THE YELLOWSTONE PETRIFIED "FORESTS"

Harold G. Coffin

I. INTRODUCTION

The Petrified Forests of Yellowstone National Park in Wyoming and Montana are perhaps the most spectacular and extensive petrified forests in the world and have stimulated scientific investigations for over 100 years.

The first historical records of the petrified trees of Yellowstone National Park came from trappers in the first half of the 19th century, some of whom developed exaggerated stories about the Yellowstone country and about the petrified trees.[1] In 1878 and 1879, W. H. Holmes gave us the first scientific accounts of these unique forests.[2]

II. GENERAL DESCRIPTION

The classic petrified forests are found on Specimen Ridge and Mt. Amethyst, both located in the northeast sector of Yellowstone National Park (Figure 1).[3] Other fossil forests in the northeastern part of the park are found in the Cache Creek Area, and on both sides of Soda Butte Creek and

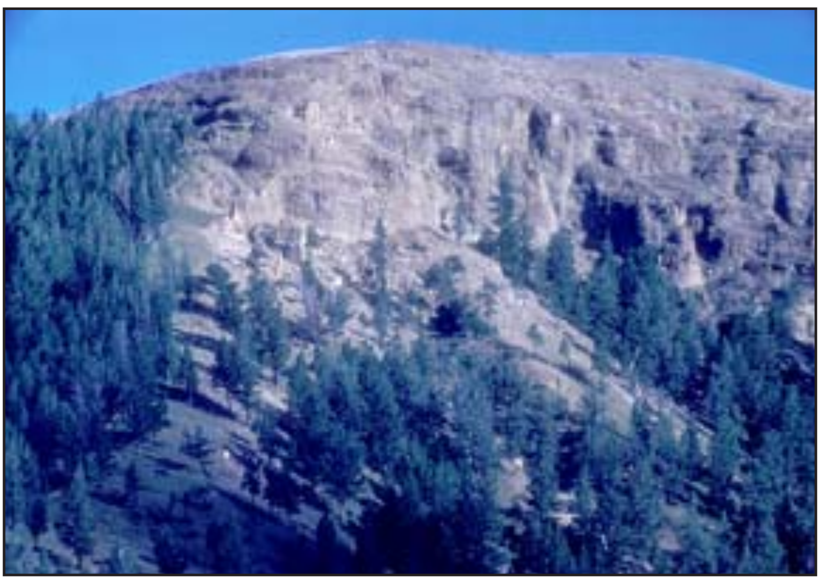

Figure 1. Specimen Ridge from the Lamar Valley. Note petrified trees left of center on the sloping ridge below the cliffs.

the Lamar Valley. The most spectacular of the fossil forests can be found along the drainage of Specimen Creek in the northwest corner of the park (Figure 2). In addition, significant petrified forests are located north of the

Figure 2. One of the spectacular exposures of petrified trees in the Specimen Creek area in the northwest corner of Yellowstone National Park.

park in the Tom Minor Basin and surrounding mountains, as well as south of the park in the Stratified Primitive Area north of Dubois, Wyoming (Figure 3).[4]

A. STRATIGRAPHY

The Eocene to Oligocene deposits containing the fossil forests consist mainly of multiple layers of volcanic conglomerates and breccias (angular pebbles and boulders) interspersed with volcanic ash and occasional flows of basalt. This series of volcanic tree-containing deposits rests on various surfaces, although most often they overlie Cambrian or Mississippian beds. In some areas younger welded tuffs (volcanic ash fused into hard rock by heat) cover the breccias and conglomerates. Extensive erosion has exposed more than 1000 vertical meters of these volcanics and has created a rugged topography. Near the northeast boundary of the Park and eastward, a sequence of beds down to the Lower Cambrian have been disrupted by a major horizontal movement of strata called the Heart Mountain Thrustfault.[5] Mountain glaciers, now absent, scoured the entire Yellowstone area and rounded some of the valley floors.[6] The large Yellowstone caldera, now largely filled with

