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GROUND-WATER CIRCULATION IN THE MEADE THRUST ALLOCHTHON EVALUATED BY RADIOCARBON TECHNIQUES

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ABSTRACT. The Meade thrust, in southeastern Idaho, is a major element of the Western Overthrust Belt. The allochthon is of geo-economic importance both as a potential hydrothermal area and as the principal mining area within the Western Phosphate Field. To assist in the development of these two resources, an understanding of the regional ground-water circulation was sought. Geologic and hydrologic data from boreholes in this area are virtually nonexistent. Waterwell development in the area has not occurred because of the abundance of springs and only a few hydrocarbon exploration boreholes have been drilled. Thus, the problem lends itself to evaluation by isotope hydrologic and geochemical methods. Ten springs from within the thrust block and around its periphery were sampled for major ions, $^{2}H/^{18}O$, and $^{14}C/^{13}C$ analysis. Data from these analyses and from field geologic evidence have identified two distinct flow regimes within the Meade thrust allochthon. Shallow flow systems lie above the impermeable Phosphoria Formation, usually within a few hundred meters of the surface. Most of the spring waters from this system are recent and cool. In all cases, they have mean subsurface residence times of less than a few hundred years. The deeper flow systems which lie below the Phosphoria formation are hydraulically isolated from the shallow system. Warm waters from these springs have ^{14}C contents suggesting mean ground-water residence times on the order of 15,000 years. Although these waters could have circulated to as deep as 1900m, $^{2}H/^{18}O$ results show that high temperatures were never reached. There is no evidence to suggest that water from beneath the Meade thrust has contributed to the circulation in the allochthon.

INTRODUCTION

The Meade thrust allochthon (Fig 1) is a major segment of the Idaho-Wyoming thrust belt, covering ca 3700km^2, includes most of the Western Phosphate Field, and is a potential source of geothermal energy and of hydrocarbons. Our aim was to understand the ground-water circulation patterns for the development of the phosphate and geothermal resources.

The relationships between ground-water flow patterns and the structures involved in thrust and block faulting in the

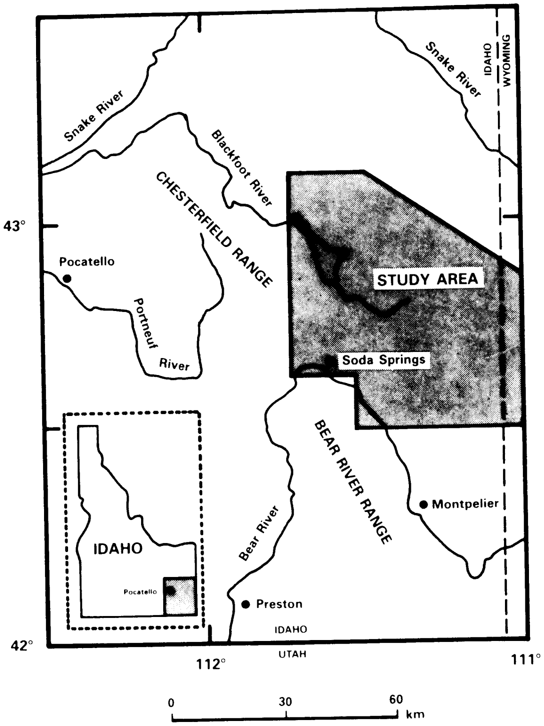

Fig 1. Index map of southeastern Idaho showing the location of the study area. Shaded region in the Idaho map inset shows location of index map.

allochthon have been poorly understood. Faults, particularly along the periphery of the allochthon, appear to be significant factors controlling the discharge from many of the aquifers within the allochthon. The larger springs and the thermal springs are concentrated along the periphery extension and thrust faults. Springs in the interior of the allochthon have smaller discharges and lower discharge temperatures. Deep drilling in the area has been limited to a few oil/gas exploration boreholes. Water wells have not been developed because of the abundance of springs. Evaluating the ground-water flow pattern lends itself readily to isotope hydrologic and geochemical methods.

