A CONTINTENTAL HOT-SPOT

by

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Summary

The Snake River Plains and Yellowstone Park provide us with one of the classical sites of recent volcanic activity. The history of the volcanic activity in both areas is describe together with the relationship of the activity with Plate Tectonics and mantle plume theories. Details of the caldera formation in Yellowstone Park are described, as are the world famous geothermal features. Much discussion revolves around the topics of possible further volcanic eruptions in Yellowstone Park. Geophysical evidence helps us to make some evaluation of the prospects of future activity in the area.

Introduction and Location

Fifty million years ago, a mantle plume with its surface expression, a hot-spot, was present in the Pacific Ocean off the Oregon coast of North America. During the period from then to the present, the American Continent has moved steadily west-south-westwards at an estimated speed of about 4 cm per annum and, in the process, has overridden marginal parts of the Pacific Ocean including the hot-spot. During the Pliocene, Pleistocene, and Holocene, this movement has resulted in the hot-spot being centred at progressively more easterly positions on the continent of North America, initially through southern Idaho and then to its present position in Yellowstone Park in Wyoming. The result of the movement has been a trail of volcanic activity left across this area of the U.S.A. indicating the progression of the lithosphere over the hot-spot. This resulted in the vast outpourings of lavas which produced the Snake River Plateau in southern Idaho and the quite remarkable volcanic events which have occurred in Yellowstone and its environs during the last two million years or so.

The Snake River Plateau and Yellowstone are located geologically in the young fold mountain belt of the Cordillera which extends along the western sea board of both North and South America. In the immediate neighbourhood of the Snake River Plateau and Yellowstone are the Basin and Range fault blocks and grabens occurring to the south, the Green River sedimentary basin to the southeast, the Middle Rockies to the east and the Columbia Plateau to the northwest.

The presentation of this address is possible as a result of 5 visits to this area during the last 10 years together with the extensive use of the vast amount of published literature. Many of the thoughts about the area have been developed by colleagues and students who have visited the area with me.

The Snake River Plateau

Introduction

Together with the Columbia Plateau, the Snake River Plateau forms one of the largest areas of continental basaltic lava outpourings anywhere in the world. Only the Deccan Plateau of India is larger.

The Columbia Plateau is considerably larger than the Snake River Plateau and has a history dating back to the Miocene period about 25 million years ago. In both the Snake River and Columbia Plateaus, the original

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relief was considerable and the initial volcanic activity, largely acidic and intermediate, produced accumulations of volcanic material which filled depressions, levelling the topography and eventually forming a fairly monotonous flat plateau area.

History of the Development of the Snake River Plateau

The Snake River Plateau itself is really a smaller version of the Columbia River Plateau. It is a high plateau built up of lava flow upon lava flow, all having been erupted fairly recently during Pliocene and Pleistocene periods with some flows, such as those in the neighbourhood of the Craters of the Moon National Monument, being no more than 2,000 years in age (Fig. 1) (Parsons 1978).

In the early stages of the volcanic history of the Snake River Plateau, much silicic volcanism took place, but quickly basic basaltic activity became dominant and a huge proportion of the plateau is composed of basaltic flows. The volcanic activity in many places appears to be related to rifts or fissures, but, nevertheless, much of the basaltic outpourings have been from central type conduits rather than fissures, and the flat plateau nature of the area is a result of many very low-angled shield volcanoes overlapping with their neighbours. The monotonous terrain is interrupted in places by small volcanic cones. In the Craters of the Moon National Monument (Crawford, 1978) a series of small but distinctive spatter and cinder cones occur along the great rift zone. To the northeast of Idaho Falls, on the southern margin of the Snake River Plateau, the Menan Buttes consists of a series of cones formed when basaltic lava rose to the surface through water-saturated gravels of the Snake River flood plain. The basic magma reacted violently with the water in the gravels to produce an explosive series of eruptions and small cones were formed of a mixture of solidified fragmented lava and river gravels, many of the gravels having been shattered by the explosiveness of the eruption (Alt and Hyndman 1972).

General Features of the Snake River Plateau

The Snake River Plateau (Fig. 1) stretches for about 300 miles from west to east and up to 60 miles from north to south. To the north, the plateau lavas reach thicknesses of 10,000 feet, burying completely the old pre-volcanic landscape (Parsons, 1978). The plateau, which to the eye appears virtually flat, does in fact slope gently from north to south. This slope has had a marked effect on the hydrology. The Snake River which is, of course, the main river, flows across the southern edge of the plateau receiving many tributaries from the highlands to the south of the plateau. The plateau itself has very little surface drainage, the basalts being highly porous with a multitude of vesicles, good vertical columnar joints and abundant lava tubes. Rivers flowing from the higher ground to the north on to the plateau have soon found their way beneath the surface on reaching the basalt.

