AN ATLAS OF THE GEOTHERMAL RESOURCES OF
VIRGINIA AND WEST VIRGINIA

with

Plates, Commentary, and Figures

by

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INTRODUCTION

A high density of thermal springs having orifice temperatures up to 40°C has long been known for the Appalachian border region of Virginia and West Virginia. This occurrence, unusual for Eastern United States, has led to considerable speculation as to the origin of the heat, its ultimate temperature at depth and its potential application as a geothermal resource. The present demand for energy and the existence of an expanding Eastern market prompted AMAX Exploration, Inc., to examine the resource potential and carry out exploration surveys. While most investigators concede that a substantial reservoir of low-enthalpy waters (100°C or less) probably is obtainable, recent discoveries of Tertiary volcanics and the probability of a pluton underlying the area, provide an argument for a possibly higher temperature resource. A 30km-long electrical resistivity anomaly is one indication of its possible extent.

The following plates summarize in a pictorial way the rationale for a viable geothermal resource in the Virginia thermal area. Testing of the conclusions is well within the technology of present-day geophysics, so that recommendations for targeting a deep drill hole are made at the conclusion of this report. Whether for hydrocarbons or geothermal fluids, it seems inevitable that a deep hole will be drilled in the area. For the purpose of understanding and evaluating the geothermal reservoir, it is imperative that such a probe be based on the results of a systematic exploration program guided by the evidence supplied by many disciplines as outlined below.

PLATE I
REGIONAL SETTING

The thermal springs of the central Appalachians are in the Valley and Ridge physiographic province that extends generally northeast/southeast along the western border of Virginia. The province is characterized by undulating topography resulting from intensive folding. A succession of upwarped anticlinal ridges and downwarped synclinal valleys extends from the Shenendoah Valley on the east to the Allegheny plateau on the west (Figure 1). A maximum altitude of 1480m (4850ft) is attained in the Elkins Valley anticline of West Virginia. Typical relief from ridge tops to stream valleys is about 600m (2000ft). The Valley and ridge province merges into the Plateau westward where the undulations gradually decrease in amplitude and become nearly horizontal toward central West Virginia. The province is terminated abruptly on the east by the overthrust Blue Ridge composed of older crystalline rocks.

Because of the higher altitudes of the anticlinal ridges, erosional processes have proceeded there more rapidly, causing their strata to be dissected, or "breached". Thus narrow anticlinal valleys have developed parallel to structure, exposing Paleozoic carbonate rocks, as old as Ordovician age in the thermal area. Being soluble in descending groundwaters charged with carbon dioxide, these rocks have been dissolved out to form extensive caverns and sinkholes of a karst topography, wherein runoff and streams funnel downward into limestones and dolomites, instead of flowing normally along the surface (Figure 3). Where streams have overflown onto the surface, they have been pirated by gaps in the walls of the anticlinal valleys to drain into the neighboring synclinal valleys composed of younger, generally clastic rocks. The Warm Springs valley is thus drained to the Jackson River on the west. Where these gaps intersect the valley axis, we find thermal springs upwelling from caves and karst channels to pour immediately through the gaps where they mingle with surface runoff (Figure 2).

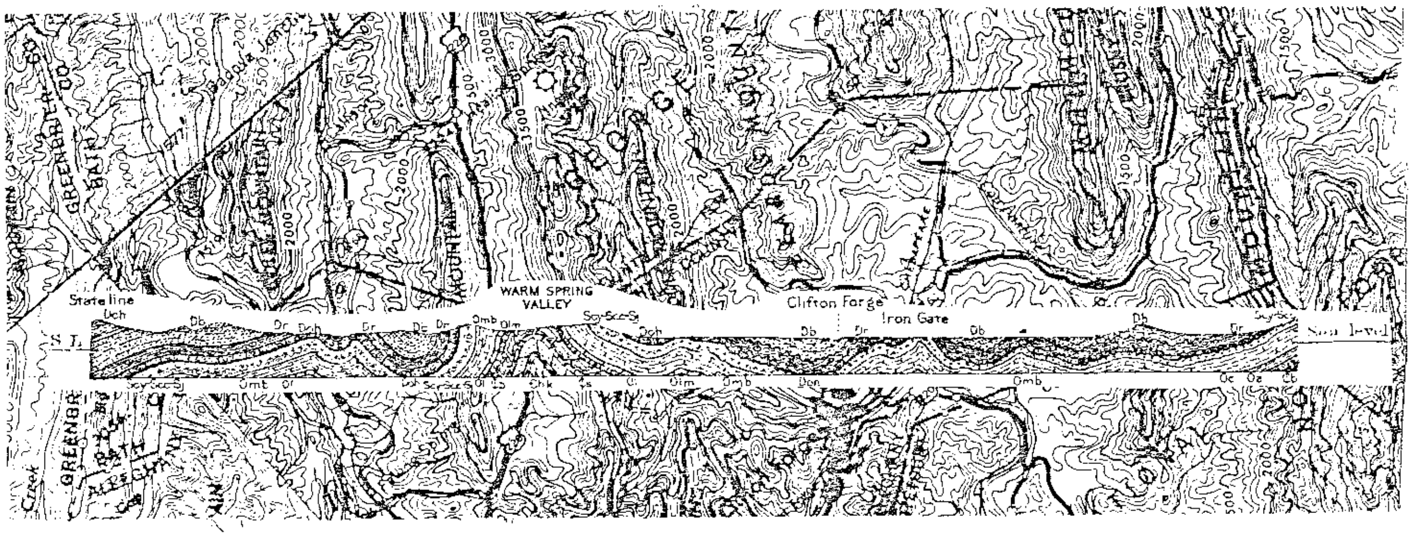

Figure 1. Northwest/southwest profile across Warm Springs anticline, showing the undulatory nature of the structure.

