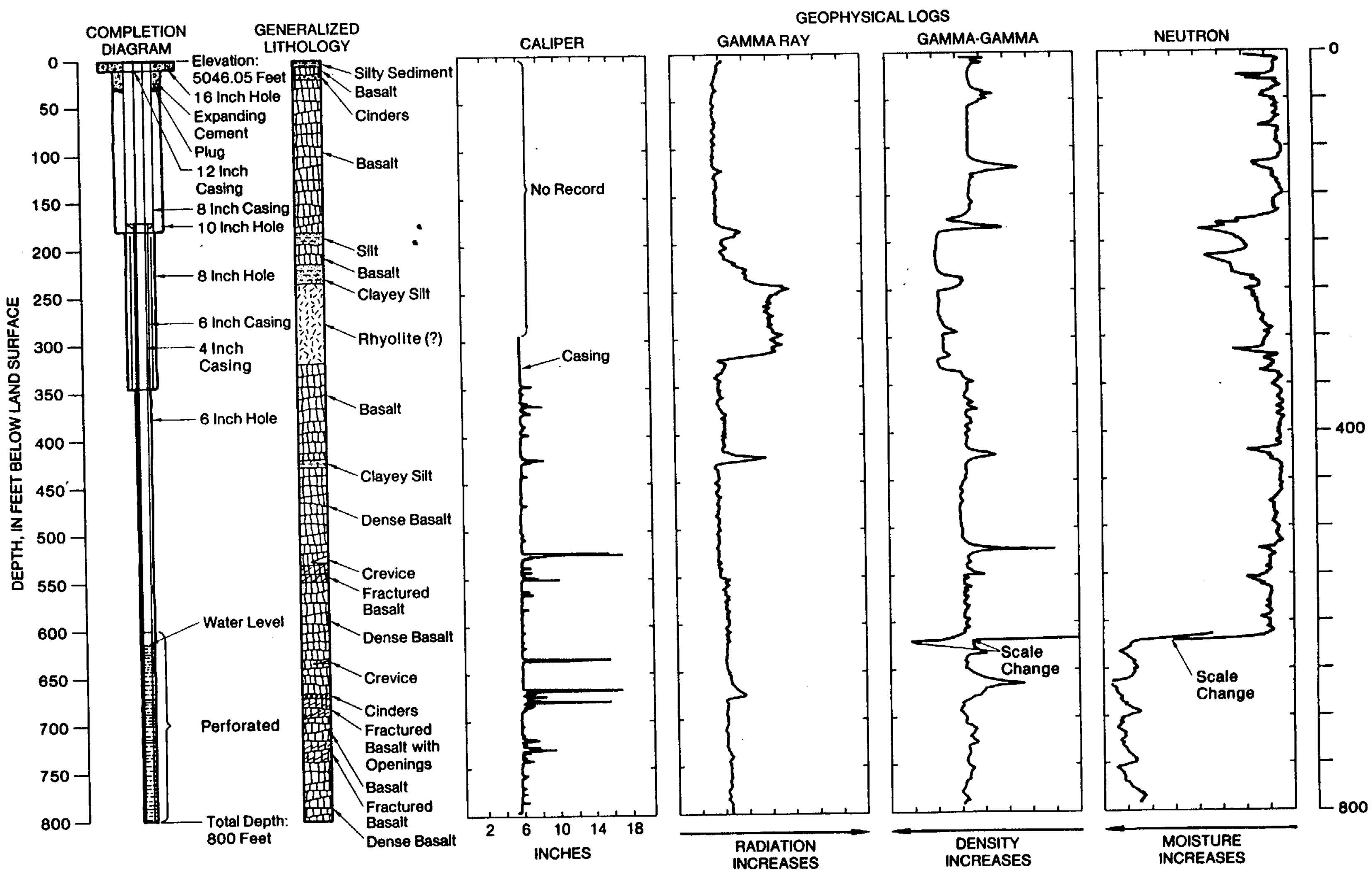


Figure 13.--Diagrams showing well completion, geology, and geophysical logs for well 109.

An aquifer test has not been made with the well because of the non-availability of a small-diameter submersible pump. Therefore, an analysis of pumped well-water is not possible, to date. A bailing method was used to collect two samples of well water directly above the obstruction, prior to well recompletion, and analyses were made for tritium and waste chloride, and the specific conductance was measured (table 1). No tritium was detected in the samples but the chloride concentrations were higher than background levels. These concentrations are similar to those in nearby well 105. The relatively high chloride concentrations may represent a natural anomalous occurrence as speculated for well 105.

WELL 110

The drilling of well 110 started on September 20 and was completed on September 27, 1980. The total depth of the well is 780 feet with an 8-inch casing set from land surface to a depth of 350 feet (fig. 14). The remainder of the well is completed as an 8-inch open hole from the bottom of the casing to its total depth of 780 feet. The measured water level in the well is at a depth of about 570 feet.

The geophysical logs depicted in figure 14 indicate that the subsurface geology is dominated by basalt. Two rather thin sedimentary layers occur at depths of approximately 460 and 580 feet. Much of the basalt, however, is fractured with several significant openings both above and below water level. Two cinder zones were also encountered in the borehole (fig. 14); one of particular importance is in the uncased part of the well below water level. Caving in this lower cinder zone and detritus from the uphole layers of sediment and fractured basalt, filled the well with material to a level about 620 feet below land surface. From April 28 to May 7, 1981, the well was cleaned and the detrital material removed; a 6-inch casing was set from the land surface to a depth of 780 feet to preclude caving material from entering the borehole. The lower 200 feet of this 6-inch casing was perforated prior to installation to facilitate well development and pumping.

A test was made on well 110 from June 16 to June 17, 1981, and lasted for about 24 hours. The pump was set at a depth of about 620 feet and pumped at a rate of 92 gpm. No measurable decline occurred in the well's water level during the test. Three water samples were taken at various times during the test for selected radiochemical analyses. No tritium was detected in the samples but the chloride concentrations were higher than background levels (table 1). As in the cases of wells 105 and 109, the high chloride concentrations may be due to a natural anomalous occurrence. Due to generator problems, the test was terminated prematurely and a sample for a standard analysis was not collected. However, on June 25, 1981 the well was again pumped for a few hours and samples were taken for selected radiochemical and standard chemical analyses. The results of the previous radiochemical analyses were verified (table 1) and the standard chemical analysis (table 2) indicates the ground water is dominated by calcium, magnesium, sodium, and bicarbonate with minor concentrations of silica, sulfate, and chloride.

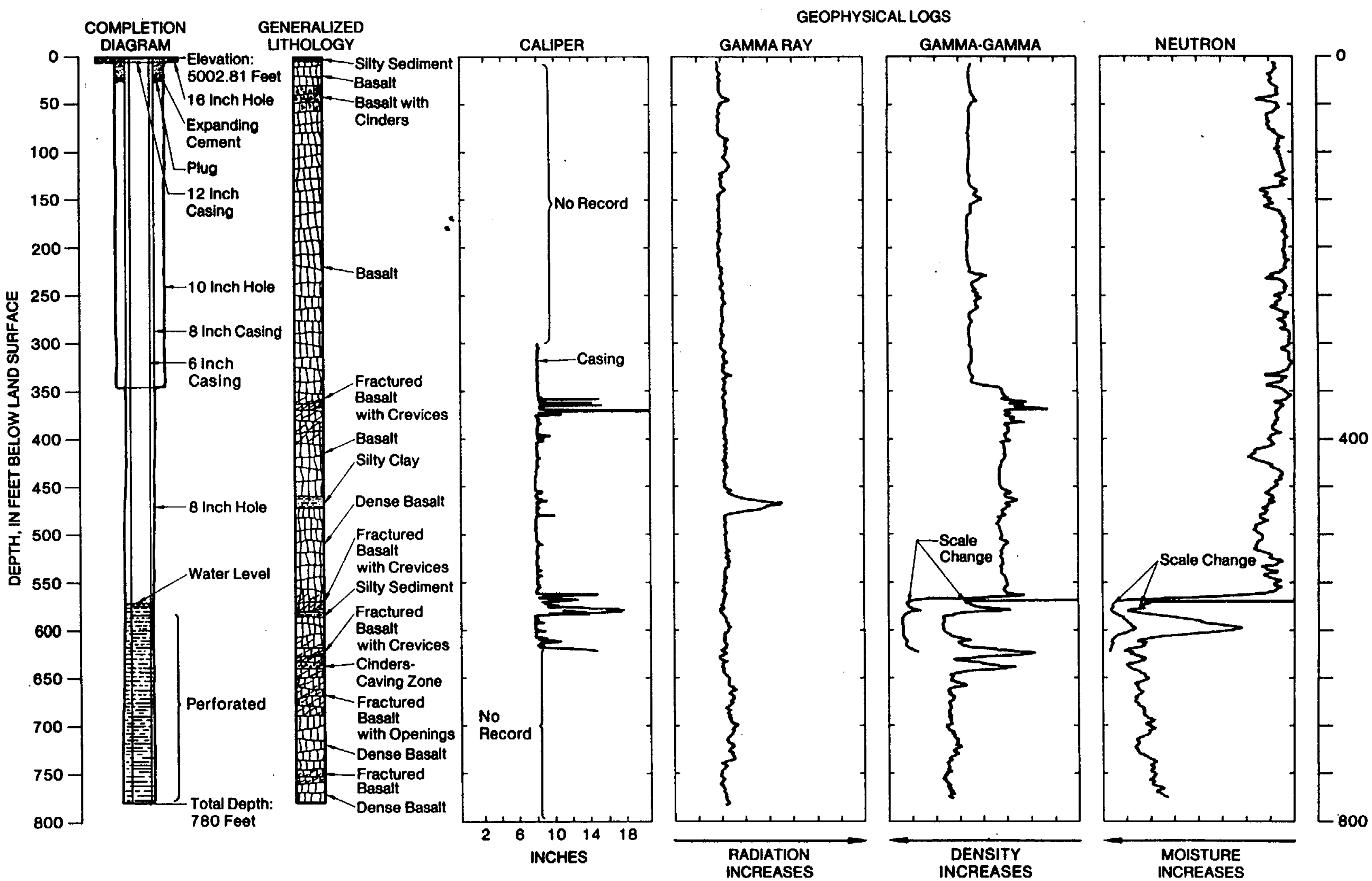


Figure 14.--Diagrams showing well completion, geology, and geophysical logs for well 110.

HYDROGEOLOGIC INTERPRETATION OF DATA

SUBSURFACE GEOLOGY

Basaltic lava flows interbedded with silty to sandy alluvial and lacustrine sediments, rhyolitic air-fall ash deposits, and ash-flow tuffs, constitute the upper 3,000 feet of the eastern Snake River Plain in the vicinity of the INEL (Walker, 1964; Zohdy and Stanley, 1973; Nace and others, 1975; Kuntz and others, 1979; Kuntz and Dalrymple, 1979; and Doherty, McBroome, and Kuntz, 1979). The lithology near the center of the INEL was quantified by the drilling of a deep well, the 10,365-foot-deep INEL-1 well (see fig. 6), in the southern part of the site during the spring of 1979. The upper 2,445 feet of the rocks penetrated by this well consist of basaltic lava flows interbedded with cinders, silt, sand, and tuffaceous silt (Doherty, McBroome, and Kuntz, 1979). Similar rock units were expected to be penetrated by drilling the eight shallow wells near the INEL's southern boundary. The proximity of rhyolitic rocks at the Big Southern Butte to the well sites indicated that rhyolitic rocks may also be encountered at shallow depths. Silicic rocks were found in the subsurface in wells 103, 105, 108, and 109 (see figs. 7, 9, 12, and 13). Silicic rocks were previously found in several other observation wells near the INEL's southern boundary; namely, the Cerro Grande, Leo Rogers, Core Hole 1, number 1 and number 14 labeled wells on figure 6. No silicic rocks were found in the other wells.

Figure 15 shows the traces of three hydrogeologic sections that consist of selected existing observation wells plus those drilled during the 1980 drilling program. Hydrogeologic section A-A′ (fig. 16) depicts the subsurface geology from the north, in the vicinity of the south-central part of the INEL, to several miles south of the southern boundary of the INEL. This section also shows that the regional water-table gradient is to the south at about 4 feet per mile. Two east-west hydrogeologic sections, B-B′ (fig. 17) and C-C′ (fig. 18), show the subsurface geology near the southern boundary of the INEL. These latter two sections also show a minor component of the regional water table gradient from the east to west of about 2 feet per mile.

Hydrogeologic section A-A′ (fig. 16) delineates the shallow subsurface geology as several basalt flows interbedded with several sedimentary deposits in its northern part. To the south the section grades into a sequence of interbedded basalt flows with fewer sedimentary deposits. Beginning with well 103, a moderately thick silicic rock unit thickens to the south toward well 14. The thicker silicic rock units are near Cedar Butte. The vertical position of the silicic layer in the geologic sequence does not give an indication of its origin. Coring of the silicic unit for comprehensive petrofabric, mineralogic, and/or age dating analyses would be the only means of determining its emplacement mechanism.