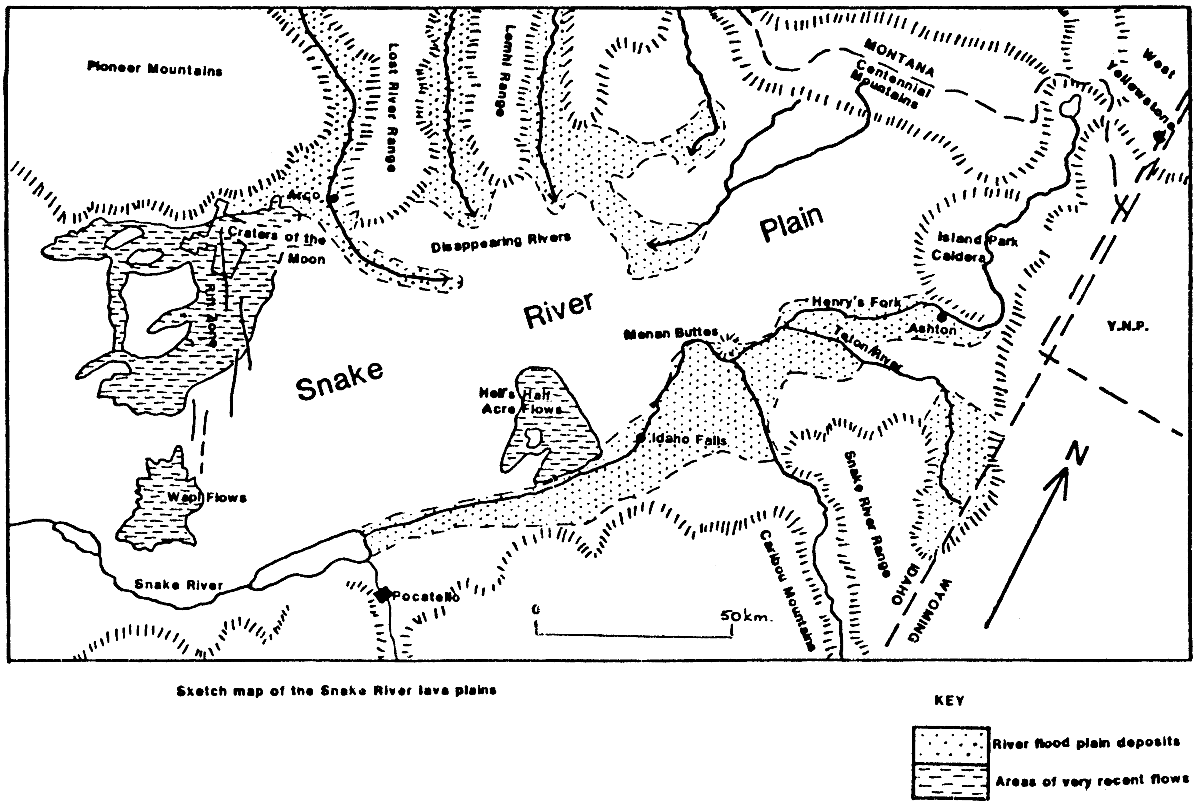

Fig. 1. The physical setting of the Snake River Plain with areas of very recent volcanic activity indicated (after Parsons, 1978).

The lavas of the plateau show typical features of low viscosity basalts. Despite their age, of around 2,000 years, the basalts of the Craters of the Moon are remarkably well preserved, having suffered little weathering in the rather dry climatic conditions. Pahoehoe and aa flows are beautifully displayed as are such features as lava tubes and pressure ridges.

Yellowstone and Island Park

Introduction

In many ways, Yellowstone should be considered as an eastward extension of the Snake River Plateau, but it has so many unique characteristics that it has to be considered separately.

As has already been explained, the Snake River Plateau is considered to have been formed as the American Plate moved southwestwards over a mantle plume and, as it did so, the volcanic activity associated with it moved relatively to the east (Smith and Braile, 1982). Yellowstone is at the northeast end of the Snake River Plain and it is likely that the Yellowstone area is over the hot-spot which produced the basaltic plain to the west at an earlier date.

History of the Exploration of Yellowstone

Although there appears to have been a long history of Indians living in Yellowstone, the first white man to visit the area was possibly a John Colter, originally a guide, who on leaving an expedition, in 1806, crossed into and explored the Yellowstone area. He returned home with stories of "fire and brimstone" which were dismissed by his acquaintances as being too far-fetched to be credible (Tuttle, 1982). Much later in 1857, another explorer renowned for his way-out tales came back with what were at their best considered good but preposterous stories about the fantastic sights he had witnessed in Yellowstone. It did, however, stimulate the geologist, Hayden, to attempt an expedition to the area in 1859. This was thwarted by heavy snowfall, but in 1870 and 1871, he was able to lead successful visits into the area and was also able to convince the Congress of the day that the area should be set aside as a national park. President Grant signed the bill authorising the establishment of this, the first and nearly the largest of America's national parks in 1872 (Kirk, 1972).

Geographical Setting of Yellowstone National Park

The National Park (Fig. 2) is mainly in the state of Wyoming but it extends to just over the borders into the neighbouring states of Idaho and Montana to the west and north respectively. The Park is about 60 miles in length from north to south, and almost as wide from east to west.

Yellowstone in many ways is surprisingly flat. It forms a plateau area of about 8,000 feet with its highest points being a little over 10,000 feet. Near the south centre of the Park is Yellowstone Lake at an elevation of 7733 feet; it is the largest fresh water lake in the United States outside the Great Lakes area (Tuttle, 1982).

The Yellowstone River rises in the south of the Park and flows northwards right across it, draining into and out of Yellowstone Lake in the process, and forming the unforgettable Grand Canyon of Yellowstone further north. The river flows on northwards to join the Missouri in Montana and, eventually, via the Gulf of Mexico, into the Atlantic Ocean. To the northwest side of the Park, the Madison River also takes a northerly path to reach the Missouri, but the southwestern part of the Park is drained by the Snake River and its tributaries to flow out of the Park to the southwest and eventually westwards to the Pacific Ocean. Yellowstone is thus situated on the 'Great Divide' between drainage to the Atlantic and to the Pacific. Surrounding Yellowstone are the mountain ranges of the Middle Rockies with heights of 10,000 to 14,000 feet. To the northwest are the Madison and Gallatin Ranges separated from each other by the Valley of the Gallatin River. Further round to the north are the Beartooth Mountains. All of these ranges have cores of Pre-Cambrian granites and gneisses, in places flanked by younger Palaeozoic and even Mesozoic rocks. On the eastern side of Yellowstone, the Absaroka Range is formed almost entirely from andesitic pyroclastic volcanic rocks which formed the extensive Absaroka volcanic field in the early Cenozoic. To the south, the famous Teton Range, again typical of the Middle Rockies, is largely constructed of granites and gneisses of Pre-Cambrian age to form a splendid background to Yellowstone when looking southwards.

Within Yellowstone Park, nearly all the rocks are associated with volcanic outbursts during the last 2.5 million years. In this period, there appear to have been three main volcanic episodes with a gradual migration of activity in a northeastwards direction across the Park (Tuttle, 1982).