THE SETTING

GEOLOGY. The Meade thrust allochthon is a body of upper Paleozoic and lower Mesozoic marine strata underlain by the Meade thrust fault. The upper Paleozoic formations are predominantly carbonate and sandy strata which have a maximum aggregate thickness of ca 2000m. The lower Mesozoic formations consist of carbonate and sandy, shaly strata which are generally less massively bedded. The Phosphoria Formation, the uppermost Paleozoic formation, is of particular importance to this investigation because it contains siliceous mudstones, cherts, and phosphate rocks which have significantly lower hydraulic conductivities than the underlying strata. The Phosphoria Formation, 150m-thick, forms a hydraulic barrier between the Paleozoic aquifers below it and the Mesozoic aquifers above it.

The allochthon is up to 40km wide in an east-west direction and up to 80km long in a north-south direction. The major structural features of the allochthon are shown on the generalized geologic map (Fig 2) and on an east-west structure section (Fig 3). The sole of the Meade thrust is thought to be continuous under the allochthon (Mansfield, 1927; Royse, Warner, and Reese, 1975). Structure sections by Mansfield (1927) and Cressman (1964) show the depth of the generally flat-lying thrust sole to 2200m below land surface. The Meade thrust fault surfaces as a series of steeply inclined thrust splays along the eastern and southern borders of the allochthon. The

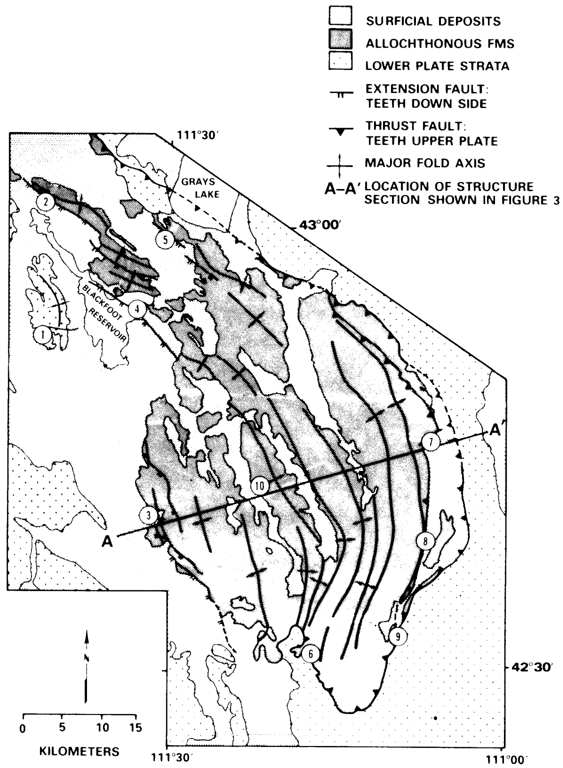

Fig 2. Generalized geologic map of the Meade thrust area showing the location of the structural section in Figure 3. Modified after Mansfield (1927).

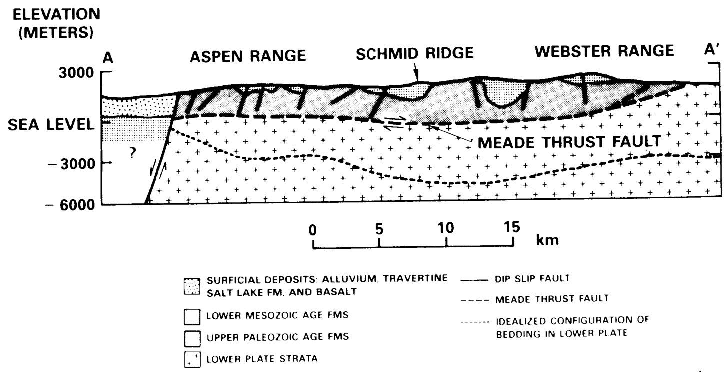

Fig 3. Generalized east-west structural section through the Meade thrust area, southeastern Idaho. The section is approximately perpendicular to the trend of the major folds in the allochthon. Modified after Mansfield (1972) and Royse, Warner, and Reese (1975). Note that minor faults not extending to the thrust fault are not shown in this figure.

eastern thrust zone is 1.5 to 4.5km wide and extends for a distance of 70km. The western portion of the allochthon is abruptly truncated by a major extension fault zone > 40km long, forming the border separating the allochthon to the east from the Blackfoot Reservoir and the Bear River Valley grabens to the west. Armstrong (1969) suggests that there is at least 910 to 1500m of stratigraphic throw along the frontal fault zone. Mabey and Oriel (1970) identified up to 1500m of Teritary sediments in the adjacent grabens.