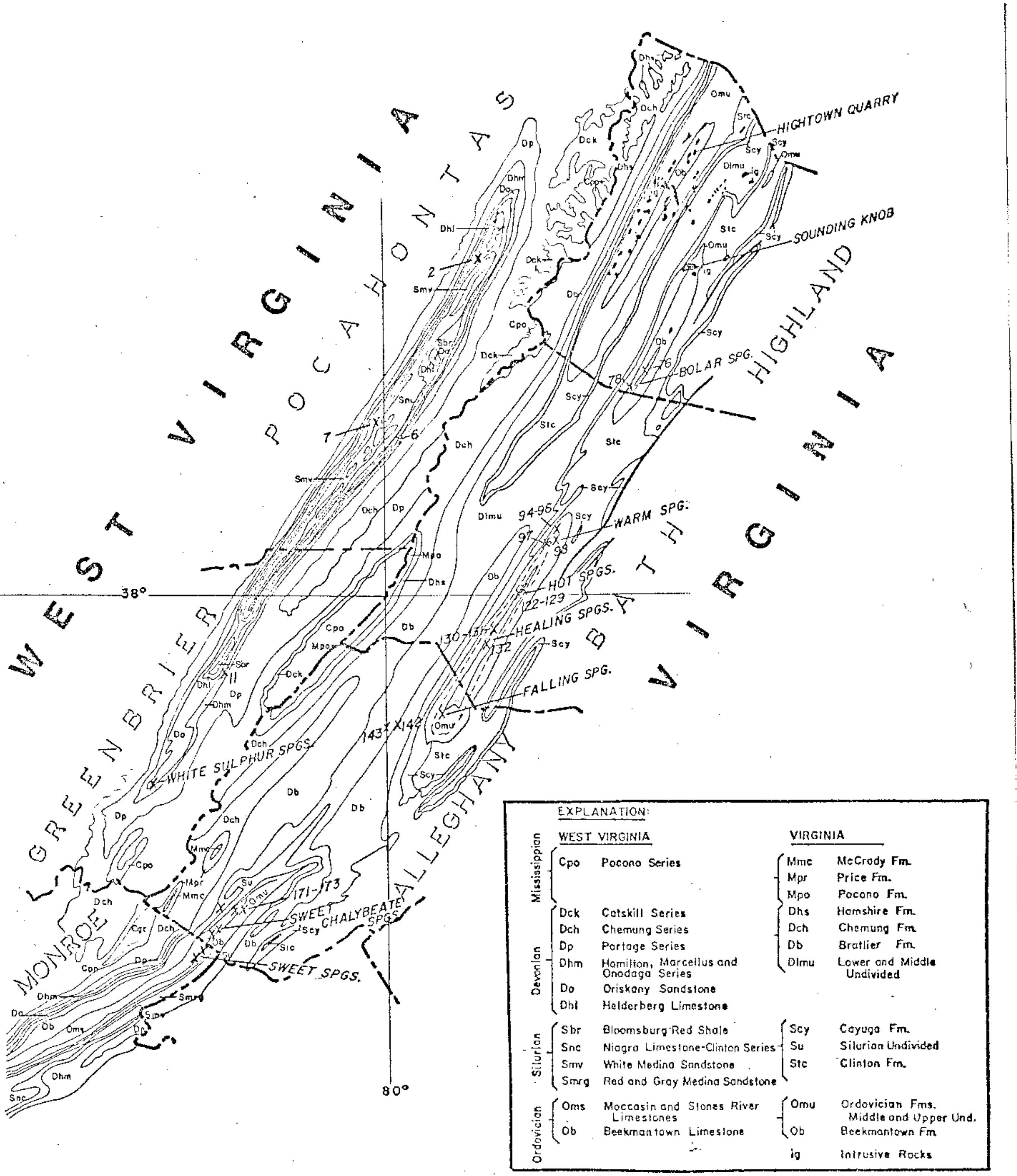

Figure 2. Relationship of major thermal springs to anticlinal structure.