Recent Volcanic Activity in Yellowstone

A great part of the central area of Yellowstone National Park is a large caldera. Just over 2 million years ago, the recent volcanic history of the area started with a tremendously explosive acidic eruption of over 600 cubic miles of rhyolitic material. To put this eruption into perspective, it was more than 5,000 times greater in the volume of volcanic material erupted than the 1980 Mount St Helens eruption (Smith and Braile, 1982). After the eruption, collapse produced a large caldera, the Island Park caldera, the remains of which can be seen today on the edge of and outside the western boundary of the Park. This early eruption and the caldera which it produced, represents the first of three volcanic cycles of the Yellowstone Plateau area.

The second eruptive cycle about 1,600,000 years ago, produced a caldera between the Island Park caldera and the present Yellowstone caldera, but most of the features of this eruption have been buried by later volcanic activity. This second cycle erupted an estimated 67 cubic miles of acid volcanics, much smaller than the Island Park eruption but, nevertheless enormous when compared with any eruption during historical times.

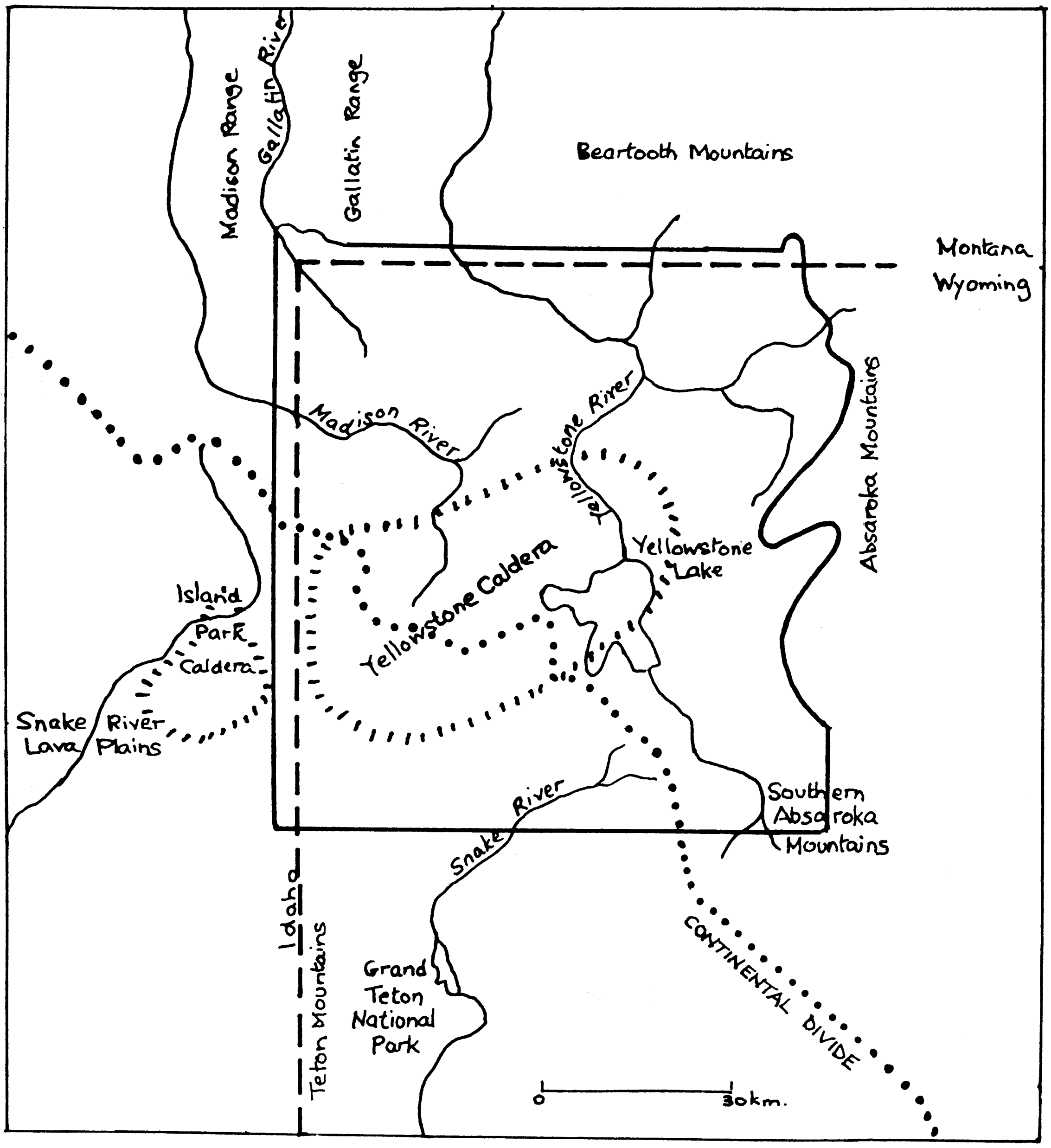

Fig. 2. Map to show the physical features of the Yellowstone area and the approximate positions of the Island Park and Yellowstone calderas (after Tuttle, 1982).

The third eruptive cycle forms most of the present Yellowstone Plateau and created the huge caldera centrally placed in Yellowstone Park (Crandall, 1977). The main eruptive phase of this cycle started about 600,000 years ago and this eruption ejected about 240 cubic miles of material. The story started with the rise of a magma chamber to a high level in the crust underneath Yellowstone (Fig. 3). This would have resulted in the arching, stretching and eventual cracking in great ring fractures of the overlying crust. The fractures produced would have provided avenues for the upward movement of the magma to the surface, and its subsequent eruption. The eruptions were undoubtedly highly acidic and explosive, with pumice, ash and rock fragments being violently ejected, accompanied by vast quantities of hot expanding gases, which swept the erupted dense debris across the countryside in the form of ash flows. The ash flows would have first filled depressions in the landscape such as river valleys but, eventually, the whole area must have completely been buried beneath the thick pile of compacted and welded ash flow deposits. This particular ash flow has become known as the Yellowstone Tuff. During the eruption, much fine ash was also carried high into the atmosphere and dispersed over a large area of north America, very much like the 1980 Mount St Helens eruption but on a far larger scale.