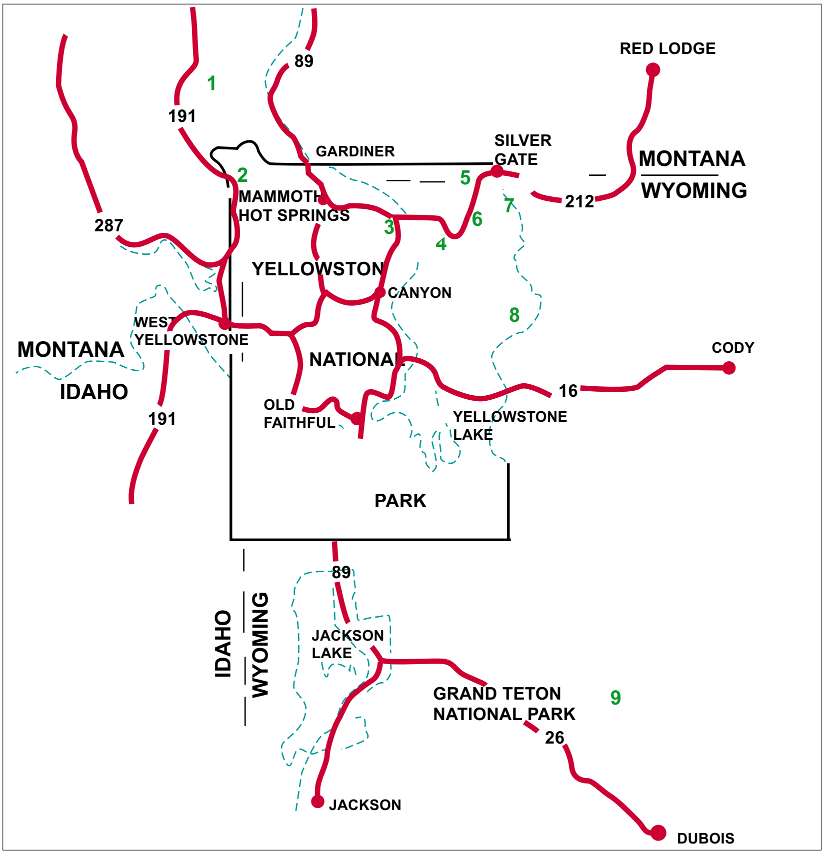

Figure 3. Map of Yellowstone National Park, Teton National Park, and surrounding areas showing the locations (numbers 1 to 9) of several petrified forests.

welded tuffs, lies south of the petrified forests of the Lamar and Soda Butte Creek valleys.[7] To the west the Yellowstone volcanics lie adjacent to the uplifted Precambrian and Paleozoic formations of the Madison Range.

B. SUCCESSIVE LAYERS

Petrified wood and trees are found in numerous locations around the world, but the Yellowstone Petrified Forests are unusual because of the many levels stacked one upon another. In 1960 Erling Dorf of Princeton University studied the Amethyst Mountain Fossil Forest and counted 27 levels.[8] I have plotted 31 levels on Mount Hornaday on the west side of the Soda Butt Creek Valley (Figure 4). The greatest sequence of superimposed fossil forest levels