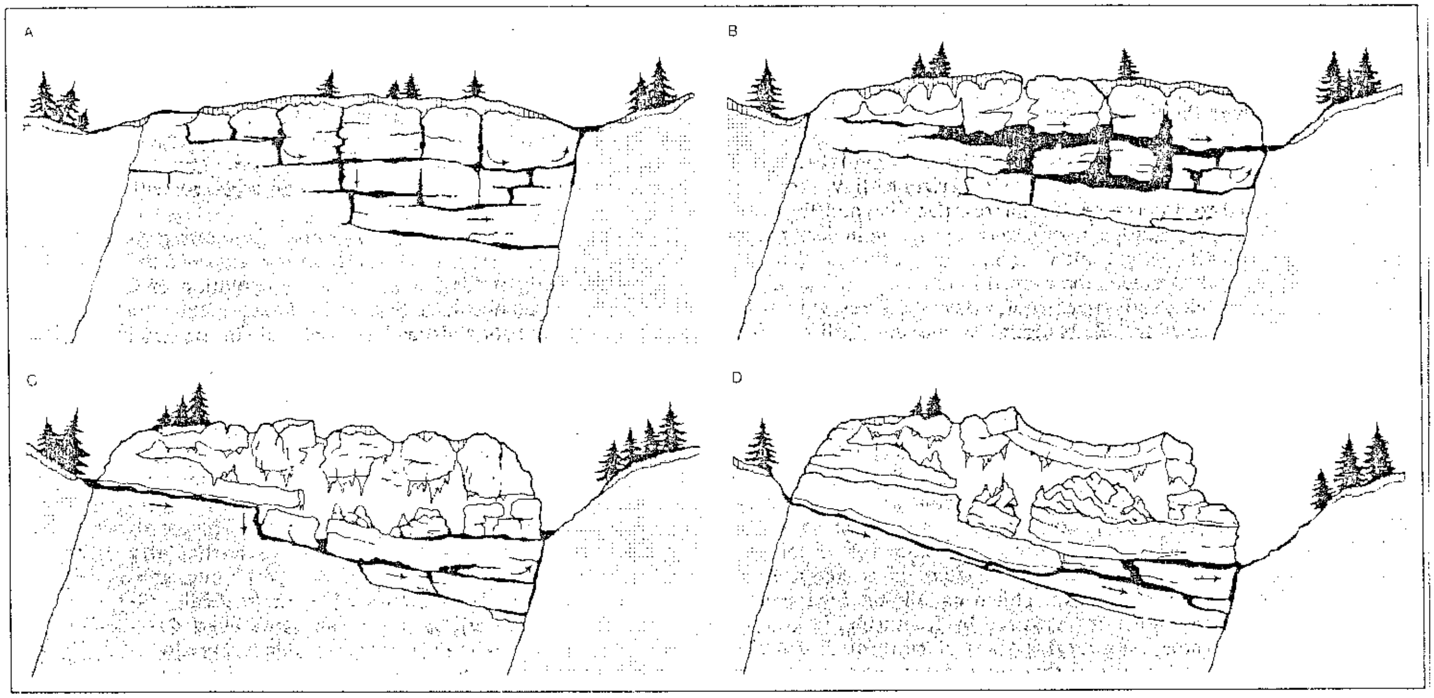

Figure 3. Evolution of a limestone cave system. (A) Fracture pattern conducts surface drainage toward discharge in a subriver spring along contact with nonsoluble terrain. (B) Low resistance paths enlarge by solution into trunk channels causing water levels to fall and sinkholes to form on the surface. (C) Deepening stream on the right drains upper portions of cave, inducing local collapse, while carbonate deposits form from trickling water; surface stream on the left has been pirated to the underground system. (D) Surface erosion and stoping from below result in extensive collapse of the cave roof, while solution continues along deeper fracture paths. (from Lange (1974))

PLATE II
THERMAL SPRINGS

The Virginia thermal spring area straddles the West Virginia boundary from about the Narrows, west of Roanoke to Berkeley Springs, West Virginia, near the Maryland border. Most have been well known for 150 years or more and have provided the locus of a thriving industry of spas during the 19th Century (Reniers, 1955). The highest density and hottest springs occur in the Warm Springs anticline (cf. Plate I). Some are clusters of individual springs, having temperatures of about 16 to 40°C where the ambient temperature is about 10-12°C. They discharge at elevations of about 700m (2300ft), 250m (800ft) above the Jackson River base level to the west.

Significant warm springs occur in the Bolar anticline to the north, in the Browns Mountain anticline to the west and in the anticline to the southwest of Covington. In addition, a halo of tepid springs appear as far east as the Shenendoah Valley and south-and northward, generally within the green line on the plate. Discharges range from mere seepage up to 94l/sec (1500gpm) at Bolar Springs.

That the springs discharge from carbonate caves is evident at several sites: 1) At Bragg Spring one can peer down into a water-filled cavern. This water discharges farther downstream at Bolar Spring, after having been cooled several degrees by mingling cold waters. At Warm River Cave, one can climb down through a sinkhole to the stream level 54m below, where a cold stream (16°C) is seen to join a warm stream (27°C) that flows along a cave passage to the orifice (Falling Springs) where it discharges at temperatures of 18 to 24°C, depending on the time of year. Descending meteoric waters collected in the karst basins mingle underground with the ascending hot waters, rendering the interpretation of chemical properties of the water difficult. Furthermore the standard geothermometric procedures for determining fluid temperatures at depth fail in a carbonate environment. Particular elements, nevertheless, have provided a clue to the nature of the hot waters. According to Hill & Roberts (1973), "The Virginia thermal springs are anomalously enriched in lithium and flourine over the other alkali metals and halogen elements... The area is anomalous in respect to elements that could be steam distilled from an intrusive body of molten rock and condensed by ground water."