The Caldera Formation

When the eruption was complete, the vast quantity of material removed from the magma chamber left a huge void beneath the surface. The overlying rocks were exceedingly unstable. A large number of fractures, mostly normal faults, developed as large blocks of the chamber roof began to collapse into the magma chamber (Fig. 3). The collapse must have been considerable, but it is not certain to exactly what depth it took place, although it is considered that it must have been certainly on the scale of several thousand feet.

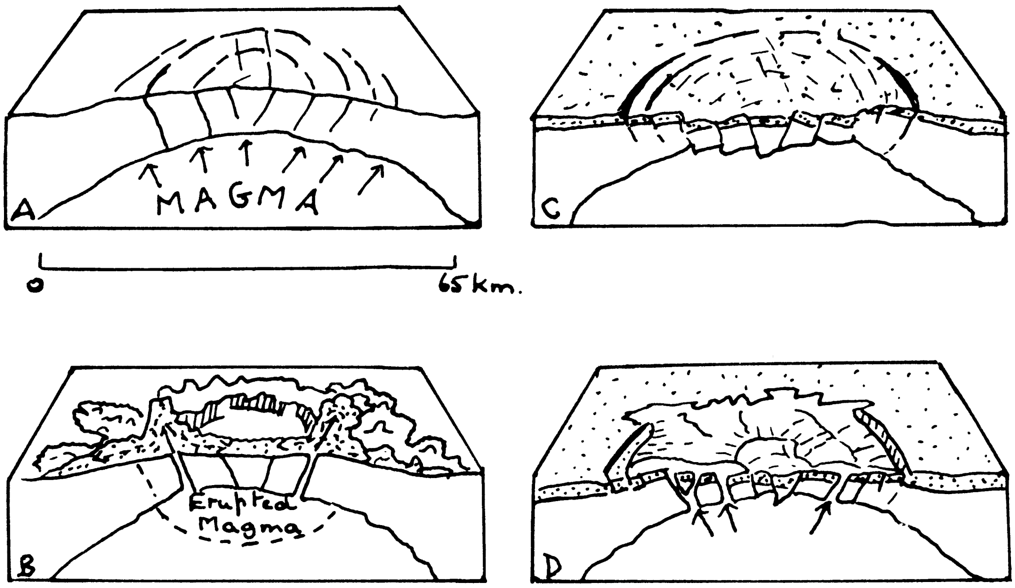

Fig. 3. Block diagrams to show the evolution of the Yellowstone caldera commencing about 600,000 years ago (after Keefer, 1971).

(*a*) Magma rising below Yellowstone arching the country rocks and producing a series of concentric fractures which extend downwards towards the magma chamber.

(*b*) Ring fractures tap the magma chamber. Gases dissolved and the magma escape. Violent explosive eruptions eject vast volumes of pumice and ash flows from the fractures. Air suspended ash distributed over huge geographical area.

(*c*) Void produced by the immense eruptions in (*b*) allow the roofing rocks to collapse along the ring fractures to produce a huge caldera.

(*d*) The caldera is gradually filled up by rhyolitic lava flows erupted from the ring fractures. These eruptions are relatively placid, the magma having been depleted in gases.

Renewed Volcanic Activity

Following the caldera formation, volcanic activity did not stop. Magma rose again in the form of twin magma chambers which arched and cracked the overlying crust. From these two magma chambers, which are situated over the present Upper Geyser Basin near Old Faithful and to the east of the Hayden Valley, lava in the form of acidic rhyolite erupted along the fractures produced by the arching. The eruptions started soon after the formation of the Yellowstone Caldera, and continued intermittently until the last eruptions about 65,000 years ago. The rhyolite lavas flowed out over the caldera floor and gradually filled the depression so that the caldera today has very little relief, and certainly it is not the spectacle it must have been immediately after formation. The rhyolite lavas were very viscous and a flow brecciated texture, produced by the breaking up of the tops of the lava flows due to the continual movement of the still liquid but highly viscous lava beneath, is a common feature. The viscosity of the lavas also played a part in producing the glassy form of the lava known as obsidian which is beautifully displayed today at Obsidian Cliff in the Park.

During the time rhyolite lavas were being erupted, a small caldera-making event took place between 100,000 and 200,000 years ago. As a result of an explosive ash flow eruption, followed by caldera collapse, a depression of 6 miles by 4 miles, now filled by the waters of the West Thumb of Yellowstone Lake, was formed.

No volcanic eruptions have occurred in Yellowstone for about 65,000 years. It is suggested (Keefer, 1971) that possibly the last eruptions have taken place in this area and that the magma chamber beneath Yellowstone is cooling. There is still, however, a high geothermal gradient, quite sufficient to provide the present day highlights of the varied geothermal features.

Geothermal Activity in Yellowstone

One of the undoubted main reasons for Yellowstone being designated a national park is the incredible range of geothermal features in the form of geysers, hot springs, mud pools and fumaroles (Marler, 1978). Within Yellowstone, there are a few thousand geothermal features, the greatest concentrations anywhere in the world. They occur in many different regions of the Park area, but most are concentrated in a few areas known as geyser basins. The geyser basins are closely associated with the areas where fracturing occurred during caldera formation, the fractures providing passageways for the rise of heat towards the surface.

Hot Springs and Geysers

Hot Springs are recognised as any spring where the water is above human body temperature. There are a few thousand of these in Yellowstone. Geysers are described as intermittent hot springs which periodically erupt fountains of hot water and steam (Plate 2). In some cases, such as Old Faithful (Plate 6) the eruptions are very regularly spaced whereas other geysers are much more unreliable time-wise (Fischer, 1960).

Research work has shown that although no two geysers are alike although the reasons for their behaviours are similar (Fig. 4). Beneath a geyser is a plumbing system which consists of a main conduit which is normally nearly vertical and a number of side channels which often tap very porous rock. This network of channels lies fairly close to the surface, usually to depths of only a few hundred feet, but the main conduit connects downward to sources of hot water at depth (Keefer, 1971).