Hydrogeologic sections B-B′ and C-C′ (figs. 17 and 18) also show increasing amounts of silicic rocks in the subsurface from the north to the south near the vicinity of the INEL's southern boundary. Section

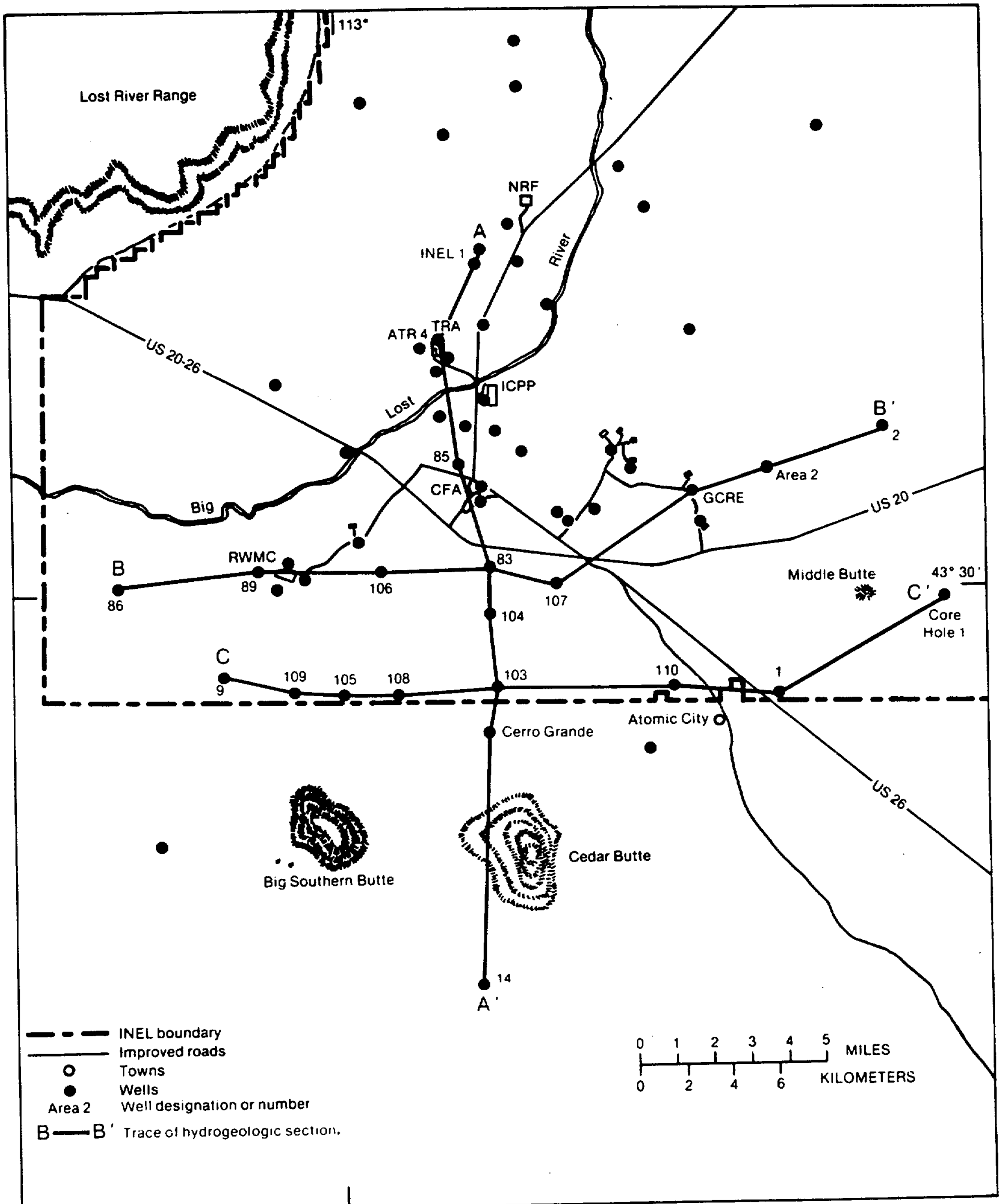


Figure 15.--Location of hydrogeologic sections in the southwestern INEL and vicinity.

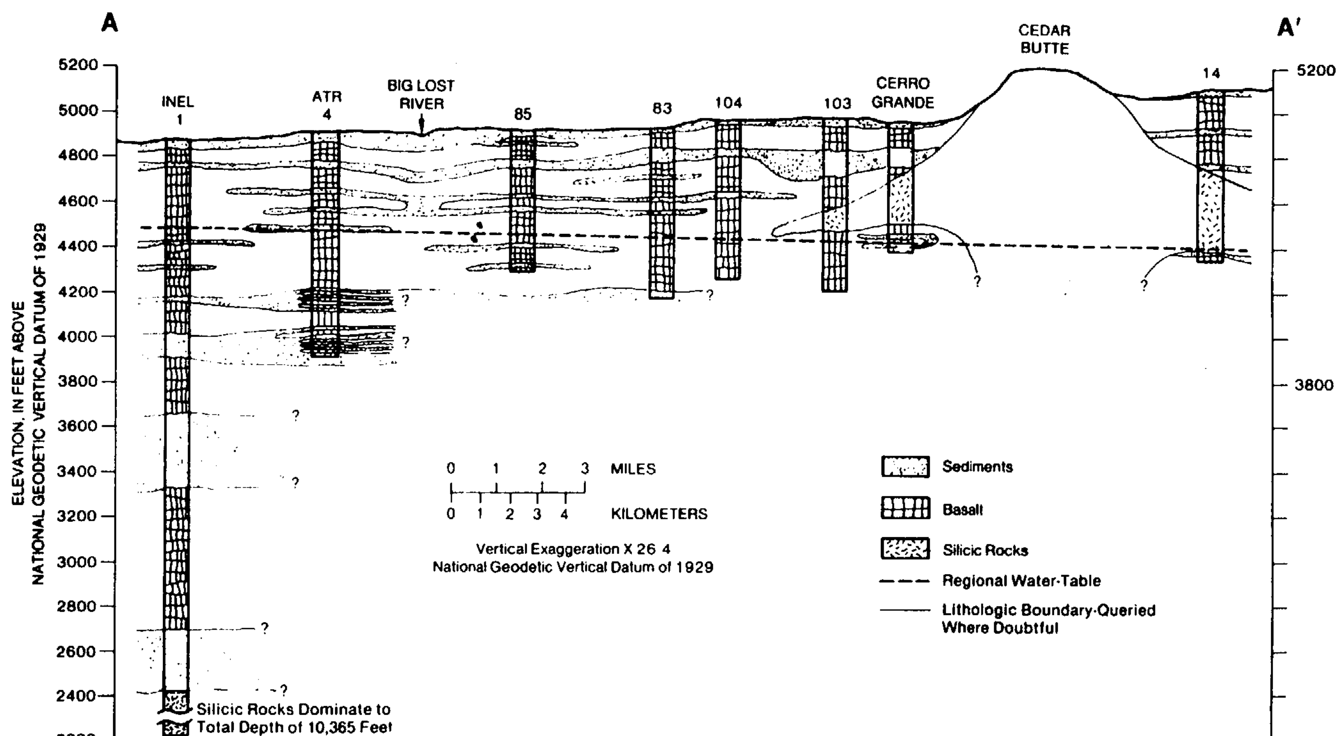


Figure 16.--Hydrogeologic section of A-A' in figure 15.

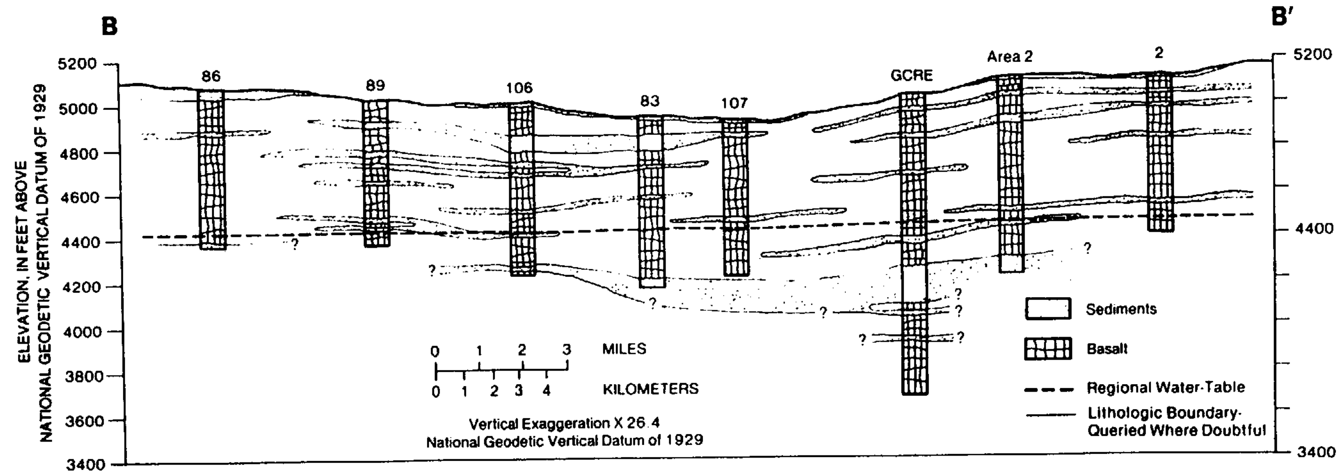


Figure 17.--Hydrogeologic section of B-B' in figure 15.

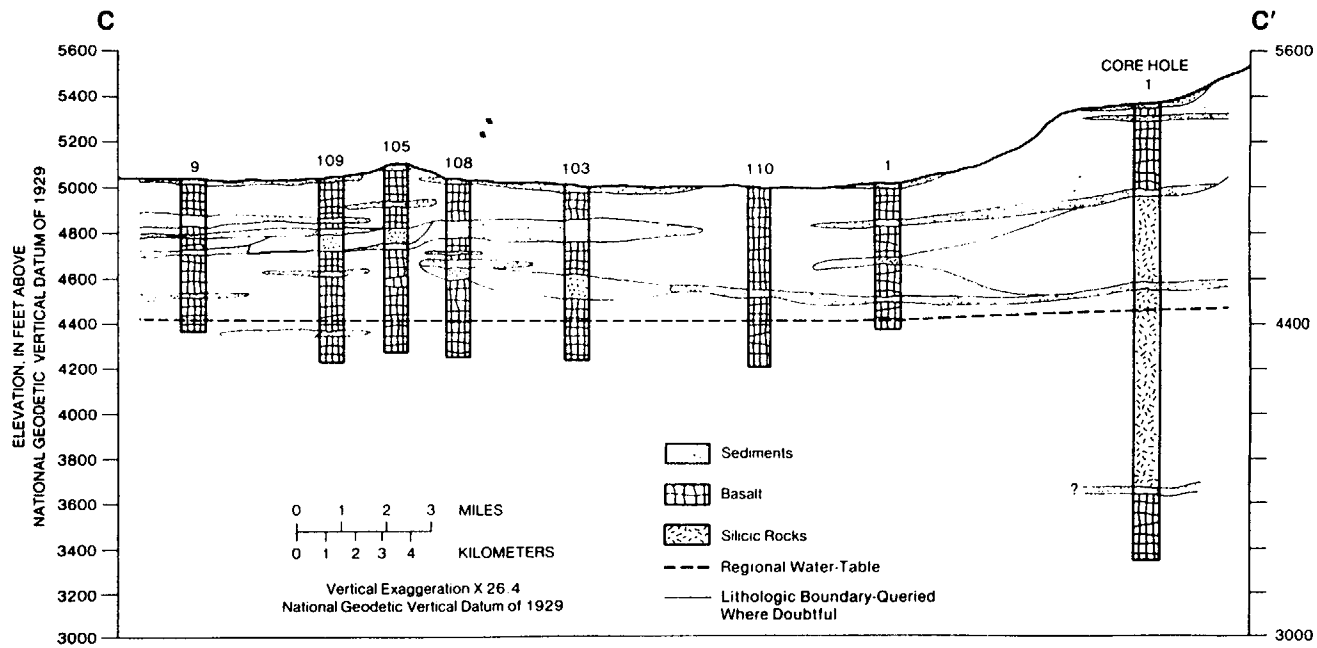


Figure 18.--Hydrogeologic section of C-C' in figure 15.

B-B′, located a few miles north of the boundary (see fig. 15), shows that the subsurface is dominated by several basalt flows interbedded with varying thicknesses of sedimentary deposits. Section C-C′, nearly parallel to the INEL's southern boundary (see fig. 15), shows subsurface silicic rock units in the vicinity of and immediately north of the Big Southern Butte. The numbers and thicknesses of sedimentary layers in both of these sections generally decrease from west to east and indicate that lacustrine and fluvial deposition, from streams exiting the mountains and valleys northwest of the INEL, has been an ongoing process through recent geologic time. Silicic rocks in section C-C′ located in the eastern part of the trace, namely Corehole 1, are part of a rhyolitic dome that is between the Middle (fig. 15) and East Butte-located about three miles east of the Middle Butte (Kuntz and Dalrymple, 1979). Silicic units that may be associated with the Big Southern Butte are present at different vertical positions; wells 105 and 109 represent one unit and wells 103 and 108 represent the other (fig. 18). Wells 105 and 109 contain a silicic unit that correlates with a layer of sediment in nearby wells. Wells 103 and 108 contain a silicic unit lying at a stratigraphically lower level than the one in wells 105 and 109, but it also appears to correlate with a fine-grained sediment layer in adjoining wells of the section. Well 108 contains a sedimentary layer directly overlying the silicic unit that may represent a part of the sedimentary deposit not altered during the intrusion of silicic rocks. Intensive studies of cored samples taken from boreholes drilled near these locations may verify or change these observations.