Many of the springs deposit travertine at their orifices, and Falling Springs in particular has built up a 30m wall of travertine that forms a kilometer-long dam across the south end of Warm Springs Valley. Trace element analysis of similar spring deposits from Warm Springs revealed anomalously high silver, lead, antimony, and particularly tungsten. With regard to the latter, the analyst comments, "Its anomalous presence in Travertine A-3 supports a hydrothermal origin for at least part of the waters at Warm Springs" (Andrews-Jones, 1973).

PLATE III
CRUSTAL STRUCTURE

Seismic wave arrivals from explosions set off in the Atlantic Ocean were recorded by the U.S.G.S. as a refraction experiment. The waves arriving across the thermal area of western Virginia were delayed by more than 5 seconds in their passage up from the mantle, relative to their travel times elsewhere. James et al. (1968) have interpreted these seismic delays in terms of a very thick crust--almost 60km thick, exceeded nowhere else in the U.S.

Several consequences of the presence of great crustal thickness are observed in the plates dealing with gravity and magnetic responses. One effect, in particular, can have a bearing on the unusual localization of the thermal springs. Under the normal Eastern U.S. temperature gradient of about 13°C/km, we can expect to find basalt and granite (in the presence of water) beginning to melt at a depth between 35 and 45km. Thus in the thermal area of Virginia we may expect to find 10 to 20-km thick layer of molten or partially molten crustal material atop the mantle. This is in line with conclusions drawn by Tuttle & Bowen (1958):

> "If the water content of a segment of the earth's crust is on the order of 1-2 percent by weight and the composition is approximately that of the average granite a zone of melting at least 10 km thick will result.
>
> It is not unreasonable to expect that at depths of 35-40km basalt could become partially liquid and that the liquid would have a composition not far from that of the andesitic rocks. If the unmelted portion then settled out, and the andesitic liquid, displaced upward, crystallized in an environment where an opportunity for settling of crystals still prevailed, liquids of granitic composition could result....It is probable that granitic liquids exist at all times beneath these thick sedimentary sections if the chemical composition is appropriate."

The presence of a lens of molten material, be it granite or basalt, would not in itself result in higher heat flow or thermal waters, since the pool is a result of the normal geothermal gradient. However, because of the length and breadth of the 55km-crustal thickness anomaly (approximately 80 x 30km) we might suspect discrete vertical migrations along crustal fractures, resulting in localized heating in the upper crust, and occasional volcanism, such as has occurred several times during the geologic history of the area. It is these apopheses of volcanism that have heated the area in the past, and may still have an influence on its groundwaters.

PLATE IV
BOUGUER GRAVITY

As is to be expected from James' deduced thick crust, a corresponding Bouguer gravity low is found to encompass the thermal area (cf. Plate III). This occurs because the acidic crustal rocks are generally lighter than those of the mafic mantle which they have displaced at depth. If a lens of partial melt is present at depth (as discussed above), its still lighter density would further enhance a negative gravity anomaly at the surface.

In addition to the regional effects, local gravity anomalies have been mapped by Kulander & Dean (1978) in West Virginia, Johnson (1972) in Virginia, and by Geoterrex Ltd. for AMAX Exploration, Inc. The principal gravity lows (terrain corrected) resulting from the latter survey are shown in green on the Plate. Since some of these flank the Warm Springs anticline where upturned shales crop out, Kulander & Dean attributed them to the exaggerated thickness of these shales. At localities where they observed localized highs (such as the southeast limb of Warm Springs anticline) they attributed the higher gravity response to a thicker section of dense carbonate rocks resulting from replication of beds by local thrust faults (splay faults). These explanations are reasonable; neverless, we should also note the coincidence of a gravity low west of Hot Springs with the major electrical resistivity anomaly (Plate X) and the fact that gravity lows intervene as well between the electrical feature and the line of spring orifices.

PLATE V
MAGNETICS

Once again, when we compare the crustal thickness map (Plate III) to that of the simplified aeromagnetic map, we observe that the effect of the thick crustal section is a broad magnetic low straddling the Appalachian range. The zone of lowest magnetization runs approximately eight kilometers east of the line of thermal springs. A conspicuous magnetic high extends parallel to the Warm Springs anticline--between it and the Browns Mountain anticline to the west, which likewise contains a chain of thermal springs. The presence of the magnetic high has resulted in an apparent shift of the low axis eastward from the so-called keel line of greatest crustal thicknesss.

Since crustal rocks are normally less magnetic than mantle rocks the broad magnetic low is to be expected to align with the axis of crustal thickening. The presence of partial melt, or mere heating above the Curie temperature (400 - 500°C, in felsic plutons (Byerly & Stott, 1977) would enhance the magnetic low, provided that the anomalous temperatures are localized by crustal.structure, or higher geothermal gradients.