Normal faults with throws of 200m or less (Mansfield, 1927; Cressman and Gulbrandsen, 1955) have cut the allochthonous strata in many locations. The limited stratigraphic throws suggest the faults are restricted to the allochthonous strata and do not displace lower plate rocks. Strata below the Meade thrust fault are believed to be continuous and nearly horizontal (Cressman, 1964; Royse, Warner, and Reese, 1975). Strata within the allochthon have been folded into broad and open, northerly trending anticlines and synclines, eroded into a ridge and valley system in which narrow, linear features dominate the topography of the allochthon's interior. The system extends almost the entire surface of the allochthon. Shallow seated extension faults commonly parallel the fold axes.

HYDROGEOLOGY. Springs in the Meade thrust area can be assigned to three classes: the Periphery extension group, the Periphery thrust group, and the Interior group. Periphery extension springs discharge from the extension faults forming the western periphery of the allochthon. These springs have nearly constant discharges, have water temperatures in the low thermal range and are associated with massive deposits of travertine. Periphery thrust springs discharge from splays of the Meade thrust fault along the southern and eastern periphery of the allochthon and generally have lower discharge temperatures and are not associated with travertine deposits. The Periphery groups appear to be the discharge locations of major aquifer systems which have not yet been described. The hydrostratigraphy and ground-water flow patterns in the interior of the allochthon were investigated by several researchers (eg, Ralston et al, 1977). They concluded that 1) the formations above and below the Phosphoria Formation are capable of containing major ground-water flow systems, 2) the Phosphoria Formation forms a regional barrier between these systems, and 3) ground-water flow systems in the lower Mesozoic formations are mostly of the local and intermediate types, and ground-water flow systems in the upper Paleozoic formations are presumably regional. Flow paths in the interior of the Allochthon are fracture dominated, tend to follow bedding planes, and are perpendicular to the trend of the fold axial traces. Flow paths are also perpendicular to the trend of the ridge and valley system, since topographic trends are coincident with fold trends. Interior fold-patterns are either intrabasin or interbasin. Intrabasin systems occur along the flanks of ridges where the strata are folded so that they form the upper and lower flanks of the ridge. Interbasin systems develop where the folded strata are continuous under a ridge and form a hydraulic conduit to the opposite ridge flank or adjacent valley.

Many valley floors in the interior of the allochthon are underlain by upper Paleozoic formations which receive significant amounts of recharge waters from snow melt and stream flows. Spring discharges from these formations usually do not occur in the interior of the allochthon. The Periphery springs are the suspected discharge locations of the system. The relationships between extension and thrust fault structures and the flow patterns of these suspected regional aquifers are uncertain, and the occurrence of ground-water circulation across the sole of the Meade thrust fault is also unknown.

GEOTHERMAL STUDY. A geothermal survey was conducted by Mitchell (1976). He found that most discharge temperatures of springs and wells in the western portion of the study area are in the low thermal range (10 to 40°C). He concluded that the thermal waters are probably shallowly circulating meteoric waters moving along normal faults. These waters may have the potential for small-scale domestic and commercial applications.

DATA COLLECTION

The periphery of the Meade thrust allochthon is outlined by approximately 40 springs and the interior of the block contains > 100 points of discharge. A survey of the Periphery springs led to the selection of four from both the Periphery extension and the Periphery thrust groups for detailed isotopic and geochemical analysis. Also selected was a spring from the Interior group and a flowing artesian well from an adjacent thrust block.

The flowing artesian well at Corral Creek (1)[1] was selected because its discharge temperature is considerably greater than those found in the Meade thrust allochthon and yet it has many geologic similarities with springs in the Periphery extension group. The Corral Creek system is actively depositing travertine and is associated with a tear fault. Corral Creek could provide additional insight into circulation patterns in the Meade thrust allochthon.