The source areas of both basalt flows and rhyolite units in this and other parts of the eastern Snake River Plain have been a subject of discussion in many recent publications (for example see Kuntz, 1978; Doherty, 1979; Doherty, McBroome, and Kuntz, 1979; Kuntz and others, 1980). Basalt flows in the southwestern part of the INEL erupted from fissure vents in rift zones (fig. 19) that traverse the Snake River Plain from the northwest to the southeast (Kuntz, 1978). One, the Arco volcanic rift zone, traverses the southwestern corner of the INEL (Kuntz and others, 1980) and was a locus for basaltic eruptions. Silicic rocks in the subsurface in the same general area are associated with rhyolite domes (for example the Big Southern Butte) that are also within the Arco rift zone (Kuntz, 1978). The geologic information gained from the summer 1980 drilling program neither supports nor refutes the existence of the rift zone in the subsurface. Hydrogeologic sections A-A′ (fig. 16) and C-C′ (fig. 18) show that silicic rocks are interbedded with subsurface basalt flows and sedimentary layers, but their exact mode of emplacement and origin cannot be determined precisely from the well data.

SNAKE RIVER PLAIN AQUIFER

Hydrology

The information gained about the Snake River Plain aquifer during the 1980 drilling program has not suggested major revisions in hydrogeologic concepts but has refined and quantified these concepts. For

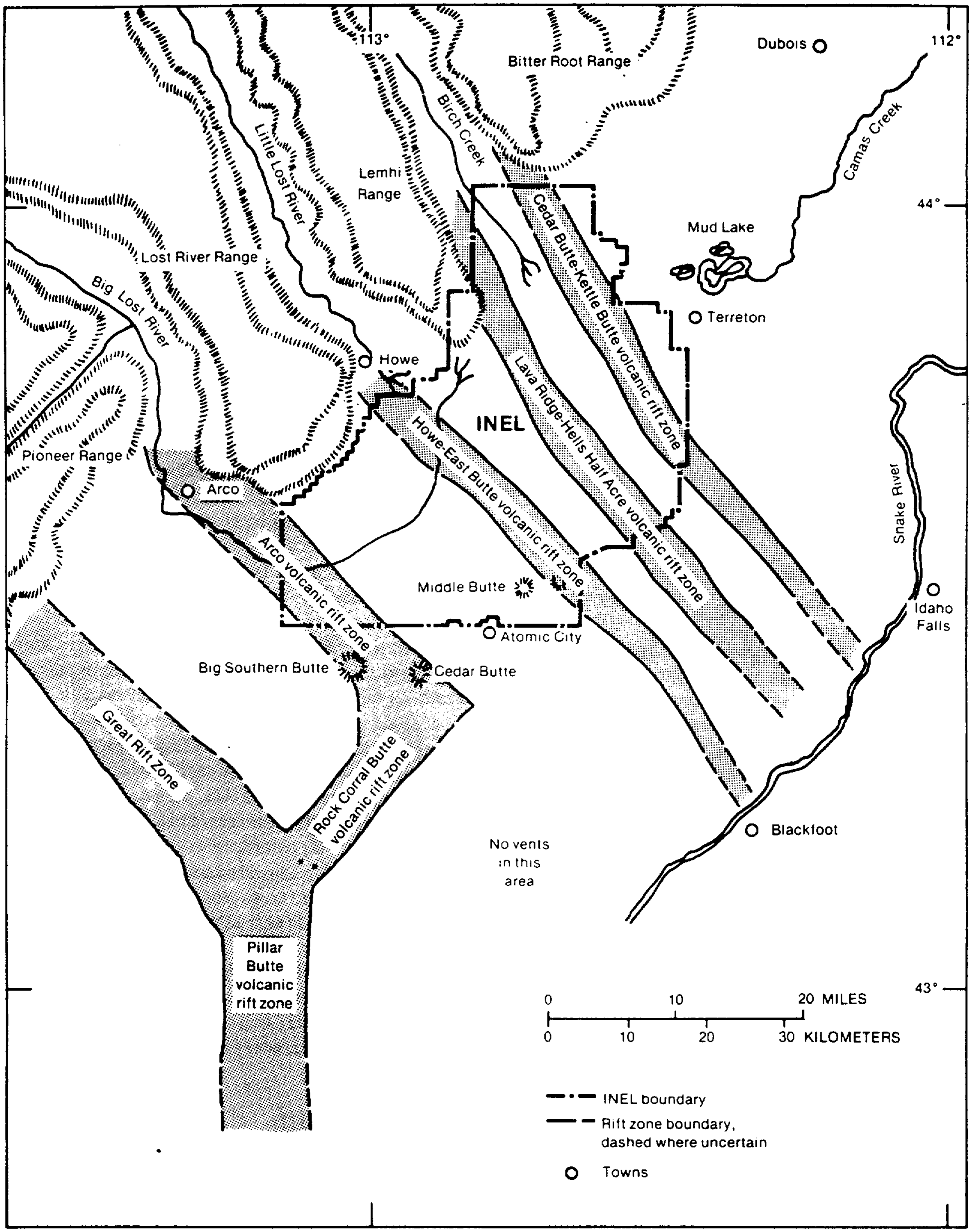


Figure 19.--Volcanic rift zones of the northcentral part of the eastern Snake River Plain (from Kuntz, 1978).

example, the water-table configuration shown in figure 3 would not be altered drastically if each of the water-level measurements for the newly drilled wells were omitted. The measurements have, however, allowed for a more precise delineation of the water-table altitude and configuration near the southern boundary of the INEL and have added to the baseline data for the INEL site.

The measurements of the ground-water altitude in each of the newly drilled wells have also emphasized that a change in the gradient of the water table occurs near the southern boundary of the INEL (fig. 3). The gradient near and directly south of the Central Facilities Area (CFA) is about 7.5 feet per mile, but changes abruptly to about 2 feet per mile near the boundary. This change to a lesser gradient was also noted by Barraclough, Lewis, and Jensen (1981) on a similar water-table depiction made for July 1978 and by Barraclough and Jensen (1976) for a July 1972 water-table configuration. A minor difference between the later and earlier depictions is that the area of lesser gradient is a few miles upgradient. This change of position may coincide with the net decline of the surface of the water table during the past few years.

The lesser-gradient zone indicates the probable occurrence of a highly transmissive zone in the immediate area and a zone of lower transmissivity upgradient. Kuntz (fig. 3, 1978) showed the geographical relationships of the Great Rift Zone, of which the Craters of the Moon National Monument is a part; the Rock Corral Butte volcanic rift zone; the Arco volcanic rift zone; and selected facilities contained within the INEL site. The Great Rift Zone, approximately 20 miles hydrologically downgradient from the southern boundary of the INEL (see fig. 19), has been depicted as a zone of low permeability by previous investigators (Mundorff, Crosthwaite, and Kilburn, 1964; Norvitch, Thomas, and Madison, 1969; and Crosthwaite, 1973). Two of these studies generalized in their treatment of the transmissive properties of the regional aquifer in the volcanic rift zone area; but Crosthwaite (1973) made a more detailed study of the water-table configuration in the vicinity of this prominent volcanic rift zone. Figure 3 from Crosthwaite (1973) shows that the water-table gradient increases dramatically as the Great Rift Zone is approached from the northeast. This change in gradient is interpreted to indicate that the rocks in the Great Rift Zone, or in a subsurface northeastern extension thereof, are less transmissive or have lower hydraulic conductivities than rock units hydrologically upgradient or downgradient. The Great Rift Zone, therefore, forms a barrier to regional ground-water movement because it is oriented transverse to the direction of flow, as is the Arco volcanic rift zone. Therefore, it appears that a northeastward subsurface extension of the Arco volcanic rift zone may be correlated with a zone of less transmissive rock units, and is responsible for the steep water-table gradient in the southwestern part of the INEL (fig. 3).

The ground-water-transporting properties of the Snake River Plain aquifer underlying the INEL and vicinity have been estimated by areal techniques rather than definitively characterized by quantitative methods such as aquifer tests. The lateral immensity of the aquifer and its heterogeneous nature, its total water volume, the lack of hydrological data in certain areas, and the improbability of drilling a well that fully penetrates the aquifer; have all added to the difficulty of quantifying the aquifer's hydrologic properties. One such diagnostic property of the aquifer is its transmissivity (T), the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient (Lohman, 1972, p. 6). The transmissivity may be defined as:

$$T = Kb \quad [L^2\ T^{-1}], \qquad (1)$$

where b is the aquifer thickness and K is the hydraulic conductivity of the aquifer. Lohman (1972) defined K as follows: A medium has a hydraulic conductivity of unit length per unit time if it will transmit in unit time a unit volume of ground water at the prevailing viscosity through a cross section of unit area, measured at right angles to the flow direction, under a hydraulic gradient of unit change in head through unit length of flow. Previous workers (such as Norvitch, Thomas, and Madison, 1969; and Robertson, 1974) have utilized flow net analyses, an areal method described by Bennett (1962), to estimate T values for the aquifer.

The flow net analysis technique used for estimating T utilizes a finite-difference approximation of the basic ground-water flow principle, Darcy's Law. A simple statement of Darcy's Law is that the rate of laminar flow of water through a sand aquifer is proportional to the hydraulic gradient. A generalized formulation of Darcy's Law follows (after Lohman, 1972, p. 10):

$$Q = -K\ dh/dl\ A \quad [L^3\ T^{-1}], \qquad (2)$$

where

K = hydraulic conductivity, previously defined for equation 1, $[LT^{-1}]$,

dh/dl = hydraulic gradient, unit change in head with unit length, parallel to flow direction, $[L^1\ L^{-1}]$ or dimensionless, and

A = Cross sectional area, transverse to flow direction, through which the rate (volume) of flow (Q) is measured, $[L^2]$.

However,

A = bw

where b = aquifer thickness, [L], and

w = aquifer width, [L],

therefore, by direct substitution into equation 2

$$Q = -Kb\ dh/dl\ w,$$

and, from equation 1, T = Kb, hence

$$Q = -T\ dh/dl\ w. \qquad (3)$$

This form of Darcy's Law gives the volumetric rate of ground-water flow in terms of the hydraulic gradient and two aquifer properties, transmissivity and width. Thus, by constructing a flow net so that flow lines intersect orthogonally with equipotential lines in a mesh-like array of squares, where a segment of the aquifer width (Δw) will be approximately equal to the distance between equipotential lines (Δl-for instance, the distance between altitude contours of the water-table configuration shown in figure 3), equation 3 may be rewritten as a finite-difference equation for the flow, ΔQ, through an elemental square of thickness, b, in the following manner:

$$\Delta Q = -T\ \Delta w\ \Delta h/\Delta l \quad [L^3\ T^{-1}]. \qquad (4)$$

But by construction $\Delta w = \Delta l$, and equation 4 may be rewritten as:

$$\Delta Q = -T\ \Delta h \quad [L^3\ T^{-1}]. \qquad (5)$$

However, Norvitch, Thomas, and Madison (1969) and Robertson (1974) assumed the aquifer thickness, b, was constant so that the changes in T values reflect only changes in hydraulic conductivity and, hence, permeability. Therefore, the T maps published in the aforementioned reports depict zones of high permeability for areas assigned high T values and conversely, low permeability for those areas with lower T values. Also, it is apparent from equation 5, to maintain a constant flow (ΔQ) through each element in question, the change in hydraulic head (Δh) must vary inversely to T when differing zones of transmissivity are encountered in the aquifer flow system. Thus, the poorly permeable Great Rift Zone is depicted as an area of low T values (Mundorff, Crosthwaite, and Kilburn, 1964; and Norvitch, Thomas, and Madison, 1969), and also as an associated area of steep hydraulic gradient as pointed out by Crosthwaite (1973). It should be noted that flow-net analyses are valid only for systems that are in steady-state conditions, which may present problems in the Snake River Plain aquifer.