Kulander & Dean (1978) modelled the magnetic high west of Warm Springs and interpreted it to be a mafic pluton whose top lies 6km below the surface and about 1.5km above the basement surface. In their words:

> "The anomaly's large amplitude, wavelength, and depth suggest its origin, however, is near the basement surface and not attributable solely to basement relief. A minimum susceptibility contrast computed from the Browns Mountain anomaly yields 0.001 cgs units.
>
> A feasible model would be a mafic intrusion into a granodioritic host rock."

While the age of this intrusive is unknown, basaltic outcrops do outcrop in the northern end of the thermal area. Two of these appear as small bulls-eye anomalies southeast of Monterey. Their age is discussed in the next section.

PLATE VI
IGNEOUS ROCKS

Felsic and basaltic rocks of Highland and adjacent counties have long been the subject of speculation and until 1969 all had been regarded as being of Jurassic age and older. Indeed Triassic and Jurassic igneous dikes and sills outcrop from the West Virginia eastward to the Shenendoah Valley along an east/west lineament of still older igneous bodies that can be traced westward to Kansas (38th Parallel lineament). Darton & Keith in 1898, described one particular basaltic eminence, (cf. Plate V) as follows:

> "The outcrop No. 16 at Sounding Knob is on the top of a high anticlinal mountain of Tuscarora (Medina-Oneida) quartzite, the igneous rock rising as a steep-sided neck about 80 feet above the crest line. The altitude of its summit is nearly 4500 feet...
>
> Section No. 16, taken from Sounding Knob, displays the most clearly fluidal arrangement. In this area of the basalt it is evident, from the appearance of the rock mass upon the ground, that it was an old volcanic neck and was produced by an injection of considerable height."

In 1971, Fullagar and Bottino published dates for felsite dikes in the vicinity of Monterey of 47 million years (Eocene epoch). Subsequently, their dates have been substantiated by other investigators, including Geochron Labs for AMAX; and by diverse methods: potassium, argon, rubidium-strontium and paleomagnetic dating. AMAX has since dated basalts of Sounding Knob as 54my and basalts immediately to the north at 47my. Hydrothermally-altered basaltic dikes in drill holes of the VEPCO damsite in western Bath County, were dated as 47my. A still younger basalt outcrop at Trimble Knob just south of the town of Monterey, has been dated at 34my (Oligocene epoch). A basaltic outcrop at Mole Hill, 28km east of Monterey has been dated at 47my (Wampler, 1975), giving an east/west extent of Tertiary volcanism of nearly 60km. The Mole Hill basalt outcrops 8km north of the Bridgewater warm springs in the Shenendoah Valley. Core, Sutter & Fleck (1975) interpret these evidences as follows:

> "Several possibilities exist for the generation of this Eocene activity. Suggestions include, the presence of a large intrusive body at depth in this area; a change in direction of North American plate motion at about 40my B.P. from southwesterly to southerly causing tensional stresses trending E-W; passage of the 38th Parallel Fracture Zone over a hot spot in the mantle at this point in time."

The dating of the Tertiary volcanics prompted Dennison & Johnson (1971) to propose that the thermal springs are directly related to an extensive felsic pluton beneath the area. They roughly delineated the intrusion by the -70mgal contour line of the Bouguer gravity. They conclude:

> "The data on thermal springs and gravity suggest that the center of the Eocene pluton is some 20 mi southwest of the position of outcropping felsite dikes and sills in Highland County. Information presently available does not show us whether the thermal springs and gravity minimum are relict phenomena related to the Eocene volcanism or whether they possibly represent a still younger deep source of heat (volcanism)."

Magnetic evidence has subsequently postulated the existence of a buried pluton centered between 30 and 50km (about 20 to 30 miles) southwest of Monterey (Kulander & Dean, 1978) (cf. Plate V).

PLATE VII
SCHOOLEY EROSION SURFACE

The highest ridges of the Plateau and the Valley and Ridge have long been recognized as a former erosion surface, originally described by Wright (1925) as the Upland, or Schooley Peneplane. He determined the approximate age for this surface to be Cretaceous or early Tertiary. Dennison and Johnson (1971) simplified and extended Wright's map (1925) of the erosion surface contours (Figure 11) noting:

> "The position of maximum uplift of a dome on the Schooley surface with 1000ft of arching is remarkably close to the presumably younger (Eocene) intrusions in Highland County. This association is even more striking when it is realized that the general scarcity of preserved uplands in Virginia prevents detailed reconstruction of the Schooley surface."

From this relationship they infer the following:

> "Thermal and mechanical energy (diapiric action) of an igneous intrusion below could upwarp the erosion surface. The near-coincidence of maximum domal uplift with the present known site of Eocene intrusion suggests a causal relationship."

In a similar vein, Dennison & Nunan (1975) encountered a local upwarp of strata, during their mapping of geology around Warm Springs for AMAX (Dennison & Nunan, 1975).