Sampling sites from the Periphery extension and Periphery thrust groups were selected to represent the springs in the groups and for their spacing along the periphery faults. Periphery extension springs are indicated in table 1. Except for Chubb (5), these springs are associated with massive deposits of travertine. Of the Periphery thrust group, Auburn Fish Hatchery (1) is the northernmost spring. Only one sample was taken from the Interior group because recession characteristics of these springs demonstrated recent recharge. The spring at Knudsen Ranch (10) was sampled to confirm this conclusion since it discharges from a flow system which is well understood. The Knudsen Ranch system circulates to ca 750 to 1000m below land surface and has a travel distance of 4 to 5km.

The discharge temperature, pH, carbonate, and bicarbonate content of the waters were determined in the field. Samples taken for later major ion analysis were passed through 0.45μ filters and stabilized with concentrated nitric acid. Previous analyses showed only trace concentrations of NO_3 in the spring waters of this area. Separate 100ml samples were taken in paraffin sealed glass bottles for deuterium and ^{18}O analysis. ^{14}C samples were collected using standard IAEA (1981) procedures. Sodium-carbonate-free sodium hydroxide was used to adjust the pH of the sample to above 11.5 and reagent grade barium chloride was used to precipitate the barium carbonate. Exposure of the treated sample to atmospheric CO_2 was minimized, and particulate carbonate was excluded from the sample by filtration when appropriate. Table 1 shows the results of the physical, chemical,[2] and isotopic[3] analyses.

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[1]Numbers in parentheses indicate sample numbers in table 1.

[2]Chemical analyses were made at the University of Idaho.

[3]Isotopic analyses were made at the Laboratory of Isotope Geochemistry, University of Arizona.

DISCUSSION

Regardless of their ionic strength and discharge temperatures, the waters from all three spring groups fall within a calcium bicarbonate geochemical facies. The chemical similarity of these waters is further emphasized by the ^{18}O and deuterium data obtained. Figure 4 shows that all these data fall near the continental meteoric water line (Craig, 1961). Although quite low in both ^{18}O and deuterium, the isotopic compositions observed do not disagree with expectations for such a cold climate and high altitude. No ^{18}O shift is observed as it would be if the waters had exchanged at high temperature with the oxygen of aquifer materials while maintaining constant deuterium content. This would indicate that the waters have not cooled from some high temperature at depth. Rather, these data show that the waters have not been exposed to aquifer temperatures above ca 80°C for any appreciable time. Knowledge of the maximum possible aquifer temperature, when combined with estimates of the regional geothermal gradient and the mean annual air temperature, can be used for estimating maximum ground-water circulation depths. A maximum possible circulation depth of ca 1900m below land surface was calculated by dividing the maximum possible aquifer temperature minus the mean annual air temperature by the geothermal gradient. This result is based on a geothermal gradient of 40°C km^{-1} (Mitchell, 1976) and a mean annual air temperature of 5°C.

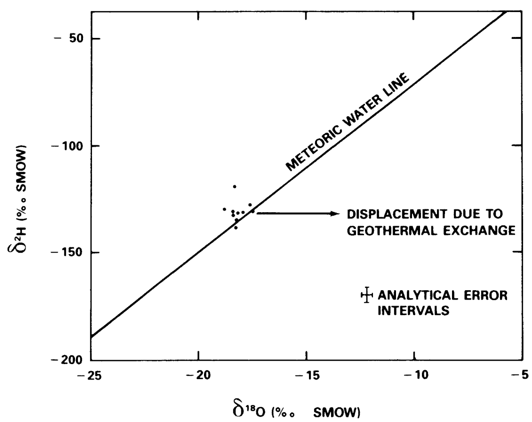

Fig 4. δ^2H vs $\delta^{18}O$ of the 10 waters reported, showing no displacement due to geothermal exchange