Figure 20 is a projection of part of Robertson's (1974) T map for the southwestern INEL and vicinity. The Arco volcanic rift zone is correlatable with the zone of low T values in the southwest corner of the INEL, indicating that it too may be a zone of low permeability as is the Great Rift Zone to the southwest. This conclusion is supported in general by the T values depicted in the same area by Mundorff, Crosthwaite, and Kilburn (1964). However, these observations are not supported by Norvitch, Thomas, and Madison's (1969) T values for the southwestern INEL, which show a zone of high T's in the same general area. The tests

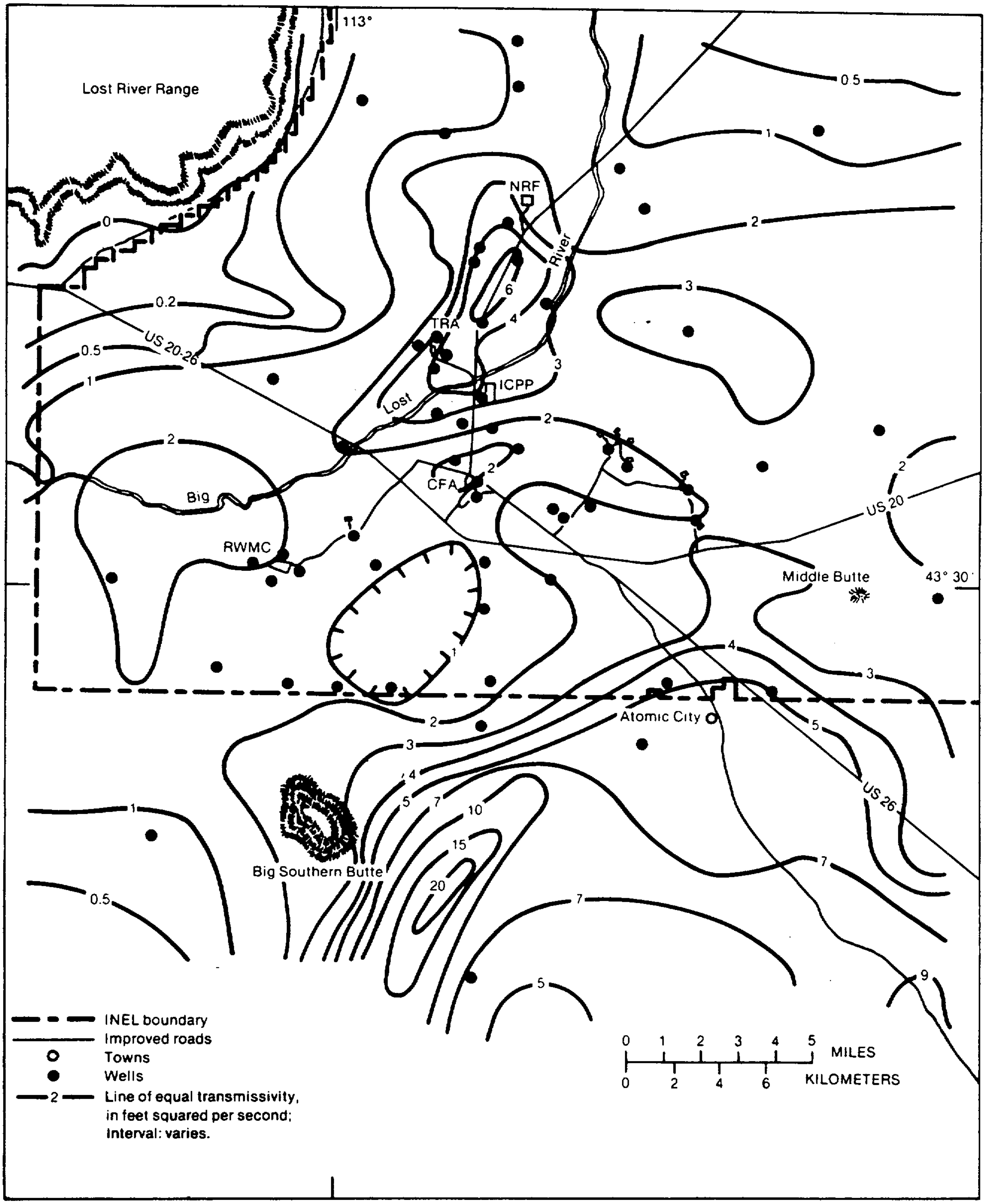


Figure 20.--Generalized transmissivity contours for the Snake River Plain aquifer, southwestern INEL and vicinity (from Robertson, 1974).

made on wells 103, 105, 106, and 108, which are located in the low T zone of figure 20, resulted in no measurable water-level declines; the water-table gradient is nearly flat in the same area; and Robertson's (1974) T map was based on a water-table map affected by local recharge and thus a transient steep gradient. Therefore, it appears that T values are high near the southwest corner of the INEL.

The basic data used by Norvitch, Thomas, and Madison (1969) were collected during several years of unusually high flow measured in the Big Lost River at the INEL diversion dam (Robertson, Schoen, and Barraclough, 1974), and large quantities of this flow were spread over the diversion areas (see fig. 2) to prevent downstream flooding of the INEL facilities. This flow diversion undoubtedly added a large amount of recharge to the aquifer in the immediate area. The anomalously high ground-water levels could have produced a flow net unrepresentative of normal flow conditions; and the recharge mound would have created a steep water-table gradient in the immediate area. T values estimated under these conditions would have been estimated to be lower than normal.

The tests on wells 103, 105, 106, and 108 were made at pumping rates of less than 100 gpm. No measurable water-level declines occurred during the tests at these pumping rates. Perhaps with increased pumping rates, significant drawdowns could be measured and the aquifer's water-bearing properties could be analyzed. The test on well 104 did yield some measurable results that were listed in a previous section of this report. Tests on well 83, located about two miles north of well 104 (see fig. 6), indicate T values similar to that of the 50 feet squared per day determined for well 104 (J. T. Barraclough, oral commun., 1981). This T value is much lower than the T contour line nearest the well (fig. 20). This indicates that an area of low permeability may exist in the immediate vicinity of wells 83 and 104; but it may also suggest that these wells were completed, by chance, near the mid part (vertically) of a laterally small basalt flow, where the most dense and least permeable basalt is found.

The steep water-table gradient shown in figure 3 may be correlated with the low transmissivity zone in figure 20; they both coincide with the Arco volcanic rift zone as delineated by Kuntz and others (1980). Earlier it was noted that the hydraulic gradient associated with the Great Rift Zone was much steeper than that either upgradient or downgradient (Crosthwaite, 1973). This also appears to be the case for the Arco volcanic rift zone. These rocks of low permeability may be associated with the rift where magmatic rocks were solidified as dikes in the vents or fissures. The dikes may tend to "heal" the volcanic rift zone by sealing many subsurface openings. This phenomenon is noticeable in many Hawaiian volcanic rift zones (M. A. Kuntz, oral commun., 1981). The dike forms a vertical "curtain" of dense rocks that tend to impede the horizontal flow of ground water because the volcanic rift zone is oriented transversely to the regional ground-water flow direction.

Figure 20 shows that the zone of very high T values located southeast of the Big Southern Butte coincides with the junction of the Arco volcanic rift zone, and the southwest-northeast trending Rock Corral

Butte volcanic rift zone (fig. 19). The contours are elongated in the same direction as the trend of the Rock Corral Butte volcanic rift zone, which is parallel to the direction of ground-water flow. These relationships indicate that where a volcanic rift zone in the Snake River Plain aquifer is oriented parallel to the flow direction, the fissures, vents, fractures, faults, and other openings connected with the rift zone may provide a conduit for ground-water flow. The Rock Corral Butte volcanic rift zone appears to be an area of high anisotropic permeability; and with additional field data, the comparable area on figure 3 could exhibit an even lesser water-table gradient than that depicted.

Water Quality

The ground water in the Snake River Plain aquifer has been classified as of the calcium-magnesium bicarbonate type with moderate concentrations of sodium, silica, sulfate, and chloride (Olmsted, 1962; Mundorff, Crosthwaite, and Kilburn, 1964; and Robertson, Schoen, and Barraclough, 1974). The results of the standard analyses listed in table 2 tend to support this concept; and as noted by Robertson, Schoen, and Barraclough (1974), suggest that the water chemistry reflects little influence of the basalts in the aquifer matrix; but rather is controlled by reactions with minerals in the rocks of the surrounding mountains and alluvial valleys, where the ground water must have had longer residency time in rocks in the saturated zone that are more soluble, and by reactions with minerals in the sedimentary deposits present in the aquifer matrix.

The information obtained from the wells drilled in the summer 1980 did not alter the concepts regarding the rock-type makeup of the aquifer except that silicic rocks were penetrated in several boreholes. In each case these silicic rocks were present in the subsurface above the regional water table (figs. 16 and 18) and probably have had no influence on the chemical composition of ground water in the immediate area. Silicic rocks may be present in the deeper parts of the aquifer not penetrated by these few wells. If the ground water from the deeper part of the aquifer contained more sodium, silica, and fluoride than that of the shallower part, especially when not accompanied by abundant chloride, the breakdown of silicic rock might be indicated as the source of the specific ions (Robertson, Schoen, and Barraclough, 1974). Regardless of the hydrogeologic interpretation, it appears that large variations in the chemical composition of ground water in the Snake River Plain aquifer are results of many influences such as numerous and thick sedimentary deposits being present in the aquifer matrix, varieties of recharge sources and, to a lesser extent, aqueous waste disposal.

DISTRIBUTION OF WASTE PRODUCTS

The distribution of a nonradioactive waste product, chloride; specific conductance values; and the radioactive waste product, tritium; all ground-water-quality parameters that are influenced by waste disposal, are discussed and illustrated in this section.

The waste plumes exhibit similar configurations and show correspondingly decreasing concentrations downgradient from the ICPP discharge well and to the south of the ICPP. The waste plumes are not as well defined south of the TRA because of gaps in the observation well data base and because of possible dilution by recharge from surface-water flow in the nearby Big Lost River. Analyses of the water samples collected from the eight newly drilled wells have aided in the depiction of the southern extent of the waste plumes and the concentrations of waste products. The water samples collected from well 109 were bailer samples and may not be representative of the ground water in this part of the aquifer. The results of the chemical analyses of samples that were collected by the thief sampler, bailer, and by pumping (table 1) indicate that the constituents in the pumped samples differ in concentration from those in samples taken by other collection methods.

Chloride

The average concentration of waste chloride disposed of through the ICPP well during 1979 and 1980 was 206 mg/L (Batchelder, 1980b and 1981b). This is an increase over the average discharge concentration of 179 mg/L for 1974 through 1978 as reported by Barraclough, Lewis, and Jensen (1981). The background or normal concentration of chloride in the Snake River Plain aquifer in the TRA-ICPP vicinity is generally between 8 and 15 mg/L. The disposal of waste chloride through the ICPP disposal well, plus a very small contribution from the percolation of waste water from the overlying chemical-waste disposal pond at the TRA, has created a large and laterally dispersed waste plume in the Snake River Plain aquifer (fig. 21). The waste chloride covers about 25 mi^2 of the regional aquifer.

Figure 21 shows the distribution of waste chloride in the aquifer in October 1980, which is similar in configuration to the distribution determined for September 1977 by Barraclough, Lewis, and Jensen (1981). However, the concentrations within the plume have increased and the concentration contours have been extended in a southerly direction, downgradient 2 to 3 miles, with the inclusion of the waste chloride found in well 106 (table 1) into the data base. The new position of the leading edge of the plume is due primarily to the inclusion of this new information from areas previously not covered by observation wells.

Specific Conductance

The disposal of dissolved ionic constituents increases the ionic strength of water and its specific conductance, which is a measure of it's ability to conduct an electric current. The specific conductance of ground water in the Snake River Plain aquifer containing no waste water normally ranges from 300 to 325 mhos/cm in the ICPP-TRA area (Robertson, Schoen, and Barraclough, 1974). Waste water disposed through the ICPP disposal well and leakage from the TRA chemical-waste disposal ponds have increased the specific conductance of the regional ground water significantly (fig. 22), and have created a detectable area of higher-than-

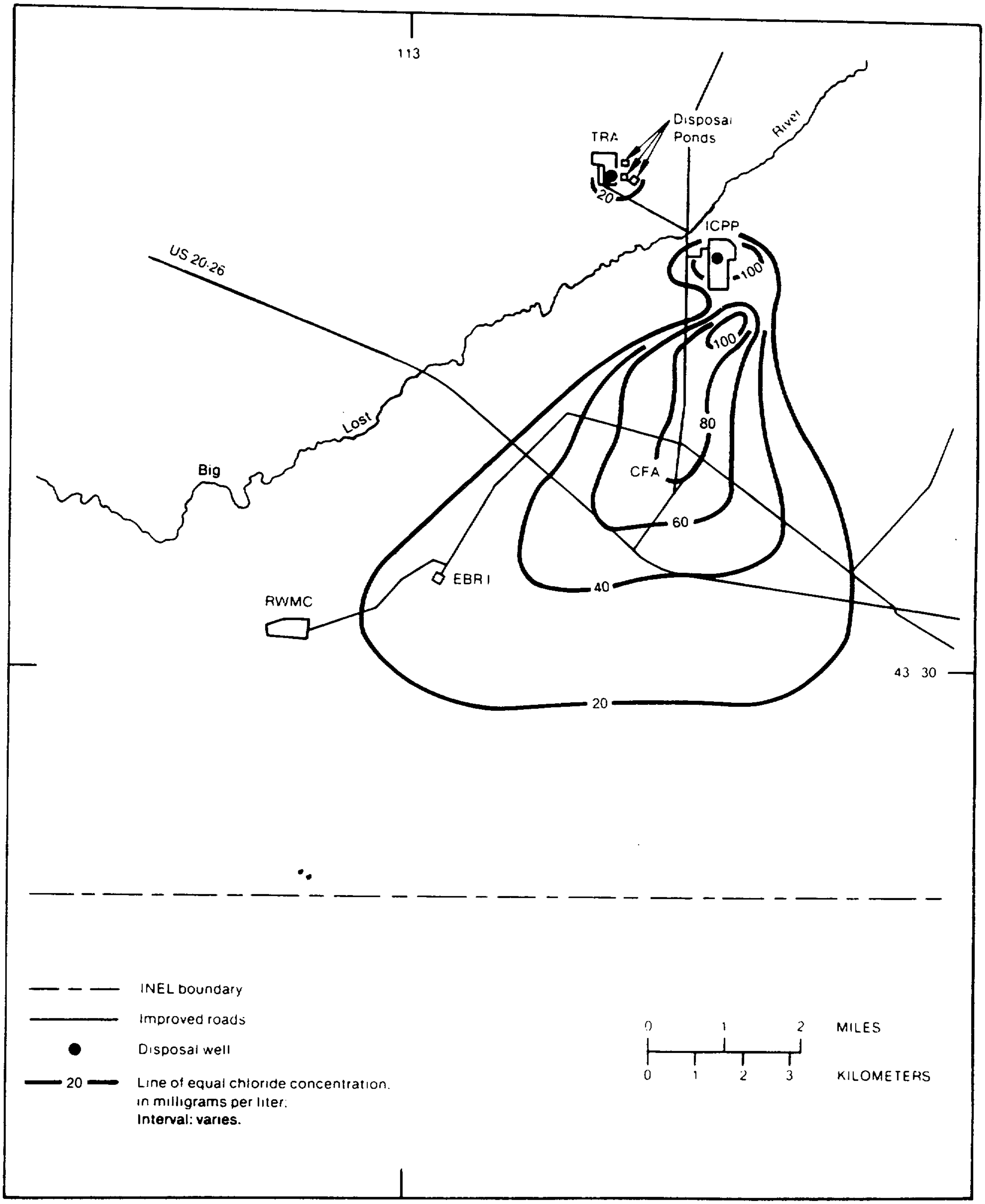


Figure 21.--Distribution of waste chloride in the Snake River Plain aquifer, ICPP-TRA vicinity, October 1980.