With this information, we can now appreciate the likely sequence of events which take place in the eruptive cycle of a geyser:

(*a*) After an eruption, the main conduit and side channels are practically emptied of water (Plate 3). Water is then replenished by flow from the side channels in the highly porous water-bearing rocks, and hotter water, often superheated, rises from the heat source at depth. The superheated water begins to turn to steam as pressure reduces during the water ascent, but at this stage, the gas bubbles often condense due to lowering of temperature by the inflow of cooler water from the side channels. Gradually, the water temperature increases and a stage is reached when no longer will the gas bubbles continue to condense.

(*b*) Almost certainly the geyser conduit will vary in width, in places being quite wide and in other places being rather constricted. The gas bubbles will grow in size and often become trapped in one of the constricted parts of the conduit. The expanding gas in these trapped areas will soon force its way up to the surface and cause a number of preliminary spurts of water (Plate 4).

(*c*) One of the preliminary spurts will eventually discharge enough water for the pressure in the whole system to be reduced sufficiently for all the water to flash to steam. This is the main eruptive phase, often with spectacular spurts of steam and water.

(*d*) In different geysers, the actual main eruption phase is quite variable although in most cases, it lasts for no longer than a few minutes. When the eruption ceases, the conduit and side channels will be nearly empty and the whole process of recharging the system has to recommence before the next eruption takes place. In the case of Old Faithful, the eruption interval is about one hour, many geysers have shorter periods of quiescence and some much longer, ranging from a number of hours to a day, weeks or even months.

The Upper Geyser Basin, which includes Old Faithful amongst its number as the most famous, has the greatest concentration of geysers anywhere in the world. Nearly all the water which supplies the geysers and hot springs originates as rain or snow at the surface, and then percolates downwards (Chronic, 1984). The cold surface waters descend to depths of several thousand feet using the fractures produced during caldera formation. The water is heated rapidly as it descends due to the high geothermal gradient which in drill holes has been shown to produce temperatures of about 250 °C at 1,000 feet depth. Some of this water goes directly into the plumbing systems of the geysers but much of it finds its way to great depths where it is heated to temperatures in excess of 400 °C. At depths of several thousand feet, it is unable to boil because of the hydrostatic pressure but it begins to expand and rise. At these elevated temperatures, the hot water will dissolve some silica from the surrounding country rocks. This water enriched in silica rises towards the surface and eventually, through geysers or hot-springs, it reaches the surface. As the temperature of the water drops, the silica is precipitated out both above and below the ground, lining the passageways of the hot-springs and geysers, or forming mounds which are often very irregular in shape at the surface. This material which is deposited is known as siliceous sinter (Plate 1). Throughout Yellowstone the deposits around hot-springs and geysers are invariably of siliceous sinter, except in the north of the Park at Mammoth Terraces. Here the water has passed downwards through limestone, and when the water has reached the surface again as hot-springs, they are charged with calcium carbonate and this is deposited on the flanks of the hill side at Mammoth Terraces as exquisite calcite formations (Plate 5).

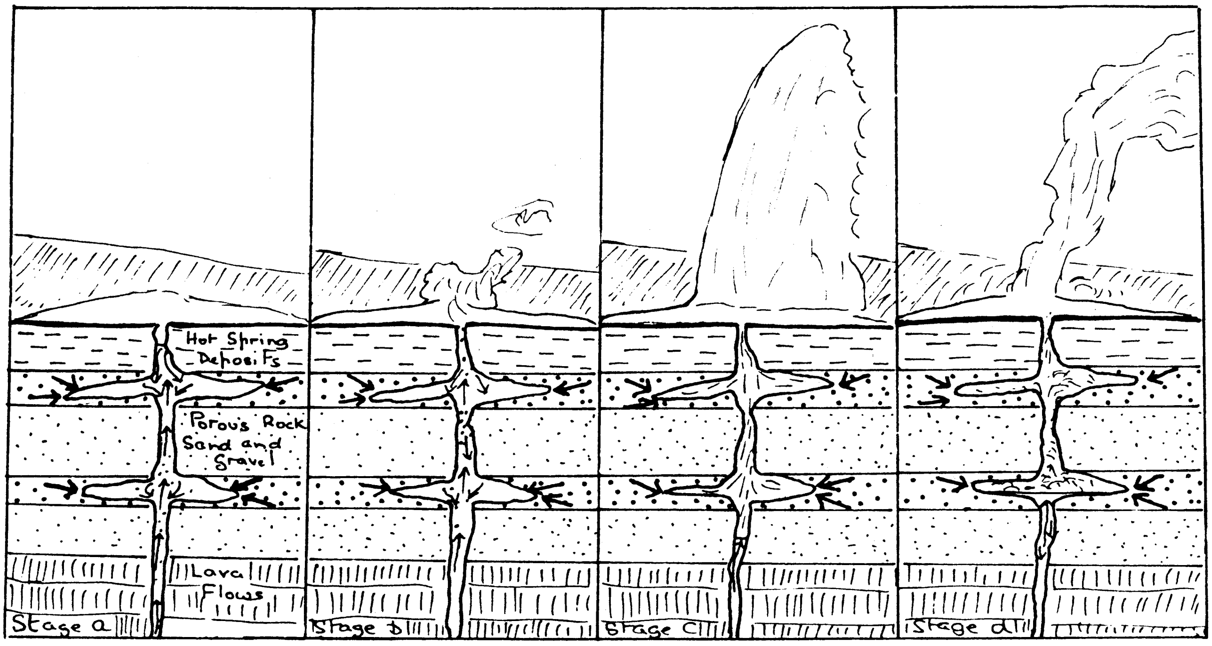

Fig. 4. Section through Old Faithful to illustrate what probably happens during a geyser eruption (after Keefer, 1971).

Stage A

This is the recovery or recharge stage when, after an eruption, the emptied conduits of the geyser fill up again with water. Hot water rises from depth and cold water infiltrates from the porous sands and gravels at higher levels. At depth, some of the water is converted to steam bubbles which on rising towards the surface, condense. As the temperature in the system increases, the steam bubbles no longer condense.

Stage B

As the temperature in the system increases and more bubbles form, they are likely to clog in parts of the system particularly where constrictions of the conduits occur. When this happens, the expanding steam suddenly forces its way to the surface causing some preliminary spurts at the surface.