TABLE 1.Data summary and results

Sample number	Spring (well) name (Lat, Long)	Spring (flowing well) description	Spring group[1]
1	Corral Creek (42°52'30"N, 111°42'20"W)	Artesian flow from phosphate test holes	
2	Sinkhole (43°02'05"N, 111°41'05"W)	Flows from Wells[2] Formation along the Enoch Valley fault; associated with Wells Formation	PE
3	Formation (42°41'55"N, 111°32'30"W)	Flows up an unnamed extension fault along the front of the northern Aspen Range; associated with Wells Formation	PE
4	Henry Warm #2 (42°54'40"N, 111°32'50"W)	Discharges on the Henry travertine terrace which conceals the intersection of the Henry and Slug Valley faults	PE
5	Chubb (42°50'40"N, 111°30'20"W)	Flows from Monroe Canyon Limestone along the Chubb Springs fault	PE
6	Georgetown Canyon (42°30'15"N, 111°16'35"W)	Flows from the Wells Formation along a splay of the Meade thrust	PT
7	Auburn Fish Hatchery (42°46'20"N, 111°06'20"W)	Flows from Meade thrust and the Thaynes Formation	PT
8	Sage Valley (42°38'10"N, 111°06'45"W)	Flows from the Meade thrust and Wells (?) Formation	PT
9	Crow Creek Ranch (42°33'25"N, 111°11'00"W)	Flows from the Wells Formation at the contact with Monroe Canyon Limestone	PT
10	Knudsen Ranch (42°41'55"N, 111°21'10"W)	Flows from Dinwoody Formation after passing under Schmid Ridge via Schmid Syncline	I

(1) PE: Periphery Extension group; PT: Periphery Thrust group; I: Interior group

(2) The Thaynes and Dinwoody Formations lie above the Phosphoria Formation while the Wells and the Monroe Canyon Formations lie below it

Field pH	Major ion concentrations in meq ℓ^{-1} (mg ℓ^{-1})							
	Ca^{+2}	Mg^{+2}	Na^{+}	K^{+}	SO_4^{-2}	Cl^{-}	F^{-}	HCO_3^{-}
6.6	44.9 (900)	22.6 (275)	3.8 (89)	6.4 (250)	18.7 (900)	1.1 (39)	0.10 (1.9)	46.4 (2830)
6.8	7.3 (147)	2.4 (29)	1.2 (27)	0.10 (3)	0.7 (33)	0.8 (29)	0.03 (0.6)	8.3 (505)
6.6	9.5 (190)	2.4 (29)	trace	0.03 (1)	1.2 (57)	0.2 (6)	0.02 (0.3)	10.2 (620)
6.3	14.2 (284)	3.6 (44)	1.1 (25)	0.20 (8)	3.0 (145)	0.9 (32)	0.05 (1.0)	14.3 (870)
7.5	3.0 (61)	1.6 (20)	1.0 (24)	0.05 (2)	1.3 (61)	0.7 (26)	0.02 (0.3)	3.0 (240)
7.4	3.1 (63)	1.2 (15)	trace	0.01 (0.5)	1.4 (69)	trace	0.01 (0.1)	3.2 (195)
7.5	3.9 (58)	1.7 (21)	0.3 (6)	0.03 (1)	0.3 (16)	0.1 (2)	0.01 (0.1)	3.8 (232)
7.5	3.2 (64)	1.7 (21)	0.3 (6)	trace	0.8 (38)	0.2 (7)	0.02 (0.4)	3.8 (232)
7.4	2.9 (59)	1.2 (14)	0.1 (2)	0.01 (0.5)	0.5 (22)	0.1 (2)	0.01 (0.1)	3.7 (226)
7.5	3.1 (63)	1.2 (15)	0.3 (8)	0.05 (2)	0.4 (17)	0.1 (5)	trace	3.9 (238)

TABLE 1.(cont)

Sample number	Spring (well) name	Discharge ℓs^{-1}	Temperature (°C)	Specific conductance (μmho cm^{-1})	log P_{CO_2} (atm)	SI_c(3)
1	Corral Creek	5	40	n/a	-0.2	17.90
2	Sinkhole	290	19	n/a	-0.2	1.13
3	Formation	490	11	920	-0.9	0.82
4	Henry Warm #2	55	20	1410	-0.6	1.31
5	Chubb	45	12	545	-2.2	1.04
6	Georgetown Canyon	410	7	n/a	-2.2	0.57
7	Auburn Fish Hatchery	140	9	440	-2.3	0.97
8	Sage Valley	245	12	460	-2.2	1.04
9	Crow Creek Ranch	160	7	360	-2.2	0.67
10	Knudsen Ranch	100	12	360	-2.2	1.13