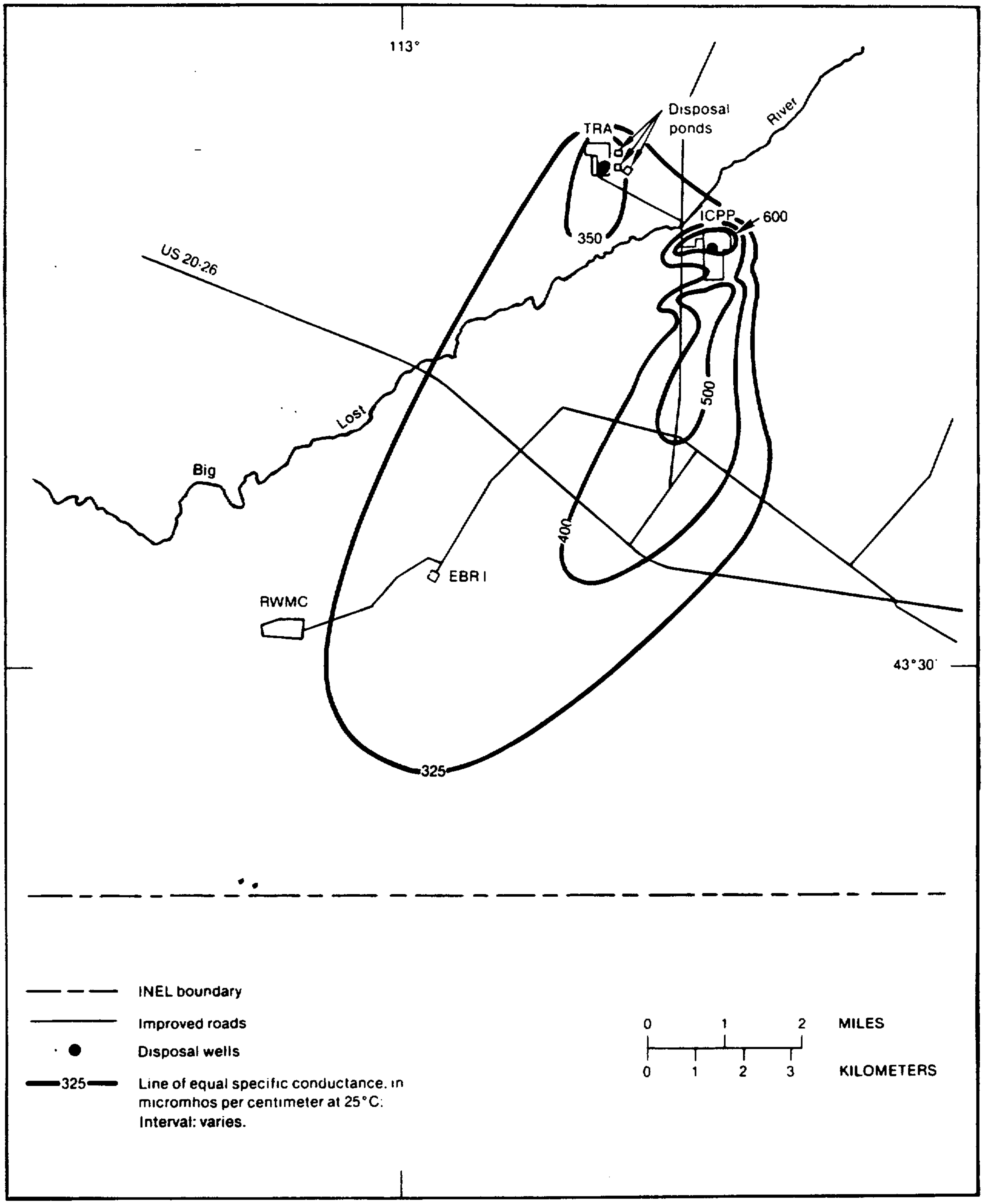


Figure 22.--Specific conductance of ground water in the Snake River Plain aquifer, ICPP-TRA vicinity, October 1980.

normal values approximately 20 mi^2 in size. The specific conductance values of the sampled water from the eight new wells created only a slight modification to the shape of the effected aquifer area as depicted by Barraclough, Lewis, and Jensen (1981) for October 1978. Wells 105 and 106 were the only new wells that indicated a significantly higher-than-natural specific conductance in the aquifer. However, as previously mentioned, the anomalous chemistry of well 105 water probably reflects natural influences rather than waste disposal effects. Natural high and low anomalies in the specific conductance or total dissolved solids content of ground water have also been observed in other areas of the regional aquifer in the INEL vicinity (Robertson, Schoen, and Barraclough, 1974).

Tritium

The injection of tritium through the ICPP disposal well into the Snake River Plain aquifer, plus the simultaneous percolation of tritium contaminated waste water from a perched ground-water zone that underlies the radioactive and chemical-waste ponds at the TRA, has resulted in a large, dispersed plume of tritium in the regional ground-water system (fig. 23). The October 1980 plume illustrated by figure 23 is closely similar to a plume depicted by Barraclough, Lewis, and Jensen (1981) for October 1978. The results of the analyses of the ground water from the newly drilled wells have, however, allowed for a better delineation of the southward leading edge of the plume. The analyses have, in fact, shown a greater degree of lateral dispersion of the plume than determined previously. The waste plume covers about 30 mi^2, and tritium has migrated about 7.6 miles downgradient from the ICPP disposal well and the TRA disposal ponds since disposal began in 1952 and 1953. The arrival of tritium at the Radioactive Waste Management Complex (RWMC) was first detected in 1975. The apparent velocity of tritium migration, based on first arrivals from either the TRA radioactive-waste ponds or the ICPP disposal well, ranges from 4 to 5 feet per day since the beginning of disposal operations. This probably is not indicative, however, of the ground-water flow velocity.

The highest tritium values were found south of the ICPP and south of the disposal ponds at the TRA as shown by the concentration contours in figure 23. The concentration contours between the ICPP and the CFA have generally retreated upgradient toward the disposal well because of a reduction of tritium disposal over the past several years.

COMPARISON OF WASTE DISTRIBUTION TO MODEL SIMULATIONS

Perhaps the most significant information gained from the 1980 well-drilling program was the determination of the waste chloride and tritium plumes for October 1980. A predictive digital model (Robertson, 1974) was developed and employed to project simulations of these waste plumes for the years 1980 and 2000. Calibration of the model was based

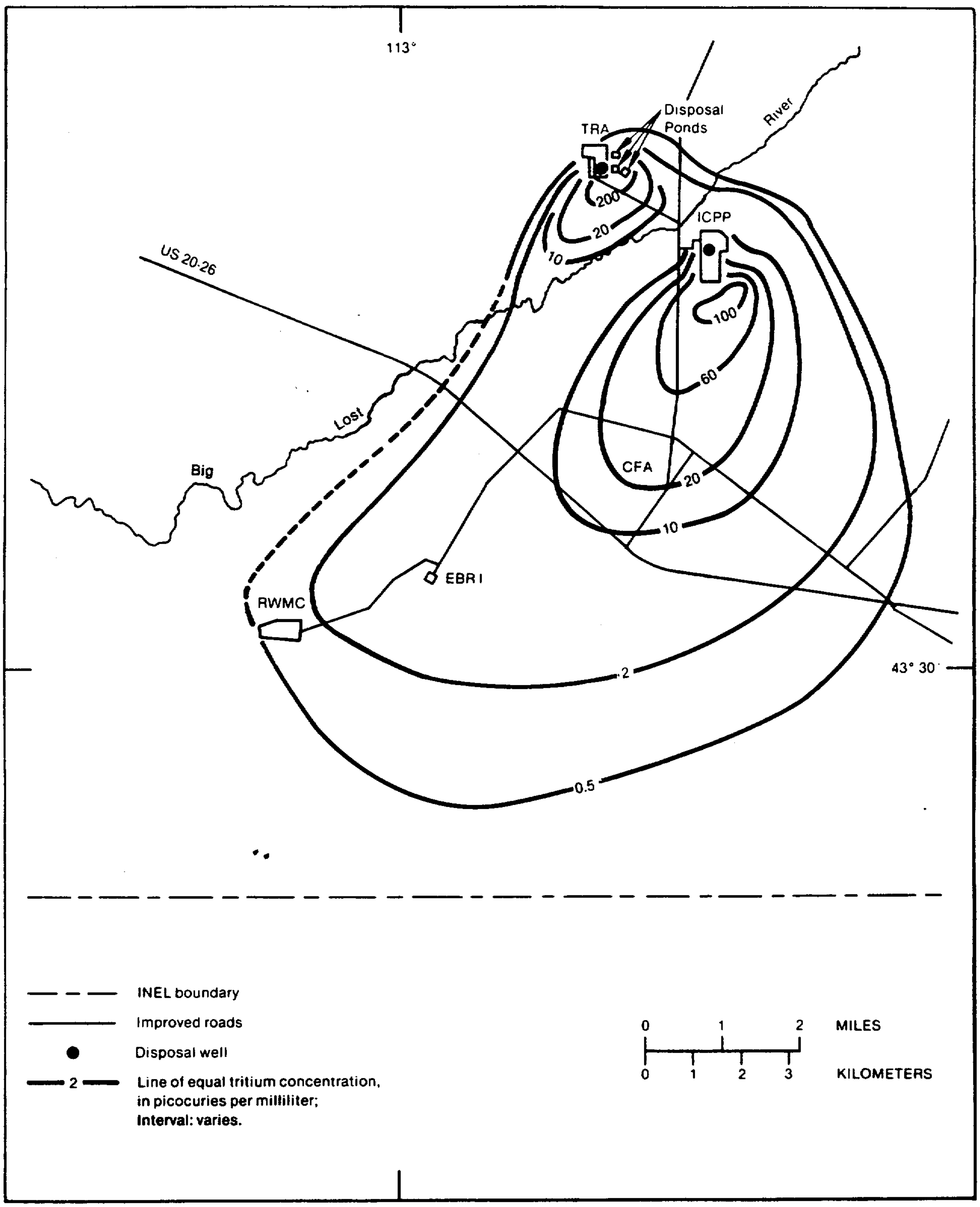


Figure 23.—Distribution of tritium in the Snake River Plain aquifer, ICPP-TRA vicinity, October 1980.

on the then existing INEL data base for hydrologic and waste-disposal information and was compared with the historical data prior to 1973. The data acquired through the drilling program and the interpretations therefrom are of great significance in providing additional input and verification data for the model. These data are essential for model recalibration and in supplying the information required to determine accurately the southern extent of the waste plumes, their overall shape, and the concentration of waste products within the affected areas.

Digital Model Description

The migration and distribution of waste solutes in ground water depend on hydraulic constraints in addition to those of dispersion and aqueous chemistry (Robertson, 1977). Therefore, it is necessary first to define and model the hydraulics of the system prior to solute-transport modeling. The solute-transport model is then coupled to the hydraulic model for simultaneous solution. The hydraulic segment of the model approximates the solution of the standard transient partial differential equation of ground-water flow in a bounded, two-dimensional, one-layered aquifer by finite-difference techniques. The flow equation employed by the hydraulic segment of Robertson's (1974) model may be formulated as

$$S \frac{\delta h}{\delta t} = \frac{\delta}{\delta x}\left(T \frac{\delta h}{\delta x} \vec{i}\right) + \frac{\delta}{\delta y}\left(T \frac{\delta h}{\delta y} \vec{j}\right) - W(x,y,t), \qquad (6)$$

where

S = storage coefficient, [dimensionless],

h = hydraulic head, [L],

t = time, [T],

T = transmissivity, $[L^2 T^{-1}]$,

x,y = cartesian coordinates, [L],

i,j = unit vectors of direction, and

W = flux of source or sink, $[LT^{-1}]$.