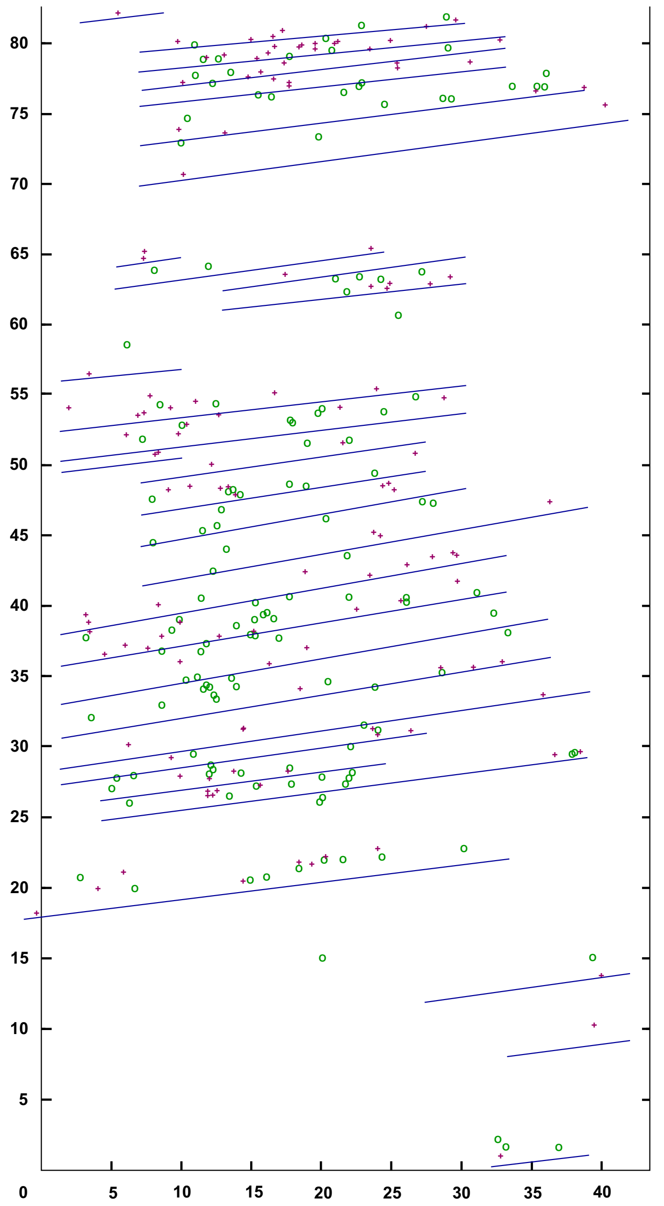

Figure 4. Plot of Mt. Hornaday Petrified Forest with 31 levels. Several more levels seen in the cliffs below were inaccessible. The solid lines are organic levels or levels upon which upright trees stand. Symbols: o = horizontal trees; + = upright trees.

SITE	UPRIGHT TREE LEVELS	ORGANIC LEVELS (No upright trees visible)	TOTAL
Cache Creek	13	12	25
Fossil Forest	32	9	41
Mt. Hornaday	37	5	42
Specimen Creek	48	17	65
Mt. Norris	5	0	5
Specimen Ridge (East shoulder)	11	3	14

TABLE 1. NUMBER OF LEVELS FROM SIX MAJOR SITES

is located in the Specimen Creek area where 65 or more levels can be counted (Table 1). Other areas with fewer levels are Mt. Norris on the east side of Soda Butte Creek Valley (5 levels), Specimen Ridge flanking the Lamar Valley (15 levels), and Cache Creek (26 levels).[9] Multiple levels are also seen at Miller Creek northeast of the Lamar Valley, in Tom Minor Basin (including Ramshorn Peak), and in the Stratified Primitive Area. Scattered trees and petrified wood can be found throughout the northern region of Yellowstone Park and other surrounding areas.

III. DESCRIPTION OF THE PETRIFIED TREES

Both upright and horizontal trees are found in the deposits, but the percentage of upright trees varies from locality to locality (Table 2). For three levels of the Fossil Forest (Amethyst Mountain) with 208 petrified trees, only 28% are upright. On the other hand, the Petrified Tree area near Roosevelt Lodge exhibits 30 upright out of a total of 40 visible petrified trees (75%). Individual levels may be even more variable — some with all trees horizontal or all upright. These figures are based upon trees revealed in the irregular cross-section exposed by the eroded cliff faces. If a surface view of the total fossil forest for any particular level were possible, the percentages for standing and fallen trees could be different.

A puzzling feature of all the petrified forests in and around Yellowstone Park is the absence of diagonal or leaning trees. I know of only three locations (two with one large tree each, and the other with three or four small trees) where leaning trees can be seen (Figure 5).

The upright trees may range in height from just above ground level to over 6 m. Sometimes they look like old dead snags, and close examination is needed to determine that they are petrified.

Most of the wood tissue of the Yellowstone forests is well preserved, even though limbs and bark are usually absent. Roots are present and often

TABLE 2. NUMBER OF TREES FOR SITES ACTUALLY PLOTTED

SITE	NUMBER ERECT	NUMBER PRONE	PERCENTAGES
Specimen Creek (Levels 33-37)	50	20	71/29
Mt. Hornaday	157	173	58/52
Fossil Forest (3 levels only)	58	150	28/72
Specimen Ridge (East shoulder)	57	26	69/31
Petrified Tree[1]	30	10	75/25
Mt. Norris	29	31	48/52

[1] Petrified forest on the ridge above the fenced petrified tree (accessible by automobile) east of Tower Junction.

Figure 5. A green stick fracture or leaning tree seen in the Tom Minor Basin northwest of Yellowstone Park. Note the absence of roots on the stump.

can be seen extending a short distance from the bases of the petrified stumps. Occasionally stumps and logs show driftwood-like abrasion or broken and reduced root systems.

The tops of many stumps terminate at or just below the next higher organic level. A few penetrate into the next overlying level and may overlap any trees that might arise from that level (Figure 6). When visible, the original broken top of the stump usually is abrupt and jagged. Despite this evidence of violent breakage, green stick fractures are almost unknown (note Figure 5 for a rare exception). Horizontal logs found near the broken tops of erect stumps never appear to belong to the stump as determined by size, rings, or species. Careful examination of the top few centimeters of the broken tops of erect stumps sometimes shows the wood tissue to be twisted and smashed, not from the breakage of the tree trunk, but from subsequent abrasion, perhaps by rocks and colliding trees.