(3)Saturation index of calcite (IAP/K_{eq}) at the measured temperature

δ^2H (vs SMOW ‰)[4]	$\delta^{18}O$ (vs SMOW ‰)[5]	$\delta^{13}C$ (vs PDB ‰)	$A^{14}C$ (pmc)	Estimated mean subsurface residence time (years BP)
-119	-18.4	2.2	0.80 ±0.14	$\left(36{,}500^{+4000}_{-3000}\right)^{(6)}$
-132	-18.2	-3.1	13.9 ±0.2	$12{,}500^{+2000}_{-1000}$
-139	-18.3	-1.7	12.2 ±0.1	$14{,}500^{+2000}_{-1000}$
-133	-18.4	-2.4	6.19±0.23	$20{,}500^{+5000}_{-2000}$
-136	-18.3	-9.0	44.1 ±0.6	1900±500
-131	-18.0	-9.6	59.87±0.63	Recent
-131	-18.5	-10.2	52.7 ±0.9	Recent
-130	-19.0	-10.0	52.7 ±0.9	450±200
-128	-17.6	-10.4	61.3 ±0.8	Recent
-131	-17.5	-11.2/ -11.3	61.7 ±0.8	Recent

(4) Analytical error interval for ^2H is ±3 ‰

(5) Analytical error interval for ^{18}O is ±0.2 ‰

(6) Maximum, see text

The concept, ground-water "age," is a difficult one. A volume of water issuing from a spring is the product of the admixture of many waters of diverse origins and histories. The water has no unique age. When differences between the chemical behavior of dissolved carbonates and the water have been accounted for, the ^{14}C in solution can give an idea of the integrated mean subsurface residence times of the water. Fontes and Garnier (1979) outline methods used to account for these differences. The mean subsurface residence time of a spring water is determined from the difference between the ^{14}C activity measured in the sample and the initial activity (A_o). The water derived its dissolved carbonate either from the absorption of CO_2 in the atmosphere or in the soil zone, or from the dissolution of mineral carbonates in the soil or in the aquifer. One method (Ingerson and Pearson, 1964) of estimating the fraction (F) of carbon derived from the gaseous reservoir is based on stoichiometry. Half the bicarbonate content and all the aqueous CO_2 content can be taken to be derived from that source according to the reaction

$$CO_{2(aq)} + H_2O + MeCO_3 \rightleftarrows Me^{2+} + 2HCO_3^-$$

Another method (Pearson and Hanshaw, 1970) depends on the similarity in ^{13}C and ^{14}C chemical behavior. When isotopic fractionation differences are accounted for, only the decay of ^{14}C differentiates between the behavior of these isotopes. Since ^{13}C must reflect all changes in ^{14}C content from recharge to sampling, it may be used to reconstruct the changes in ^{14}C activity due to all mechanisms except decay. These two methods estimate A_o using independent sets of variables to calculate F. If both approaches are valid, the equations for F may be set equal to each other and be solved for the variable known with least certainty. The carbonic acid (a), bicarbonate (b) and ^{13}C contents (δ_m) of the sample are measured. The $\delta^{13}C$ of the mineral reservoir presumably has not changed since the recharge occurred and therefore can be measured from well cuttings or outcrops. This leaves the ^{13}C of the soil gas at the time of recharge (δ_g) to be estimated by the relationship

$$\delta_g = \frac{a + b}{a + 1/2b} (\delta_m - \delta_c) + \delta_c$$

Calcium carbonate mineral samples at the springs at Sinkhole, Chubb and Sage Valley had δ_c values of 4.0, 2.6, and 3.3‰ respectively. These values, having a relatively small spread of 1.4‰, provided the data base for δ_c in δ_g and A_o calculations. The δ_g values estimated for Chubb Springs, the Periphery thrust springs sampled and Knudsen Ranch fall in the range of -19 to -24‰, which is consistent with the temperate forest environment of the area. The estimates of A_o obtained by the two methods converged at these values, suggesting the mean subsurface residence times of these springs as quite short. Chubb and Sage Valley Springs were calculated at 1900±500 and 450±200 years, respectively, while the other springs could be reconciled only with a modern gaseous carbon reservoir, possibly containing some anthropogenic ^{14}C from the bomb test era.