> "The Bacova Junction syncline is not a major syncline extending to full depth. It is much higher in elevation than is usual for a one-layer structure. The elevation of the Oriskany Sandstone is about -600 feet, compared with an expected elevation of -5300 feet if this was a full-depth major syncline. Some mechanism must be used to account for this 4700 feet discrepancy of Oriskany position.
>
> One possible mechanism is multiple stacking of structural layers, with the 4700 feet corresponding to the thickness of the extra stack of rocks.
>
> Another mechanism is to insert another kind of rock material to raise the Bacova Junction syncline. In our diagrams we postulate a sill-like Tertiary pluton to fill the void. This has the advantage of producing the abnormally high elevation of the crest line of the Warm Springs Valley anticline south of the plunge of the Wills Mountain and Big Valley (near village of Bolar) anticlines, resulting from uparching of the earlier decollement above the sill. The mechanism also causes the higher elevation along the Bacova Junction syncline. Needless to say, a still-cooling, solidified pluton would be an attractive heat source for the thermal springs of the district.

> Arching of the decollement by a Tertiary sill could explain several geologic anomalies in Bath, Highland, and Pendleton Counties:
>
> 1. Source of heat for thermal springs, especially if thicker and cooling more slowly in the south.
>
> 2. The only occurrences of Beekmantown (= upper Knox) dolomite in the western anticlines from Pennsylvania to the southwest Virginia imbricate fault slices. Regional uplift by the sill could raise the general level of the anticlines upward without requiring multiple tectonic slices and without affecting the generally planar nature of the top of basement <u>beneath</u> the sill.
>
> 3. Patterns of warping of the Schooley Peneplain as outlined by Dennison and Johnson (1971).
>
> 4. Regional Bouguer gravity negative anomaly, if the sill is still hot and not as dense as cold rock."

Supportive evidence of an intrusive was found from research on conodonts (thermally affected fossil teeth) by Epstein et al (1975). They report:

> "CAI (Conodont) isograds for Ordovician and Upper Silurian-Lower Devonian rocks have been superimposed on maximum isotherms for hot springs. The western bulge of the isograds in northern Highland County on both maps can be explained by a higher than average heat flow associated with the known Eocene intrusions in that area. Known overburden alone could not account for the high CAI values......The isotherm configuration and the CAI highs may be related to a buried pluton from which the waters in the area derive their heat."

PLATE VIII
SEISMICITY

Natural earthquakes have been found to relate to geothermal systems in the following ways:

a) Microearthquakes: (attributed to a slowly expanding thermal shock wave) occur in swarms around the thermal area (Ward, 1972: Lange & Westphal, 1969):

b) Seismic waves passing through a geothermal reservoir are delayed or accelerated, attenuated or enchanced, by lithologic properties of the reservoir (Majer & McEvily, 1979):

c) Shear waves passing through a magma chamber or zone of partial melt are attenuated or completely absorbed, while higher frequencies of compressional waves are filtered out (Matumoto, 1971) (Horai & Simmons, 1968).

In 1973, Virginia Polytechnic Institute monitored the thermal area for seismicity, using roving seismographs. Bollinger & Gilbert (1974) report on the results of the work:

> "A swarm of 43 microshocks was recorded at the Duncan Knob Station over the 4-day period, June 18-22. These events generally had an S-P time of less than 0.2 sec and were, therefore, within 2 km of the instruments (Figure 6). Unfortunately, the swarm stopped before the other instruments could be moved into the area. Record amplitudes of the microearthquakes ranged from 2 to 7.mm, implying magnitudes between approximately -1.2 and -1. A tendency toward swarm-type episodes has been noted for some major geothermal areas (Ward, 1972) but this is the first such observation for a thermal springs area."

In November 1973 AMAX commissioned a microearthquake survey at six sites during a 10-day interval. Although only one local event was detected, it appeared almost simultaneously on all stations, indicating that it occurred at great depth. Furthermore, its waveform contained a nearly single frequency (2hz), and exhibited no shear wave. Because no shocks were reported worldwide at this time, the occurrence is believed to be a local microearthquake originating at a depth near the mantle, with an epicenter due west of Bolar Springs (the southern extremity of volcanic outcrops). The record has the appearance of seismic waves passing through molten material.

The Charleston, South Carolina, earthquake of 1886 was felt over a wide area of Eastern U.S. as far north as New England. Dutton (1889) noted, however, a shadow or, "dead" zone, wherein residents did not feel the shock (orange on the plate). A similar zone of dampening was observed by Bollinger & Hopper (1969) during the Elgood, West Virginia, earthquake of 1969 (yellow contour).

Commenting on the seismic behavior of the area, Bollinger and Gilbert (1974) conclude:

> "....the thermal springs region of Virginia and West Virginia correlates spatially with the eastern half of the "earthquake shadow." If the 2 to 10-sec-period surface waves from the Charleston shock carried the greatest particle velocities (Nuttli, 1969) in the Virginia-West Virginia border region, then perhaps a still-cooling pluton in the crust could have contributed to a marked absorption in that area.
>
> Also relevant here are two additional points: a gap in historical seismicity, and a thick Appalachian root as interpreted by James et al. (1968). Figure 4 depicts the gap that is present in the general northeast-southwest trend of Appalachian seismicity in the Hot Springs area. From their studies of the ECOOE data, James et al. (1968) mapped crustal thicknesses from about 30km on the coastal plain to nearly 60km under the crest of the Appalachians. A relatively hot crustal mass could be an influencing factor in both of these observations."