Some observers have suggested that the petrified trees originally grew on the hillside and thus give the impression of multiple layers of trees one above another. This opinion cannot be substantiated. Trees growing on a

Figure 6. Overlapping trees in the Specimen Creek Petrified Forest. The larger tree arises from a lower level and overlaps the base of the smaller tree. Some time after this picture was taken, the smaller tree fell from its perch into the canyon below. This photograph first appeared in: Coffin HG. 1983. Origin by Design. Washington DC: Review and Herald Publishing Assn., p 136.

hillside have roots extending up and down slope. Such root arrangement was not observed for any of the petrified stumps. The flat spread of the roots of the petrified stumps indicates that they grew on a relatively flat surface. Furthermore, the surfaces on which the trees stand, which can be traced in gullies back into the mountain, deviate from horizontal only by 7º or less.

A. TAXONOMY

The original identification of fossil trees and plants was based largely on leaves and needles.[11] Identifications of fossil wood and pollen have increased the number of plant species to over 200.[12]

Table 3 lists identified woods from the Specimen Creek Petrified Forest. The most abundant trees are sequoia. Pines are second in abundance. Deciduous trees are well represented in some areas by sycamore leaves. Wood of angiosperms (most deciduous trees) appears to be less common but is not rare.[13]

TABLE 3. FOSSIL PLANTS OF YELLOWSTONE: A PARTIAL LIST *

Abes	fir	Juglans	walnut
Acacia	acacia	Larix	larch
Acer	maple	Laurus	laurel
Aralia	spikenard	Magnolia	magnolia
Arctostaphylos	bearberry	Myrica	bayberry
Artocarpus	breadfruit	Pandanus	screw pine
Betula	birch	Persea	bay
Carya	hickory	Pinus	pine
Castanea	chestnut	Platanus	sycamore
Castanopsis	chinquapin	Quercus	oak
Cercidiphyllum	katsura	Rhamnus	buckthorn
Cinnamonum	cinnamon	Salix	willow
Comus	dogwood	Sapindus	soap berry
Corylus	birch	Sequoia	redwood
Cycad	sago palm	Sparganium	bur-reed
Euonymus	staff tree	Thuja	cedar
Ferns (several species)		Tilia	linden
Ficus	fig	Ulmus	elm
Fraxinus	olive family	Viburnum	arrowwood
Horsetails (several species)		Vitis	grape
Hydrangea	syringa		

*From Dorf 1960, and Fisk 1976

Note the wide range of habitats and ecological requirements. The fossil wood and leaves have been identified to modern genera that live in widely differing habitats and environments.

Upright stumps range from broom handle size to over 4 m in diameter (Figures 7 and 8). Some stumps consist of little more than a mat of roots, whereas others include lengthy portions of the trunk. What may well be the tallest erect petrified tree in the world (estimated at approximately 15 m) is located at the base of Ramshorn Peak in the Tom Minor Basin (Figure 9).

Figure 7. A beautiful petrified tree (4.5 m high) on the slopes of Specimen Creek Petrified Forest.

B. ORIENTATION OF LOGS AND STUMPS

The alignment of the fallen petrified trees on any particular level is parallel (Figure 10).[14] The compass direction of these aligned trees is not the same for all levels. Wind and gravity could cause such alignments, but these forces may not be the factors involved. The compass directions of the long axes of the cross sections of the upright stumps that are not a perfect circle are often also parallel to the lay of the fallen trees.

C. DENDROCHRONOLOGY

In 1929-1930 A.E. Douglas, a pioneer in dendrochronology, was unable to cross-match the rings of the Yellowstone petrified trees on Specimen Ridge.[15] Little additional dendrochronological work has been done on petrified trees until recently. In 1979 and 1991 Michael Arct located several small trees in the Specimen Creek forest that had similar bands of distinctive anomalous growth-ring patterns.[16] Another report claims to cross-match two trees on the same level on Specimen Ridge.[17] Because of the good preservation of the wood tissue, rings are clearly visible and often reveal

Figure 8. A small petrified tree that arises from a thin organic level. Note the coarseness of the sediments surrounding it. This is typical Yellowstone volcanic breccia.

Figure 9. A magnificent petrified tree (nearly 15 m tall) located on the lower slopes of Ramshorn Peak in the Tom Miner Basin. This may be the tallest standing petrified tree in the world.