The approximation uses the iterative, alternating-direction implicit method as described by Pinder and Bredehoeft (1968), and Bredehoeft and Pinder (1970). The hydraulic model generates the velocity of ground-water flow at each finite-grid point and time step, and these flow rates and directions are then used for the velocity field in the chemical-solute transport segment of the model to simulate the migration of the waste products in time and two-dimensional space (Robertson, 1974).

In modelling a complex system, it is necessary to make simplifying assumptions to solve the problem efficiently and still maintain a model that is adequately representative of the real system. Many of the assumptions employed by Robertson's (1974) and other modeling studies of the Snake River Plain aquifer (see Norvitch, Thomas, and Madison, 1969; and Moreland, 1976), are as follows:

(1) Ground-water flow within the aquifer obeys Darcy's Law, and the aquifer is composed of isotropic and homogeneous material;

(2) Flow in the aquifer is two-dimensional, no vertical component is considered;

(3) The aquifer is sufficiently thick so that T does not change with water-level changes;

(4) Recharge and discharge to and from the ground-water system is instantaneous, no transit time is involved;

(5) The model area is large enough for the justification of neglecting aquifer effects outside the model boundaries;

(6) Ground-water storage changes occur instantaneously with water-level changes, a constant value of 0.1 was used for the storage coefficient;

(7) Intermittent recharge from significant surface-water flow is simulated by recharge wells at each node along the course of the Big Lost River; and

(8) The recharge to, or discharge from, a node occurs at a constant flux rate over the entire nodal cell.

Many of the above described assumptions about the hydrologic system are not entirely true on a local scale. With the size of the area involved and the time transgression required for the many iterations needed to simulate accurately a particular parameter, it appears reasonable to assume that ground-water flow in the aquifer will approximately obey Darcy's Law (Robertson, 1974); in non-recharge or non-discharge areas, flow will occur only in two dimensions with the given physical constraints, but in areas of recharge or discharge there may be significant components of vertical flow; and the aquifer effects outside the model area may be validly ignored (Robertson and Barraclough, 1973). The assumption that T values are constant at a node despite changes in ground-water levels appears to be valid when comparing the relatively small changes in water levels to the total saturated thickness of the aquifer. Also many of the assumptions are time independent, such as ground-water recharge, discharge, and storage changes, with water-level changes. These assumptions are certainly not true for very localized situations of a short duration, but again with the large size of the modeled area and over longer time periods, year-to-year conditions, the minimal time dependent changes may be ignored (Moreland, 1976). The assumption that recharge or discharge occurs at a constant flux rate over the entire nodal cell appears legitimate for the spatial and temporal scales involved and the very high transmissivities of this aquifer (Moreland, 1976).

The second segment of the model consisted of simulating the chemical-solute transport in flowing ground water. This transport is described by a partial differential equation and its approximated solution must be correlated simultaneously with that of the hydraulic flow equation (equation 6). The following differential equation describes the transport of dissolved constituents that are subject to the effects of convective transport; velocity divergence; two-dimensional hydrodynamic dispersion; instantaneous equilibrium, linear isotherm, reversible adsorption; and radioactive decay (Bear, 1972; Robertson, 1974; and Robertson, 1977):

$$\overbrace{\frac{\delta C_n}{\delta t}}^{a} = \overbrace{\left(\frac{1}{\varepsilon+K_d-\varepsilon K_d}\right)}^{b}\left(\overbrace{\nabla.\vec{\vec{D}}.\nabla C_n}^{c}\overbrace{-\nabla.(C_n\vec{q})}^{d}\overbrace{-\;QC_s}^{e}\right)\overbrace{-\lambda_n C_n}^{f}, \qquad (7)$$

where

C_n = concentration of solute n in the ground water, $[ML^{-3}]$,

t = time, [T],

ε = effective porosity, [dimensionless],

K_d = equilibrium distribution coefficient for instantaneous, linear isotherm, reversible adsorption, [dimensionless],

$\nabla = \frac{\delta}{\delta x}\vec{i} + \frac{\delta}{\delta y}\vec{j}$, where $\vec{i}$, $\vec{j}$ are unit vectors of direction,

$\vec{\vec{D}}$ = dispersion coefficient tensor, $[L^2\ T^{-1}]$,

$\vec{q}$ = specific discharge vector of ground-water flow, $[LT^{-1}]$,

Q = production rate of a source or sink, $[T^{-1}]$,

C_s = concentration of solute n in a source or sink $[ML^{-3}]$, and

λ_n = radioactive decay constant for solute n, $[T^{-1}]$.

Term "a" in equation 7 indicates the change with time in the concentration of solute n at any nodal point of the model grid system. Term "b" accounts for the effects of reversible sorption and is commonly referred to as the retardation factor. The distribution coefficient, K_d, is defined as the equilibrium ratio of volumetric solute concentration in the solid phase to volumetric solute concentration in the liquid phase $[L^3/L^3]$ of the porous medium (Robertson, 1977). Term "c" describes the effects of two-dimensional hydrodynamic dispersion where the longitudinal and transverse dispersion coefficients are related to the corresponding dispersivities by $D_L = \alpha_L V$ and $D_T = \alpha_T V$ (Bredehoeft and Pinder, 1973); and where D_L and D_T are the dispersion coefficients, respectively longitudinal and transverse; α_L and α_T are the dispersivities, of consistent notation, and V is the ground-water flow velocity. Term "d" describes the effects of convective transport; and term "e" accounts for source or sink terms, such as input from the ICPP disposal well. Term "f" adjusts for radioactive decay where the decay constant, λ_n, is related to an isotope's half-life, $H_{1/2}$, by the relationship $\lambda_n = 0.693/H_{1/2}$ (Robertson, 1974). The dispersion tensor, $\vec{D}$, and term "d" in the equation, depend on the specific discharge or flux, $\vec{q}$ (Robertson, 1977). This flux is calculated in the hydraulic segment of the model for each node in time and space, and stored for use in the transport model. Therein lies the reason for the simulataneous operation of both the hydraulic and solute-transport segments of the model.

Equation 7 is a partial differential equation for which analytical or direct solutions are not feasible except for systems where the most simple boundary conditions exist (Robertson, 1977). The equation must, therefore, be solved approximately by numerical techniques for depicting chemical-solute transport in the Snake River Plain aquifer. With some adaptations, Robertson (1974) employed the method of characteristics as developed and described by Pinder and Cooper (1970) and Bredehoeft and Pinder (1973) to approximate the movement of solutes in the regional ground water. The reader is referred to these references for a detailed description of the method of characteristics.

The data input into the solute-transport segment of the model included natural (background) concentrations of the solute of interest at each node, transverse and longitudinal dispersivities (characteristic mixing lengths), location of waste sources and sinks, radioactive decay factors, and distribution coefficients for sorption (Robertson, 1974). The effective porosity of the aquifer is considered to be of prime importance to a solute-transport model (Konikow and Bredehoeft, 1978) and for this study it was assumed to be 10 percent, based on the best available field data. The most speculative of these input data were the dispersivities and the distribution coefficients. These parameters had to be estimated because there was, or is, no practical or effective method to measure them in the field where large-scale aquifer heterogeneities exist.

A potentially significant shortcoming of the solute-transport model is that it assumes no vertical dispersion, which certainly occurs in reality. The magnitude of the error from this assumption is not known, but would increase with increasing time and transport distance.

Chloride

Perhaps the best tracer for waste behavior in the Snake River Plain aquifer is chloride (Robertson and Barraclough, 1973), and as such, was first used to test and calibrate the solute-transport segment of the digital model (Robertson, 1974). Chloride has been a continuous non-radioactive waste product since disposal began at both the TRA and ICPP. It has probably been discharged in more consistent and uniform quantities than any other waste product, although the concentration of chloride in the ICPP waste water has increased over the past few years. Chloride is a conservative solute in ground water and is virtually free from many chemical reactions such as sorption and precipitation, that would complicate its behavior. Therefore, K_d and λ_n of equation 7 were zero in Robertson's (1974) analysis; and the transverse and longitudinal dispersivities of the aquifer were the principal unknowns. By comparing simulated waste chloride plumes with those depicted for 1958 and 1969 from actual field data, Robertson's (1974) best simulations were obtained by using 300 feet for the longitudinal dispersivity, α_L, and 450 feet for the transverse dispersivity, α_T. Most of the discrepancies between the correlations were considered simply due to the coarseness of the model grid which was set at 4,200 feet between nodal points.

The simulations depicting the waste chloride distribution within the aquifer by 1980 were projected by varying the input of normal recharge data and the discharge rate of waste chloride through the ICPP well. Figure 24 shows Robertson's (1974) predicted waste chloride plume for 1980, assuming disposal ceased in 1973 and the Big Lost River did not recharge the aquifer. The apparent effects on the plume by this set of imposed conditions were that the absence of recharge from the Big Lost River allowed the plume to spread transversely through the aquifer in the ICPP-TRA vicinity; the higher chloride concentrations within the plume moved downgradient to encompass the CFA; and a preferential flow path developed as the plume's leading edge approached the INEL's southern boundary. This flow path may be controlled by a high transmissivity zone south of the boundary (fig. 20).

Robertson's (1974) original plume maps also included an outer 15 mg/L equal concentration line, intended to represent background levels. However, background chloride concentrations are somewhat variable so concentrations above 20 mg/L are used here to denote the effects of waste disposal.

Figure 25 shows the simulated waste chloride plume projected for 1980 (Robertson, 1974), assuming chloride disposal continued at 1973 rates and flow in the Big Lost River recharged the aquifer in odd numbered years. Here again, the high T zone near the INEL's southern boundary has aided in creating a preferential flow path in that direction but the lateral extent of the entire plume was greater for this case. With continued disposal of waste chloride, the concentration contours were no longer centered near the CFA but were progressively higher toward disposal points, as would be expected. Also, recharge from flow in the

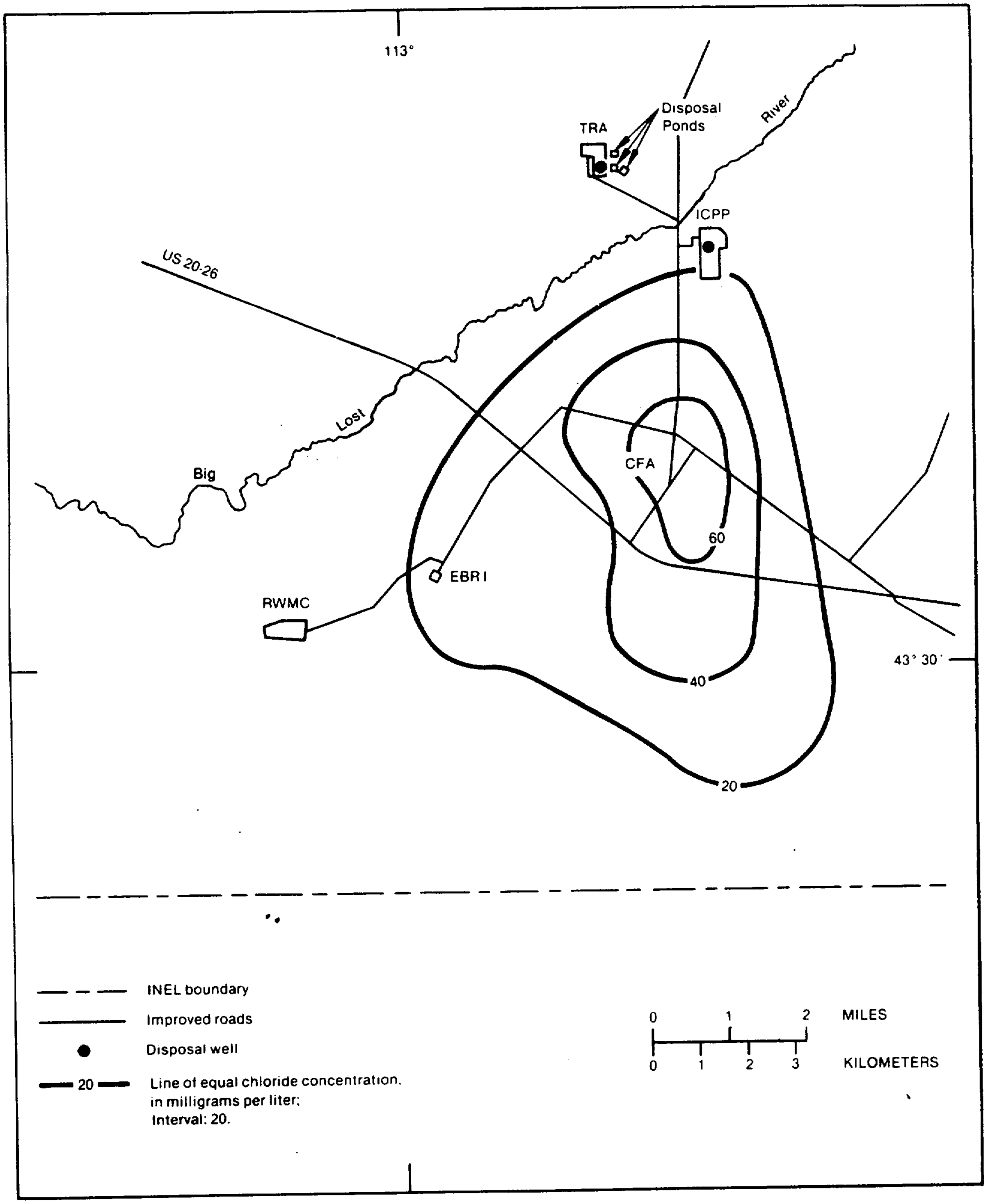


Figure 24.--Model-projected distribution of waste chloride in the Snake River Plain aquifer for 1980, ICPP-TRA vicinity, assuming disposal ceased in 1973 and the Big Lost River does not recharge the aquifer (from Robertson, 1974).