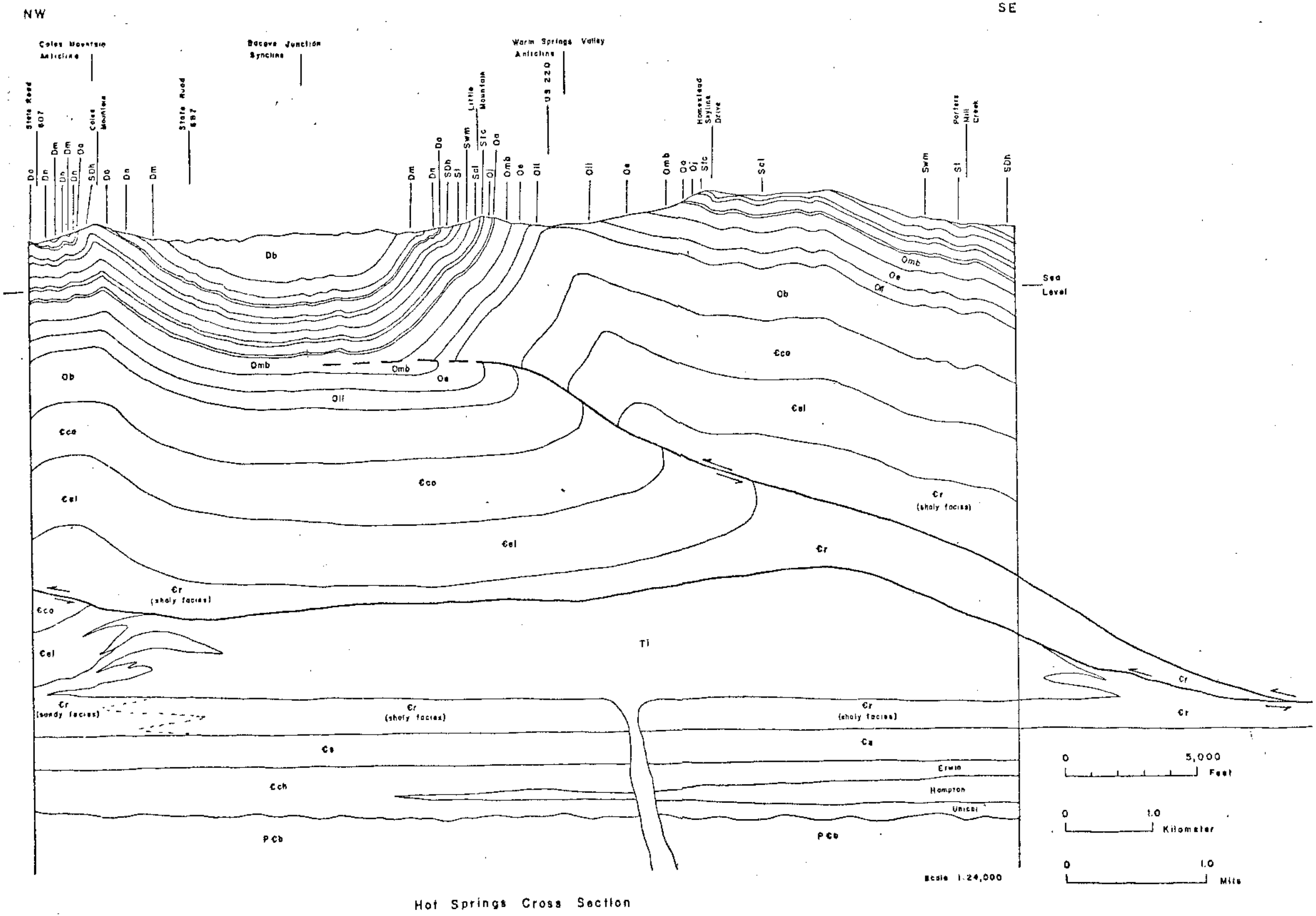

Figure 4. Detailed cross-section through Hot Springs, showing postulated intrusive body (Ti) (Dennison & Nunan, 1975).

PLATE IX
HEAT FLOW

The most powerful tool of geothermal exploration short of deep drilling is the heatflow survey. Temperatures are logged in boreholes or available wells and temperature gradients determined. The product of gradient times thermal conductivity of the rock yields heatflow, a measure of the rate of thermal energy rising toward the surface. Normal gradients and heat flows in western U.S. are about 25-30°C/km and 1.5-2.5hfu (heatflow units): in eastern U.S., values of 10-15°C/km and 1.0hfu or less are the rule.

To be effective, temperature surveys must involve numerous holes including some sufficiently deep that they penetrate below convective groundwaters and near-surface warm water acquifers. Many deep wells have been drilled on thermal anomalies that disappeared when the drill bit passed below shallow aquifers.