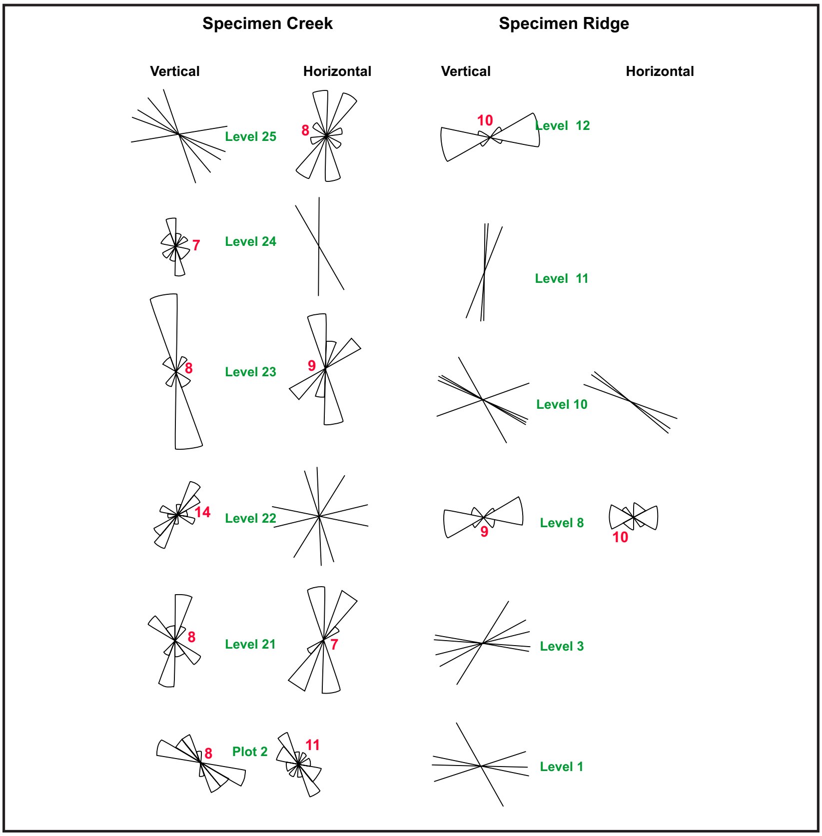

Figure 10. Orientation of upright and horizontal petrified trees on several levels in the Specimen Creek and Specimen Ridge Fossil Forests. Note that the orientations of the cross-sections of the long axes of the standing stumps are usually similar to that of the horizontal logs. Each tree from levels with five or less specimens is represented by a line. Those levels with more than five trees are represented by a rose graph with the number of specimens indicated. Colorized edition of the illustration first appeared in: Coffin HG. 1976. Orientation of trees in the Yellowstone Petrified Forests. Journal of Paleontology 50(3):539-543. Reprinted with permission of the Society of Economic Paleontologists and Mineralogists.

variable widths suitable for tree-ring studies (Figure 11). However, sequoia is not the best tree for such studies because of tendencies for rings to split or merge from one side of the stump to the other. In Yellowstone the ring studies are not for the purpose of dating the trees but for comparison of trees from the same or different levels. Thus it may be possible to ascertain if they are in situ or transported from elsewhere.

IV. DESCRIPTION OF THE "SOIL" LEVELS

The petrified trees usually are seen to arise from layers or zones of ash containing needles, leaves and organic debris. These organic levels that look like the surfaces in which the petrified trees originally took root have been called soil levels or growing surfaces (Figure 12). Much of the discussion of these forests relates to the nature of these fine sediment layers (hereafter referred to as organic levels).[10] Are these true soils that show mature time-dependent characteristics, or are they merely sediments containing organic matter that was transported and deposited rapidly?

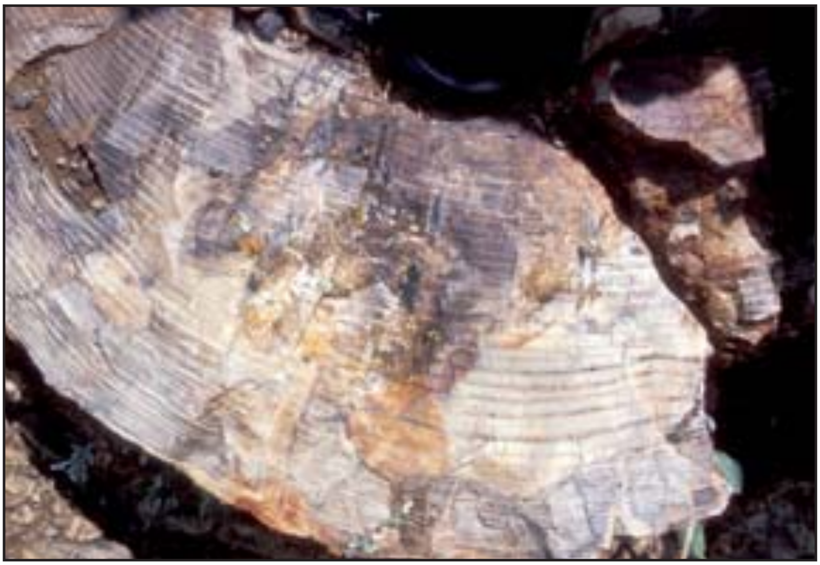

Figure 11. An illustration of the good preservation of most of the Yellowstone petrified trees. This stump with variable ring widths is suitable for dendrochronological studies.