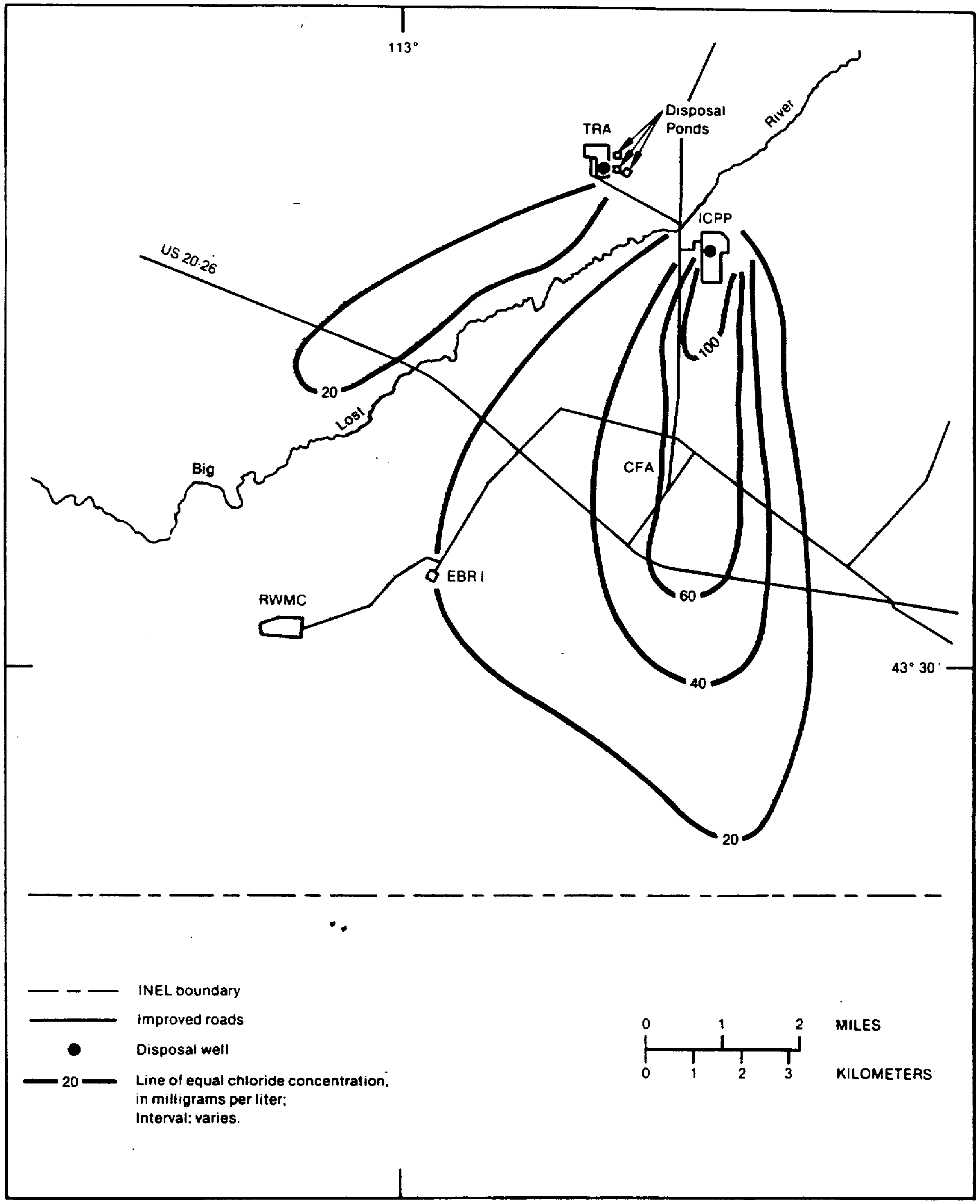


Figure 25.—Model-projected distribution of waste chloride in the Snake River Plain aquifer for 1980, ICPP-TRA vicinity, assuming disposal continues at 1973 rates and the Big Lost River recharges the aquifer in odd numbered years (from Robertson, 1974).

river caused a separation of concentration contours within its immediate area, and with obvious continued discharged at the TRA, the plume contained a much larger area of higher concentration values on the TRA side of the river.

Comparison of the two simulated waste chloride plumes, dependent on the above discussed sets of conditions and shown in figures 24 and 25, with the plume depicted for October 1980 (fig. 21), immediately indicates that the 1980 simulated projections crudely resemble the field data but differ in detail. The waste chloride concentration in water samples collected from each newly drilled well did not verify a plume with an extended lobe toward the zone of supposedly high T values in figure 20. It is apparent that the projected simulation represented in figure 25 more nearly corresponds to the actual situation than that in figure 24.

The projected simulation of the 1980 waste chloride plume shown in figure 25 assumed that disposal of chloride through the ICPP disposal well would continue at 1973 rates and flow in the Big Lost River would recharge the aquifer in odd-numbered years. These conditions have not been duplicated in the time period that elapsed between 1973, when the model study was completed, and October 1980, but have approximated the actual conditions more closely than the other simulated projection. Disposal of waste chloride has not only continued through the ICPP disposal well, but has increased during the seven year elapsed time period. Noticeable from figure 21 is that the aquifer has apparently received less waste chloride than assumed from the overlying chemical waste disposal pond at the TRA.

Following 1973, three years with exceptionally high flows in the Big Lost River were recorded at the INEL diversion (fig. 2) and the aquifer received recharge from the diversion areas and the river itself (Barraclough, Lewis, and Jensen, 1981). However, following these high flow years, little or no flow was recorded at the INEL diversion from 1977 to and including 1980. Water levels have declined to record and near record lows in many wells of the INEL observation well network. This hydrologic phenomenon would undoubtedly have affected the distribution of equal concentration lines within the waste chloride plume due to the effects on hydraulic head gradients and the amounts of diluting recharge water.

There are two main variations between the plume depicted in figure 21 and the projected plume in figure 25. The first is that the field data (fig. 21) show more dispersion laterally in the 20, 40 and 60 mg/L equal concentration lines within the main portion of the plume. The second difference is that the actual distribution (fig. 21) does not exhibit the elongated flow trend toward the INEL's southern boundary that was drawn in the model-projected plume (fig. 25). The reasons for these variations could result from mathematical, physical, or chemical causes or a combination thereof. The reasons for the differences may be summarized as follows:

(1) The 1977 to 1980 period of below-normal aquifer recharge from river flow could have resulted in higher concentrations in the actual plume, due to reduced recharge dilution;

(2) The increased chloride disposal rate through the ICPP disposal well over the past several years, coupled with the hydrologic conditions presented in number 1 above, would have caused increased concentrations within the central portion of the plume;

(3) The model grid was, perhaps, too coarse for an accurate projected simulation of the waste plume and a better fit might have been obtained using a finer-meshed grid;

(4) Inaccurate aquifer hydraulic parameters such as transmissivity and porosity, were used in the model;

(5) Inaccurate dispersivities, transverse or longitudinal, were used in the model;

(6) The aqueous waste being disposed of through the ICPP disposal well contains a higher specific conductance value than that of the aquifer ground water and, as such, the waste water would have a slightly higher density and would tend to sink in the aquifer system;

(7) There may be significant components of vertical flow or thickness variations which are not included in the two-dimensional, constant-thickness model;

(8) There may be an inadequate distribution of observation wells to accurately map the plume, and some of the wells might not have the appropriate depth nor construction to yield representative data; and

(9) The numerical method of approximating the solution to the solute-transport partial differential equation produces some error, although there is no indication that the error is sufficient to account for the observed differences.

Perhaps the most critical factor in the solute-transport equation is the ground-water flow velocity, q/ε, which is calculated using Darcy's Law (eq. 2). The assigned value for the effective porosity, ε, in the solute-transport segment of the model was 0.1, or 10 percent. Other studies concerning the aquifer hydrologic properties have determined that the average effective porosity ranged from 8 percent (Isherwood, 1981b) to 10 percent (Nace and others, 1969). Therefore, it appears that the 10 percent value used by Robertson (1974) is reasonable; but small errors in ε would result in proportionate changes in the extent of and concentrations within the chloride plume. For example, if ε were really 12 percent instead of the assumed 10 percent, the velocity would be reduced by a factor of about 17 percent, which would have a significant retardation effect on the movement of a solute in the ground water.

Another porosity factor is the difference between total and effective porosity. Total porosities of Snake River Plain basalt core samples range from 12 to 20 percent (Robertson, Schoen, and Barraclough, 1974). Although part of this porosity is not effective in transmitting water, dissolved ions may diffuse into and out of pore spaces. This diffusive process, herein termed matrix diffusion, was described by Freeze and Cherry (1979), and discussed in detail by Grisak and Pickens (1980). The process occurs in the following manner. When the waste chloride moves through the fractured aquifer system, there initially exists a solute concentration gradient between the ground water in the fracture and the ground water in the unfractured material. A portion of the solute mass will move by molecular diffusion from the fracture into the matrix, if the matrix is porous. This mass of the solute is removed temporarily from the flow regimen in the open fracture. The flow of the solute in the fractured system then appears to be retarded because part of its mass has been transferred to the aquifer matrix. As time progresses, the solute will diffuse farther into the aquifer matrix until a concentration equilibrium is reached with the matrix material and the fracture. This equilibrated situation would occur only if the waste solute was being disposed of over many years at nearly uniform rates and the matrix diffusion process, therefore, could occur undisturbed for a long time.

Matrix diffusion, coupled with the large apparent dispersivities of the Snake River Plain aquifer and the fractured nature of the aquifer, which may provide large masses of rock in which diffusion may take place, is probably an important factor affecting the rate of waste chloride movement in the aquifer. The waste chloride plume depicted in figure 21 has not advanced downgradient as much as was expected, which may be due in part to matrix diffusion effects.

The density variations noted in item 6 could conceivably cause the waste products, including chloride, to move downward into a deeper part of the aquifer. This natural reaction between liquids of differing densities was well documented by Freeze and Cherry (1979) for a waste disposal situation. The implications of this relationship to the waste chloride plume are: (1) perhaps a third-dimension of the October 1980 plume exists that is not represented in map view; (2) the wells drilled during the 1980 drilling program, especially wells 104 and 107 (see fig. 6), were not drilled deep enough to intercept the advancing front of the plume; and (3) the higher lines of equal chloride concentration within the plume may extend to even greater depths than the supposed effective permeable zone that is contained within the upper part of the Snake River Plain aquifer. The waste chloride could, therefore, have entered a dimension not accounted for in the model and was not represented in the projected simulations.

Another source of dispersion error in the model, as mentioned by Robertson (1974), results from ignoring vertical dispersion. This effect would also result in downgradient concentrations lower than those projected by the model.

The Arco rift zone and its subsurface extension may be partly responsible for the greater degree of lateral extension of the waste chloride plume in figure 21 compared to that of the simulated plume in figure 25. The spreading effect would be due to flow divergence, rather than hydrodynamic dispersion. This volcanic rift zone of lower permeability may, therefore, be an impedence to ground-water flow, as is the Great Rift Zone, and a localized flow component is parallel to its emplacement. The Arco volcanic rift zone of lesser transmissity near the southern INEL boundary (fig. 20) may be more influencial than previously determined or as indicated from water-level data.

Grove (1977) made a study to compare finite difference, Galerkin-finite element, and the method of characteristics for approximating the solution to the solute-transport equation for the waste chloride plume at the INEL. He concluded that for this type of problem, the method of characteristics is as accurate as the Galerkin-finite element method and because of less numerical dispersion, is more accurate than the finite difference method. Therefore, it does not appear that significant improvements in simulation accuracy would be obtained by changing numerical methods.

Tritium

Tritium was included in Robertson's (1974) solute-transport study to test the radioactive decay parameter in the model, term "f" of equation 7. Tritium, like chloride, is also a fairly conservative solute in ground water and not generally subject to chemical reactions; so that term "b" in equation 7 may again be omitted. Little or no background tritium in statistically positive amounts is detectable in the Snake River Plain aquifer, which also makes this solute an excellent tracer in the ground water. Simulations of the model-produced tritium plumes were compared with those depicted from historical data. The best simulations were accomplished by using the same dispersivities as for the chloride simulations; α_L was equal to 300 feet and α_T was equal to 450 feet. These correlations of simulated to actual plumes indicated that the radioactive decay portion of the model accurately simulated conditions in the aquifer.