Thermal gradient logs were obtained by Costain (et al.) (1976) from 3 sites in the thermal area:

a) A cluster of 4 holes in synclinal rocks in a ridgetop at the VEPCO damsite in western Bath County ranged in depth from 400 to 560m. Measured gradients varied from 7 to 47°C/km. Normally, one finds that temperature gradients decrease with depth; here, on the contrary they increase towards the hole bottom. Two of the wells exhibit gradients at depth (25, 31°C/km) that are unusually high for eastern rocks, corresponding to heatflow values of 1.5-1.6hfu. If terrain corrections for the narrow ridge were applied to these data, the figures would increase by 20 to 30%. It appears that only toward the bottom of these holes, we begin to penetrate beneath the cold groundwaterr egime to experience gradients increasing downwards.

b) At the south end of Warm Springs anticline, Costain drilled a well to 305m in soluble dolomite of a sinkhole karst wherein meteoric waters funnel downward. It is no surprise that the upper 260m of the resulting thermal log yield very low and negative gradients. In the lowermost 50m, the log stabilized to a 10°C/km-gradient corresponding to 1.2hfu. Costain concludes that this 50m segment is typical of the area.

c) Finally, a well drilled in dolomite to 220m at the Homestead at Hot Springs produced an increasing gradient of 90 to 190°C/km (7 to 15hfu). Because of its proximity to the springs, however, we might attribute the exceedingly high result to a near-surface aquifer of hot water.

Due to the presence of erratic near-surface hot and cold water zones in karst environment, a heatflow survey in the area will require many more than 3 sites, and at least several holes to depths of 500m or more, prefereably in clastic rocks.

PLATE X
ELECTRICAL RESISTIVITY

Electrical surveys are run in geothermal areas in order to map electrically conductive hot waters at depth. Active methods apply or induce a current into the ground and measure voltage differences in a region around a current source. Passive methods utilize natural earth currents and magnetic fields. Conductive zones, mapped by these methods must be interpreted with caution to insure that they do indeed arise from hot brines and not conductive shales, evaporites or graphites.

Keller & Crewdson (1976) report on an active electrical survey undertaken for V.P.I. in the thermal area. Three methods were employed (bipole-dipole, dipole-dipole, and Schlumberger soundings). Several conductive zones were indentified from the first method (shown in green on the Plate), whose resistivities were found to be considerably lower than those measured by 27 Schlumbereger soundings for the lithologic environment. In addition, they ran a dipole-dipole line between Hot Springs and Falling Springs, along the valley axis. The northern half of the line (Hot Springs to Healing Springs) contained resistivities below 1 ohmmeter; the southern half gave much higher values. Regarding these findings, the authors conclude:

> "The most striking feature of the dipole resistivity maps is the area of low apparent resistivity between Warm Springs and Healing Springs, and apparently extending to the east beneath Warm Springs Mountain. This low is bounded to the north and to the south by east-west striking bands of moderately low resistivity, which appear to be associated with windgaps and other topographic expressions of east-west striking structural features. The lower resistivity in this area could be explained by any of a number of factors, including an increase in average porosity over the section by a factor of 1.2 to 2.5, an increase in average salinity of groundwater over the whole section by a factor of 1.5 to 5, or an increase in temperature over the whole section by 100° to 200°C. There is no surface evidence for highly saline groundwaters, and so, it is likely that the low resistivity is caused by fracture-induced porosity in the section and/or elevation of temperatures."

A magnetotelluric survey utilizing natural electromagnetic fields was operated by Terraphysics for AMAX. The survey discovered a persistent conductive zone underlying the Bacova syncline west of Hot Springs for a distance of 30km. In his report, Mazzella (1976) writes:

> "It is perhaps significant to note that the synclines and anticlines repeat about every 3 to 6 kilometers. Low apparent resistivity values on the order of 180 to 300 ohm meters are associated with these and other synclines....These values are about what one would expect on the basis of the computer results of the model in Figure 14, the model without the conductive zone at depth. Thermal springs do not occur with these other synclines.

The results suggest that the reservoir for the thermal waters at the Hot Springs, Warm Springs and possibly the Warm Springs Cave lie to the west in the Bacova Junction synclines and ascend the Warm Springs anticline in the limestone and dolomite formations."

CONCLUSIONS

Evidence from gravity, magnetics, and seismic refraction surveys corroborate the argument for an exceptionally thick crust beneath the Virginia thermal spring area. As a consequence, molten or partially molten lenses can be expected to reside at depth--a deduction reinforced by several lines of seismological evidence. The wide distribution of igneous rocks and the recognition from magnetics of a deep intrusive demonstrate that molten material has migrated upward as recently as Oligocene time (34 million years). Doming on a regional as well as local scale accompanied the intrusions and contemporaneous heating is indicated from paleontological evidence. Latent heat from the dated and possibly undetected younger volcanic events could explain the unusual localization and high density of thermal springs in this area of Eastern United States.

Electrical measurements suggest a migration of thermal fluids from the synclinal zone on the west, upward along bedding to their locus of discharge from carbonate caverns exposed in the breached valleys of the anticlines. A considerable fluid potential and temperature must exist at depth in order that the thermal fluids overcome the downward movement of meteoric waters in karst collecting basins and still emerge as recognizable thermal springs.

Testing of these conclusions may be made using the following methods:

1) Acquisition and examination of existing proprietary seismic reflection profiles;

2) Deep electrical soundings by magnetotellurics and/or electromagnetics;

3) A network of thermal gradient holes extending from 300m to 600m or more.

4) A deep test targeted on results of the above.

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