A. THICKNESS OF ORGANIC LEVELS

Sixty-five levels of organic matter on the slopes above Specimen Creek range from a trace to as much as 20 cm thick. The average thickness is close to 3 cm. These dimensions are for the total depth of the organic matter or "soil." Of 130 different levels with upright trees representing several petrified forests, 24% contain no discernible organic matter. However, different sites vary widely. The number of levels without forest debris is 16 out of 37 (43%) for Mt. Hornaday, and 2 out of 48 (4%) for the lower 48 levels of Specimen Creek.

Figure 12. Most of the petrified trees arise from organic levels best seen on the right in this photo.

B. SOIL PROFILES

Cross-sections of true soils usually have an organic profile detectable as a downward color gradient from dark to light. There is a decrease in organic matter from the top downward. The top of the profile may consist of needles, leaves, etc., recently fallen and little changed; whereas the forest litter at the bottom of the profile has been changed by decay and chemical alteration until no longer recognizable. Such typical soil profiles are difficult to find for the Yellowstone Petrified Forests — one or two percent at the most.

Some of the organic levels have multiple bands of forest litter only a few centimeters apart. They may not contain visible petrified trees. Could the upper organic bands of these levels represent the leaf-fall zones associated with air-drop ash in volcanic eruptions? In such cases the lowest band would represent the true soil level, whereas the upper one (s) would result from physical and chemical stripping of leaves and needles from the trees by volcanic activity. These upper bands should not be growth surfaces unless no further ash accumulation occurred for many years and a new forest established itself on these levels. Study accompanying the survey of the complex Specimen Creek Petrified Forests failed to distinguish any significant differences between levels from which visible fossil trees arise and adjacent levels containing no visible upright trees. Levels both with and without upright trees, and also organic bands within levels, were sampled and examined in thin-section studies. If leaf-drop zones are present, they are not readily apparent and cannot be distinguished from the other levels.

V. EVIDENCE FOR TRANSPORT OF THE "SOILS"

Since the time of Holmes (1879) these petrified forests have been interpreted as living forests that were buried by successive volcanic mud slides over many thousands of years. However, research within the past 30 years has unearthed facts that seem to indicate that the trees were somehow transported to their present locations. If the in situ model (trees in position of growth) is incorrect, what is the correct picture? What model better fits the available evidence?

Support for the transport model coming from a study of the organic levels deals mainly with their physical structure, organic contents and lack of weathering. Eight of the more important considerations are discussed below.

A. INSUFFICIENT ORGANIC MATTER

Many of the organic levels of the Yellowstone petrified forests are thin and contain insufficient organic matter to qualify as "soils." Modern forests, with growing trees several meters in diameter, have deep humus floors unless they are growing on significant slopes. Often large petrified trees in Yellowstone sit on only a trace of organic matter. Other trees may arise from 2-3 cm of "soil" — far short of the amount expected from the age of the trees, based on study of modern trees of comparable species and size growing on a level forest floor.

B. ORGANIC AND INORGANIC SORTING

In this research, gross identification of the wood specimens in the organic levels was undertaken. Trees were classified as pine-type (resin ducts present), sequoia-type (no resin ducts), and deciduous (vessels present). Leaves and needles in the organic levels were identified using the same categories.

Taxonomic sorting of the constituents in the organic bands (needles and leaves not mixed together) was noticed early in the research. Under normal conditions leaves, needles, cones, limbs, bark, etc., fall as a well-mixed litter onto the forest floor year by year as the seasons pass and the trees grow. A flotation experiment involving aspen and poplar leaves and fir needles in a tank of water showed that the needles became saturated and sank to the bottom first. Thus flotation in water is a possible explanation for the observed taxonomic sorting in the "soil" levels.