The model-projected distribution of tritium in the aquifer for 1980 is shown by figure 26 with the assumptions that disposal ceased in 1973 and the Big Lost River did not recharge the aquifer (Robertson, 1974). Because these assumed conditions have not been met, the simulated plume could not be expected to correlate accurately with the observed plume for October 1980 in figure 23. Flow in the Big Lost River, and hence aquifer recharge, has not been totally absent during this seven-year period; and discharge of tritium did not cease in 1973, although it has been reduced since that time.

The many hydrologic variables and subsurface geologic uncertainties discussed in the section on chloride could also have similar effects on the configurations of and the lines of equal concentration within the actual and 1980 simulated tritium plumes.

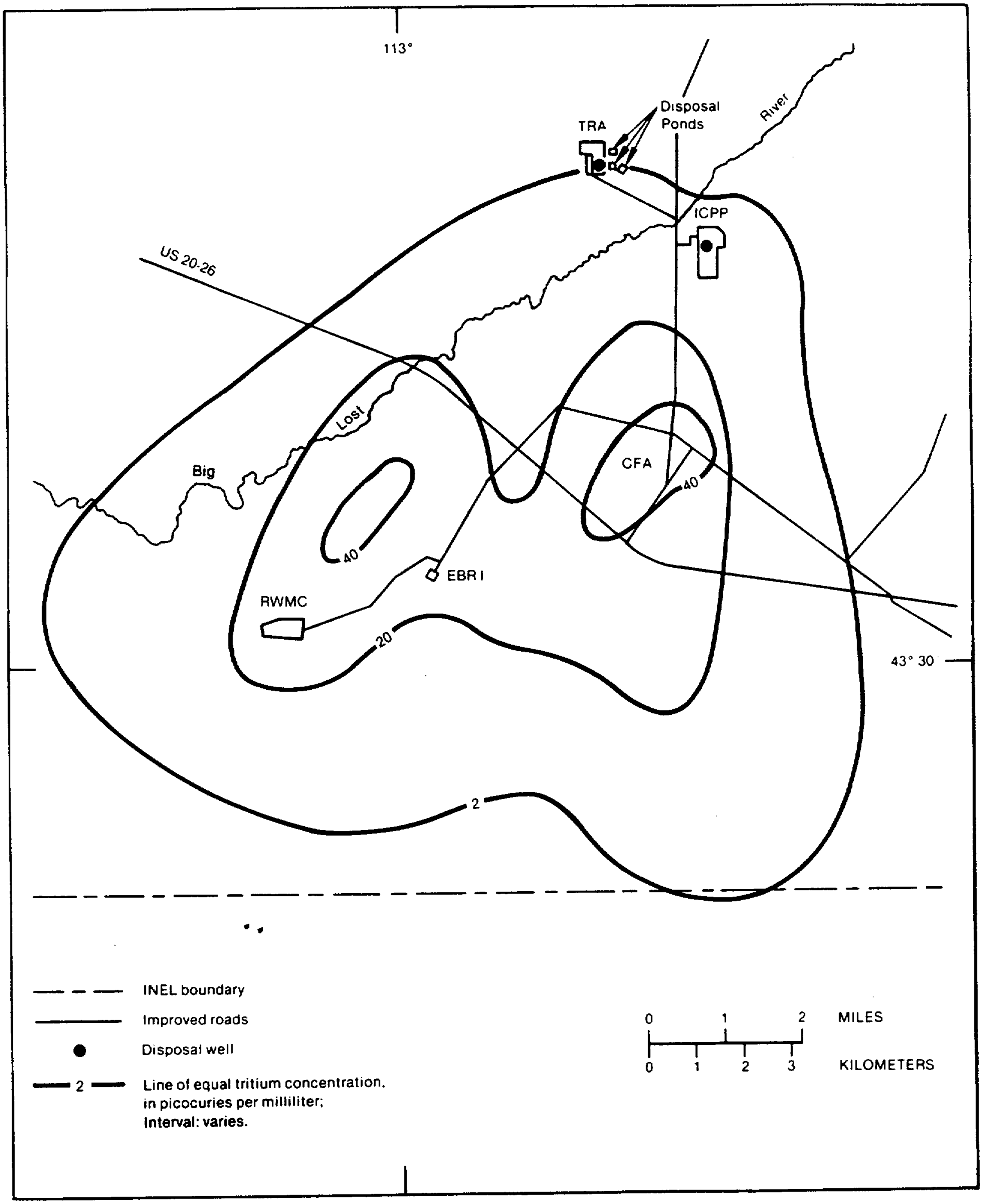


Figure 26.--Model-projected distribution of tritium in the Snake River Plain aquifer for 1980, ICPP-TRA vicinity, assuming disposal ceased in 1973 and the Big Lost River does not recharge the aquifer (from Robertson, 1974).

FUTURE PROGRAMS

The information collected and the interpretations made during and following the 1980 well-drilling program near the southern boundary of the INEL have shown that most of the chloride waste plume is approximately one to two miles upgradient (north) from the position projected for 1980 and that the advanced front of the actual tritium plume is about 2 miles upgradient from the projected position. However, the central parts of both plumes are close to the simulations. The subsurface geologic structures and rock types control the subsurface hydrologic system and the movement of the wastes through this system. However, many questions still exist about this complex system.

Additional drilling and coring programs in future years would enhance our knowledge about the natural hydrogeologic character of the Snake River Plain aquifer, and about waste movement within this vast aquifer. These drilling programs would be useful in providing:

(1) Better identification of natural chloride concentrations in the ground water and identification of anomalous zones;

(2) More comprehensive determination of subsurface geologic structures and delineation of their influence on the ground-water flow system and waste product movement;

(3) Understanding of the effects of silicic or other non-typical rock types on the aqueous geochemistry and on the physical framework of the flow system;

(4) Additional information on the transmissive and storage characteristics of the aquifer in general;

(5) Better understanding of the hydrologic properties of the deeper part of the aquifer, more than 200 feet below the water table, and identification of the possibilities of waste products moving deeper into that part of the aquifer;

(6) Filling existing deficiencies in monitor well locations in order to better define waste plume concentration distributions;

(7) Determining the possibility of upward flow from deeper zones of the aquifer near the INEL's southern boundary and within the Arco volcanic rift zone; and

(8) Better determination of the arrival times of waste products, south of the INEL boundary when and if they move that far in detectable concentrations, and identification of the hydrolgic properties of that area.

A less expensive method than drilling or coring to delineate subsurface geologic features near the INEL's southern boundary would be surficial geophysical methods. The two methods which might be useful are seismic refraction or reflection, and resistivity surveys, which may be run transverse or parallel to the supposed low-transmissivity zone. The applicability of these methods to determine subsurface geologic features in a basalt environment is questionable at present, but new techniques have been and are being developed that will enhance their utility.

Mathematical methods, such as the kriging technique, may be employed to interpolate the aquifer's hydrologic properties into areas where well data are sparse in the INEL's basic data network and would not involve the use of external physical methods such as well drilling or geophysical surveys. These interpolation methods are mathematically complex but are readily solvable by digital computer techniques and, therefore, may be easily incorporated into a digital modeling scheme.

Varying techniques of interpolation have been employed to solve many problems that require the projection of data or their interpretation in space and time for the filling of a gap in a network of basic data. Such techniques have included the classical Lagrange interpolation, the least squares approach, and several weighted interpolation methods (Gambolati and Volpi, 1979). When applied to the science of hydrology, many of these techniques yielded estimations that contained large interpolation errors and were very limited in their use. However, several recent studies have shown that one method, the kriging technique, may have broad applicability to hydrologic situations (Delhomme, 1978; Gambolati and Volpi, 1979; and Skrivan and Karlinger, 1980). The reader is referred to the references for detailed descriptions and applications of the kriging technique.

The ultimate use of the information gained in the recently completed drilling program and planned programs will be for inclusion into and the recalibration of a revised predictive digital model that approximates chemical solute-transport in the aquifer. This primary goal of updating the model should continue for many years at the INEL as an ever expanding data base makes possible a continued refinement of model simulations.

SUMMARY

This report describes the data collected, and the interpretations made therefrom, during and following the drilling of eight shallow wells near the southern boundary of the Idaho National Engineering Laboratory (INEL) during the summer of 1980.

The information gained from the drilling program and existing information in the INEL data base about the subsurface hydrogeology in the southwestern INEL vicinity and the movement of aqueous wastes within the Snake River Plain aquifer are summarized below:

1. The general direction of the regional ground-water movement is to the south and southwest with an average slope of the water table of about 4 feet per mile. In the southwestern part of the INEL, near the site's southern boundary, the gradient is rather

low, sloping southwestward at less than 2 feet per mile. The water table has declined from about 2 to 6 feet during the two-year period from 1978 to 1980. The greatest declines were measured in areas where the aquifer is subject to large changes in recharge from the Big Lost River, whose average discharge has been abnormally low for the five years preceding preparation of this report.

2. Geophysical logs recorded in each of the eight wells, supplemented by driller's logs, show that the subsurface geology consists of basalt flows and interbedded layers of sediment. Silicic rocks (rhyolite) encountered in four wells located near the INEL's southern boundary appear to be associated with Cedar Butte or Big Southern Butte, both of which lie in the Arco volcanic rift zone. The silicic rocks appear to be correlated with sedimentary layers at corresponding elevations in adjacent wells of the hydrogeologic section. The geophysical logs also show that many of the wells contained severely fractured zones of basalt below water level and indicated the wells should be good water producers when pumped.

3. Tests performed on six of the eight wells indicated that the Snake River Plain aquifer has high water yielding characteristics, as expected. However, the test on well 104 indicates an unusually low transmissivity for that part of the aquifer. The well was pumped at 21 gpm, which resulted in a drawdown of 51 feet and a computed transmissivity of about 50 feet squared per day, compared with 134,000 to 13,400,000 feet squared per day generally associated with the regional aquifer. A possible reason for the difference is that well 104 could have been completed near the vertical center of a laterally small basalt flow, where the most dense rock is located.

4. The analyses of water samples collected from seven of the eight wells indicated that the water in those wells not affected by waste products was predominantly of the calcium, magnesium, and bicarbonate type with minor concentrations of sodium, silica, sulfate, and chloride, water chemistry consistent with that determined to be representative of the Snake River Plain aquifer in the INEL vicinity by previous investigators. Water samples from two wells were found to contain detectable concentrations of waste products. Well 104 ground water contained tritium; and the ground water from well 106 contained both tritium and waste chloride, and higher specific conductance values. Both of these wells are 2 to 3 miles upgradient from the INEL's southern boundary and may depict the approximate position of the leading edges of the chloride, and tritium waste plumes, and an aquifer area with higher-than-background specific conductance values.

5. It is postulated in this report, based on water-table gradient data, that a zone of low permeability exists in the southwestern

part of the INEL site within the Arco volcanic rift zone. This rift zone is situated transverse to the regional ground-water flow direction. The zone of low permeability may be caused by solidified igneous rocks that "healed" fractures and fissures that constitute the volcanic rift zone. This hypothesis may also be supported by the fact that the waste plumes exhibit a greater lateral dispersion near the INEL's southern boundary than estimated previously. This spreading effect may be a result of flow divergence and in direct response to a geologic feature in the subsurface that is of low permeability; and may be directly correlated with the Arco volcanic rift zone. The anomalously high concentrations of various chemicals in samples of water from wells located along the INEL's southern boundary that are not apparently affected by waste products, may result from aqueous reactions with varying rock types of the Arco volcanic rift zone.

6. The model simulations made in the early 1970's of the 1980 waste chloride and tritium plumes were approximately correct, but differed in detail, as expected, because of several conservative assumptions that tended toward "worst case" conditions. The frontal parts of the actual plume are upgradient one to three miles of their correlating model simulations, which indicates that either the projected modeling assumptions for the disposal or recharge rates were inaccurate, and/or that the hydrologic parameters included in the model format for the Snake River Plain aquifer were not completely representative of the physical conditions. The aquifer properties to which the solute-transport model segment is most sensitive are effective porosity, hydraulic conductivity, aquifer thickness, and the longitudinal and transverse dispersivities. The hydraulic gradient is also an important parameter but is the least subject to error of the properties cited. The coarseness of the modeling grid itself perhaps limited the accuracy and precision of the simulations. The methods of approximating the solution of the partial differential equation for solute transport appear to be as accurate as any available for these particular conditions.

7. Future programs are recommended for the INEL to delineate more accurately the subsurface hydrogeologic structures; to determine their effects on the regional aquifer flow regime and the movement of aqueous wastes in the aquifer; to quantify spatially the hydrologic properties of that part of the Snake River Plain aquifer which underlies the INEL; to determine more accurately the aquifer's background ground-water chemistry and the areal extent of the waste plume; to better understand the hydrologic properties and dynamics of the deeper part of the aquifer, more than 200 feet below the water table; and to determine the possibilities of waste products moving into this deeper part of the aquifer. Much of this information could be obtained from drilling, coring, geophysical logging, sampling,

or various surface geophysical surveys. In addition, interpolative mathematical techniques (kriging methods) could be employed to expand data into areas of little or no information. The ultimate use of the information and data gained by the physical methods or mathematical techniques will be for incorporation into a revised predictive digital model, that will make possible more accurate simulations of waste-solute movement under various assumed disposal and hydrologic conditions.

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