Similar convergence of modeled A_o values did not occur at realistic values of δg for the remaining four springs because of the remarkably high ^{13}C contents measured. These values suggest the evolution of a light gaseous component leaving isotopically heavy residual bicarbonate in solution. This is consistent with the evolution of $CO_{2(g)}$ at these springs, driven by the precipitation of travertine or with the evolution of methane. The values are consistent with observations made in other waters from carbonate terrains. Corral Creek and the remaining Periphery extension springs show high discharge temperatures and are near saturation or are supersaturated in calcite. Although some of the other spring waters are also near calcite saturation, they are cooler, have appreciably lower bicarbonate concentrations, and do not precipitate travertine. The initial ^{14}C activities of these four springs were modeled with only the stoichiometric approach modified to account for fractionation. The Periphery extension springs showed mean ground-water residence times of $12{,}500\pm^{2000}_{1000}$ to $20{,}500\pm^{5000}_{2000}$ years, while Corral Creek showed a value of $36{,}500\pm^{4000}_{3000}$ years. This last result can only be interpreted as very old water, since assigning a numerical age to water with measured ^{14}C activity of 0.80±0.14 pmc is very uncertain due to potential contamination and to the extreme sensitivity of the radioactive decay equation at this activity range. The evolution of $CO_{2(g)}$ from these waters will cause an increase in ^{14}C as well as in ^{13}C. This can be on the order of 2 pmc, which would correspond to an underestimate of residence times on the order of 3000 years. This is reflected in the error intervals assigned in the table. Another potential source of error is the possible introduction of ^{14}C-free bicarbonate into solution from the thermal decomposition of mineral carbonates. The low maximum water temperatures indicated by the $^2H/^{18}O$ data suggest that this has not occurred in these waters, although the possibility of this mechanism cannot be ruled out.

PROPOSED FLOW MODEL

The geologic, chemical, and isotopic data collected during this investigation may be used to help define the nature of ground-water flow patterns in the Meade thrust allochthon. A preliminary three-tier ground-water flow model is proposed. Possible flow patterns are illustrated in figure 5.

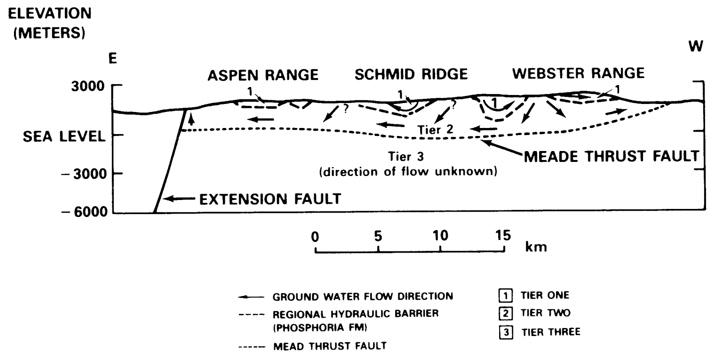

Fig 5. Postulated three-tier ground-water flow model in the Meade thrust area

1) The very short residence times of ground-water flow systems which are contained in the formations above the hydraulic boundary created by the Phosphoria Formation have been confirmed by ^{14}C methods. Such residence times are consistent with the shallow, intra- and inter-basin flow systems in the interior of the allochthon. These systems constitute the first tier.

2) Short mean residence times were determined for ground-water flow systems which discharge from Periphery thrust springs. These springs occur at the base of the Webster Range and appear to be recharged in the higher elevations of the range. Most of those systems constitute the eastern lobe of the second tier. The northernmost springs of this group are part of the first tier.

3) Long mean residence times were determined for ground-water flow systems discharging from major exterior faults which truncate the western periphery of the allochthon. These hot, carbonate-laden waters appear to be contained in the formations below the hydraulic barrier created by the Phosphoria Formation, and constitute the western lobe of the second tier. An apparent ground-water divide separates those lobes. The appreciably different ground-water residence times in the lobes result from the much greater distance from the recharge area in the western lobe (see Fig 5).

4) A maximum circulation depth of ca 1900m below land surface is suggested by the ^{18}O data and the regional geothermal gradient. Thus, circulation of ground water in the second tier probably is restricted to the allochthonous strata. Possible circulation in the lower plate is designated as the third tier. There is no evidence to suggest that water from the third tier is contributing to circulation in the overlying tiers.

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