Occasional organic levels from Specimen Creek Fossil Forest, and Mt. Norris and Miller Creek petrified forests show a relationship between the size of the ash sediment and the size of the organic material — fine sediments, fine organic matter, coarse sediments, coarse organic matter. The Eagle Creek Formation of the Oregon Cascades is a coarse volcanic sediment that contains many petrified trees similar to the breccias of Yellowstone. That these trees in Oregon have a similar origin and history to those of Yellowstone is a reasonable assumption. An example from an organic level from this Oregon formation shows similar size sorting of the inorganic particles among or between leaves (Figure 13).[18] The leaves are seen in cross-section as long, somewhat undulating lines. The sediments show normal grading between the lines (grading from coarse to fine upward).

Figure 13. Cross-section of an organic zone from the Eagle Creek Formation in Oregon. See text for discussion of similarities of this Oregon site with Yellowstone. Note that sediments are sorted between the deciduous leaves (dark wavy horizontal lines). This illustration first appeared in: Coffin HG. 1983. Origin by Design. Washington DC. Review and Herald Publishing Assn., p 143.

C. ATYPICAL SOIL PROFILES

The organic levels associated with the Yellowstone petrified forests range from soil profiles typical of a true growing surface to reverse profiles; however, the majority 86 (71.6%) of 120 microscopic cross-sections through organic levels give evidence of water sorting. The rest, although not typical soil profiles, do not give clear evidence for either in situ or transported origins. The organic matter is usually randomly oriented (Figure 14). Ten percent of the organic cross-sections showed a reverse profile — more dense at the bottom and less dense toward the top.[19] Sufficient water to rework the soil would also wash out growing trees, especially smaller ones. The water transport of both the "soil" and the trees is a more reasonable explanation.

Figure 14. A microslide of a thin section from an organic level in the Cache Creek area. The wavy dark horizontal lines are cross-sections of deciduous leaves. Note the following features: a) clean ash or sand between the leaves; b) sudden change in grain size between the upper and lower halves of the organic level; and c) different types of organic debris in the fine and coarse sediments.

Differential decay of the organic matter characteristic of a forest floor — better preserved leaves and needles on top and more decayed downward — is not seen.[20]

The movements of volcanic lahars over the ground could produce atypical soil profiles, but, most likely, any soil profile would be eliminated. These anomalous profiles might be produced by small streams sorting and redepositing humus and forest litter. However, these organic levels are often widespread and uniform in thickness. This feature and the lack of evidence of widespread erosion would appear to eliminate small streams as agents for sorting and redepositing the organic matter.

Three transects (50 m long and 1 m wide) that I did in a Central California mature redwood forest revealed 135 sequoia cones and 79 other cones on the surface of the forest floor. Although sequoia cones are small and fragile, they do remain intact and visible for several months after falling. Sequoia cones are absent or rare in the Yellowstone fossil forests despite the dominance of sequoia trees. Cones of any type are uncommon in the petrified forests (Figure 15).

In a mixed forest of redwood and deciduous trees such as exists in California, the redwood needles greatly predominate in the forest floor litter. For the area overshadowed by a tree, conifers appear to drop proportionately many more needles than do deciduous trees their broad leaves. In 1899, Knowlton remarked about the absence of needles in the organic levels associated with the large fenced petrified tree near Roosevelt Lodge in Yellowstone National Park.[21] Our studies there are summarized in Table 4. There is a lack of taxonomic agreement between the dominant petrified trees in the area and the leaves and needles. One would expect to find great numbers of sequoia needles and some cones, since most of the upright trees are sequoia. However, large numbers of broad leaves and only a few pine needles

Figure 15. A rare but beautiful petrified cone (not Sequoia) found on Mt. Hornaday. This photograph first appeared in: Coffin HG. 1983. Origin by Design. Washington DC. Review and Herald Publishing Assn., p 145.

are seen in the organic levels. Sequoia needles were rare or absent. Although petrified sycamore stumps are not common, leaves of sycamore are the most abundant broad-leaf fossils. Transport by water could bring about sorting and separation of plant parts.

TABLE 4. TAXONOMIC BREAKDOWN OF THE PETRIFIED FOREST 2 KM WEST OF ROOSEVELT LODGE, YELLOWSTONE NATIONAL PARK

	SEQUOIA-TYPE	DECIDUOUS	PINE-TYPE	UNKNOWN	TOTAL
Petrified Trees	28	5	4	3	40
Organic Samples	0	75	27	0	102

If a volcanic mud slide buried only the lower parts of the trunks of the trees of a growing forest, the taxonomic composition of the new forest that grew on this new surface would be similar to the composition of the forest that was buried. The cones, seeds, nuts, and fruits would fall from the unburied branches and foliage and repopulate the new surface with a similar forest. Such correlation between adjacent levels of the Specimen Creek Petrified Forest has not been found.[22]