Stage C

At this stage, one of the preliminary spurts removes sufficient rocks from the top of the system to cause a reduction in pressure sufficient to trigger the whole system, causing the water in the system to flash into steam and cause the geyser to surge into full eruption.

Stage D

Small pockets of water in the system are converted to steam but generally when the eruption is over, the system once more begins to fill with water and the whole cycle starts again.

Mud Pools

Mud Pools are really types of hot springs, but ones with a limited supply of water. Hot water rising from below chemically weathers the surface rocks which are decomposed to a clay. The clays produced vary in colour from black, white or cream, and sometimes are tinted by reds and browns of iron oxides; the most common colour, however, is a light grey. The consistency of the mud varies from what could be described as dirty water through to a very thick paste, depending on the amount of water available. The availability of water varies with the seasons, and in July and August some of the mud pools have a tendency to dry out completely.

Fumaroles

These are thermal features which only discharge steam and other gases and are often referred to as steam vents. They are extremely numerous through the Yellowstone area.

Yellowstone in the Future

'Is Yellowstone going to be the site of further eruption in the near future?', is, of course, the one million dollar question. Geophysical studies in the area have helped to give us some insight into possibilities (Smith and Braile, 1982).

The upper crust beneath the Yellowstone Caldera has p-wave velocities of between 4.0 km/sec and 5.7 km/sec (Fig. 5). These are very low values compared with surrounding areas where p-waves are in the order of 6.0 km/sec in the upper crust. The boundary of the 5.7 km/sec p-wave body closely corresponds to the outline of the Yellowstone caldera, with the 6.0 km/sec velocities representing the surrounding thermally undisturbed basement.

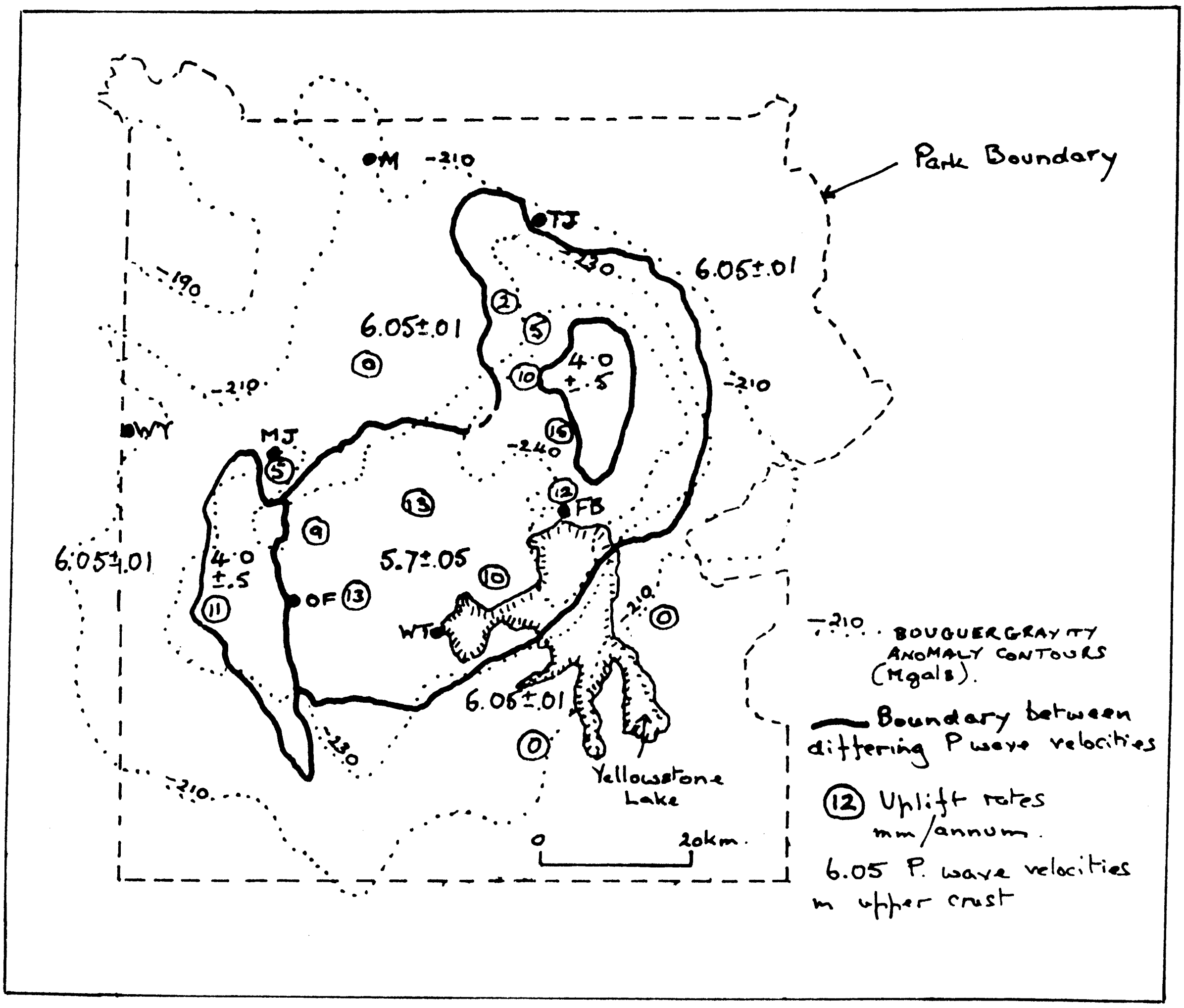

Fig. 5. Map of the Yellowstone area (after Smith and Braile, 1982) to show the area of low P. wave velocity zone in the upper coastal rocks (2 km–10 km), the negative Bouguer depth gravity anomaly contours (Mgal) and the zone of relatively rapid uplift particularly in the north east and south west parts of the Yellowstone caldera (figures in mm per annum).
FB: Fishing Bridge, M: Mammoth, MJ: Maddison Junction, OF: Old Faithful, TJ: Tower Function, WT: West Thumb, WY: West Yellowstone.

There are two bodies which are represented by p-wave velocities of about 4.0 km/sec, one to the northeast side and the other to the southwest side of the Yellowstone caldera. The low velocity body to the northeast also has an additional gravity low (minues 240 m.gal.) in addition to the large regional anomally of minus 60 m.gal. Smith and Braile (1982) considered that this low velocity, low density zone may well correspond to an upper crustal fluid-filled silicic body.

The southwestern low velocity body is not accompanied by a gravity low and Lehman *et al* (1982) suggested that this body is possibly the result of a fractured fluid saturated zone representing the northward extension of the Teton fault system which further south provides the impressive fault scarp on the east side of the Tetons.

In summary, the 5.7 km/sec zone beneath the Yellowstone caldera appears to represent a hot plastically deforming body of granitic composition, possibly rhyolitic lavas and associated ash flow tuffs which filled the deep Yellowstone caldera during the Quaternary. The features of the 4.0 km/sec body to the northeast of the caldera boundary have been suggested as representative of an acid body which could range from a highly porous water/steam saturated system to a 10-50% partial melt of the upper crustal rocks. The southwestern 4.0 km/sec body is thought to represent quite possibly a highly fractured northward extension of the Teton fault belt (Smith and Braile, 1982) as previously mentioned.

Recent Surface Uplift in the Yellowstone Area

Changes of surface level in the Yellowstone caldera during the last 55 years have been carefully monitored by Pelton and Smith (1982). Data obtained have indicated anomalously high uplift rates over the area of the Yellowstone caldera as a whole with variations from 5 mm per annum towards the outer edge of the caldera to local uplifts of as much as 15 mm per annum in the area of the northeast low velocity body (Fig. 5). Over the 55 year period, this has produced high uplift rates resulting in a total of 700 mm elevation. This uplift corresponds closely to other observed uplift rates in volcanically active regions such as Hawaii and Iceland.

Speculation on Possible Future Eruptions in Yellowstone

Smith and Braile (1982) suggest that the 5.7 km/sec body under Yellowstone may well represent a relatively solid but plastically deforming body. What is of considerable interest, however, is the northeast 4.0 km/sec low velocity body, interpreted, as already stated, as possibly a fluid filled steam/water body or a partial melt. Whether this situation represents a pre-eruption feature is debatable but the coincidence of a low density, low velocity body with associated surface uplift suggests that in the northeast of the Yellowstone caldera, we may have a site for a future eruption. If an eruption occurred, the inference from the fairly small volume of the 4.0 km/sec body is that an eruption would not be on the catastrophic scale of the major eruptions which have devastated Yellowstone in the last 2 million years. It may well be a future potential hazard, but on the other hand, the crustal deformation which is taking place may only represent the successive introduction and solidification of melts in the upper crust with associated inflation and deflation of the surface, but with no eruption.

Under the rest of Yellowstone the geophysical date do not give rise to any suspicion of a possible volcanic episode in the near future.

Conclusions

The volcanic history of the Snake River Plateau and Yellowstone Park provides abundant evidence of the movement of the North American Plate in a south westerly direction over a mantle plume which has produced a line of volcanic activity indicating this movement. In the Snake River Plateau, the initial silicic eruptions followed by a long history of basic eruptions have produced the thick sequence of basaltic lavas now present. Beneath Yellowstone Park, the present position of the mantle plume coincides with the Middle Rockies and, consequently, a much greater thickness of continental crust which undoubtedly has had its influence on the dominance of acidic eruptions from this area.

Today, and during the last 60,000 years, the Yellowstone area has had no true volcanic eruptions and activity is represented by the famous and varied geothermal features.

The possibility of a future eruption in the Yellowstone area has been discussed, and the geophysical evidence suggests that the northeast part of the Yellowstone caldera is the most likely candidate. It is probably underlain by a melt which has the possible potential of producing a future eruption, albeit on a scale likely to be much smaller than the three caldera-forming eruptions of the last 2 million years or so (Smith and Christiansen, 1980).

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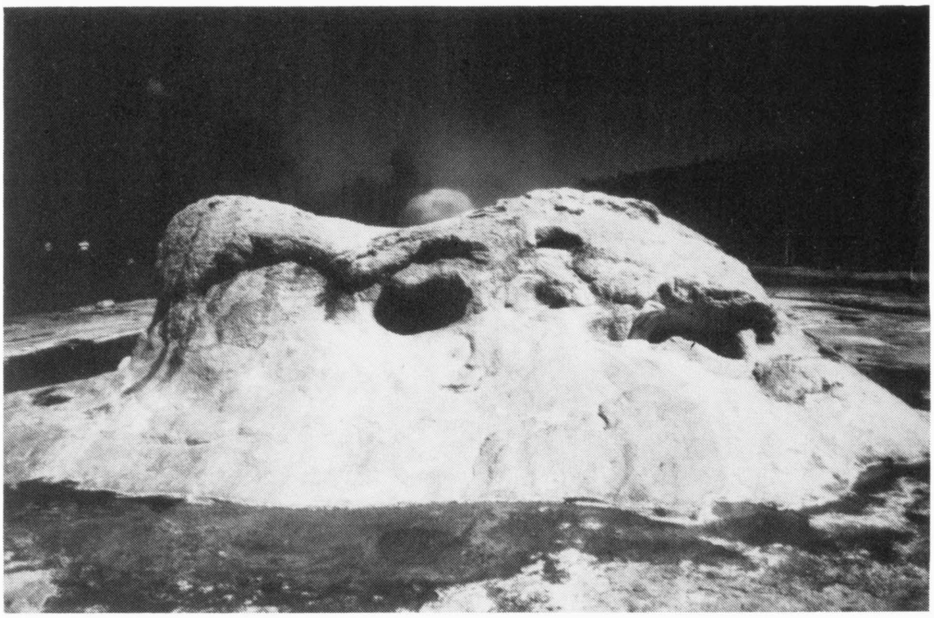

Plate 1. Grotto Geyser, Upper Geyser Basin, with appreciable deposits of siliceous sinter.

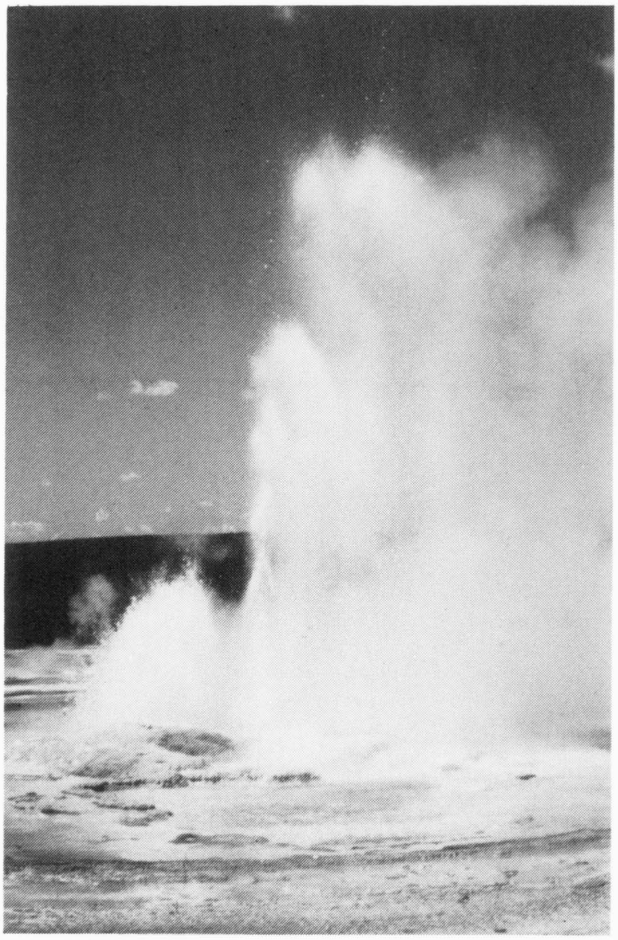

Plate 2. Clepsydra Geyser, Lower Geyser Basin. A geyser which is in almost continuous eruption.

Plate 3. Echinus Geyser. Norris Geyser Basin. The geyser after eruption and before recharge has commenced.

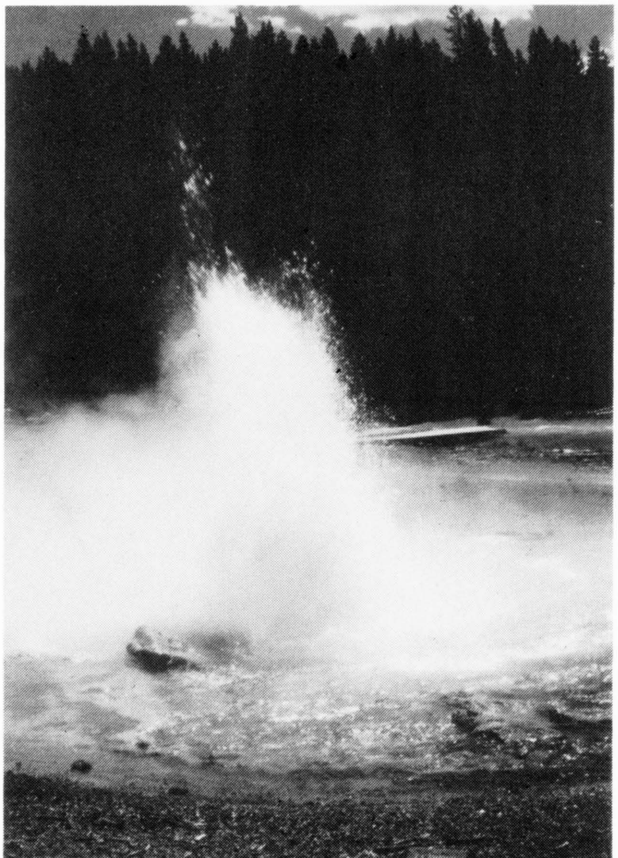

Plate 4. Echinus Geyser, Norris Geyser Basin. The geyser erupting at about half normal strength.

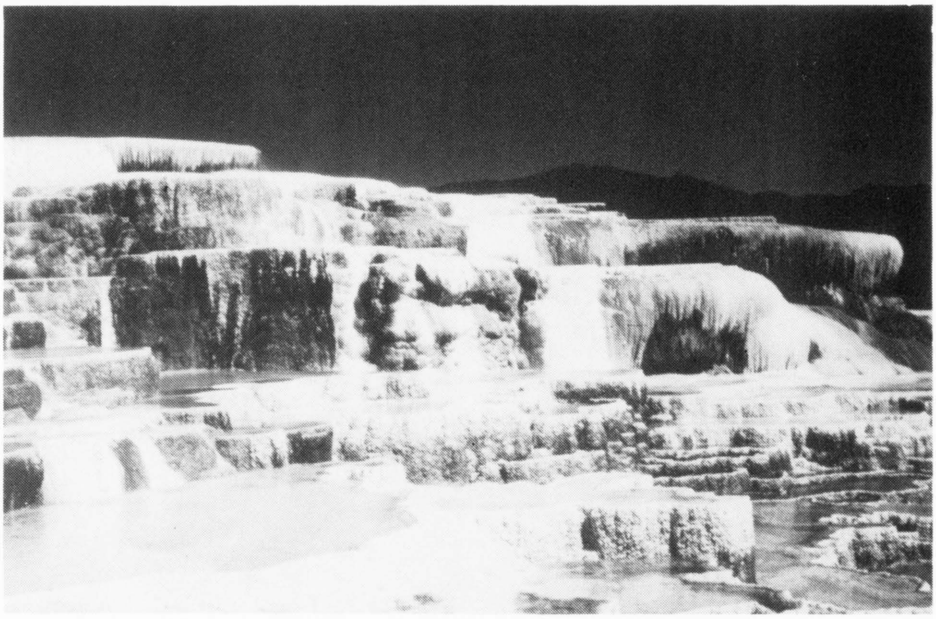

Plate 5. Minerva Terrace, Mammoth Hot Springs. This is a view of the active part of the terrace formed of calcium carbonate from hot spring water which has risen through limestones.

Plate 6. Old Faithful in full eruption.