D. COMPLEX ORGANIC LEVELS

Most modern growing surfaces are a single layer of humus. I have seen multiple growing surfaces that were caused by shifting sand dunes. The organic levels of the Yellowstone Fossil Forests are more complex than would be expected to result from these modern processes. Flooding could cause humus to be redeposited, perhaps creating multiple levels. This is apparent especially in the Cache Creek and Specimen Creek petrified forests (Figures 16 and 17). Note the penetration of trees b and e through overlying organic zones as seen on a section of cliff face from the Cache Creek Petrified Forest. The Specimen Creek organic levels are even more complex.[23] Some of the organic levels associated with this forest split and recombine. Levels one and two are less than a meter apart. Such multiplicity and complexity of organic levels is beyond that reasonably expected for growing surfaces and are better understood as organic matter brought in and deposited by water.

E. PALYNOLOGY

Many genera are represented only by pollen, but this might be expected, since the wood samples have not received thorough study. On several levels in the fossil forests, wood and pollen have been identified. There is not a good match between the types of wood and pollen, as would be expected in an in situ forest. More difficult to explain, if the trees are in position of growth, are the cases represented only by wood or leaves. Trees with wind-transported pollen, such as walnut and sycamore, should have left a pollen record in the forest floor, but little or no pollen of these two has been found.

Modern forest floors contain pollen in abundance inversely proportional to the distance from the source trees — especially trees for which wind is the pollen-transporting agent. Research done on four levels of Specimen Creek Petrified Forest showed no positive correlation between fossil pollen abundance and the proximity of possible source trees.[24] No positive correlation was found to exist between the taxonomic composition of pollen of one organic level with that of levels directly above or below. Pine is a prolific pollen producer, but pine pollen was severely under-represented in three of the four forest levels analyzed. One of these three levels showed a severe under-representation of pine pollen and a severe over-representation of deciduous pollen compared to the number of petrified trees in these categories.

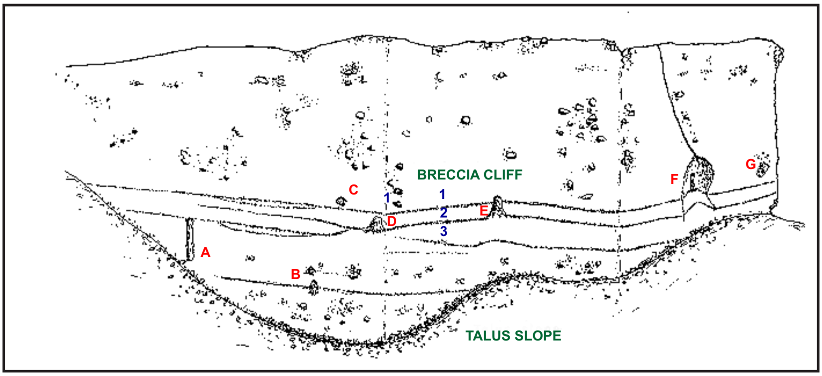

Figure 16. A section of a cliff from the Cache Creek Petrified Forest showing complex organic levels and associated trees. Modified from the illustration in: Coffin HG. 1979. The organic levels of the Yellowstone Petrified Forests. Origins 6(2):71-82.

F. LACK OF EVIDENCE FOR WEATHERING

The formation of clay by the slow breakdown of feldspar and other minerals occurs during the normal maturation of soils. Analyses by x-ray diffraction and infrared scans were done on over 350 samples from 65 levels in the Specimen Creek area.[25] Nine bands of clay that included 7 organic levels were found distributed through this sequence of 65 levels. Clay content was up to 60%, but no typical soil profile was detected in any of the 7 organic zones. Horizontal sampling of two of the clay bands at 2.5-3 m intervals for 30 m showed a constant mineral distribution. Abundant unweathered feldspar is scattered throughout the Yellowstone organic levels, suggesting rapid burial and limited diagenesis or alteration of the feldspar to clay.

None of the 58 organic levels outside the 9 bands of clay contained detectable amounts of clay. The apparent absence of clay in the majority of levels (implying that normal weathering of soil did not occur) raises questions about the passage of long time intervals between levels. This datum also questions the validity of the assumption that the organic levels, upon which trees with hundreds of rings sit, represent true soils. Furthermore, the sudden abundant appearance of clay in a few horizontal bands that included both organic levels and layers of clay in the associated breccia beds between levels suggests transport rather than in situ formation of the clay minerals.

The rate of clay formation is variable, depending on climate and the parent rock. A sequence of mud slides on Mt. Shasta that occurred from 27 to 1200+ years ago does not show much increase in clay content with age.[26] In contrast, clay formed on the volcanic ash soils of the West Indian

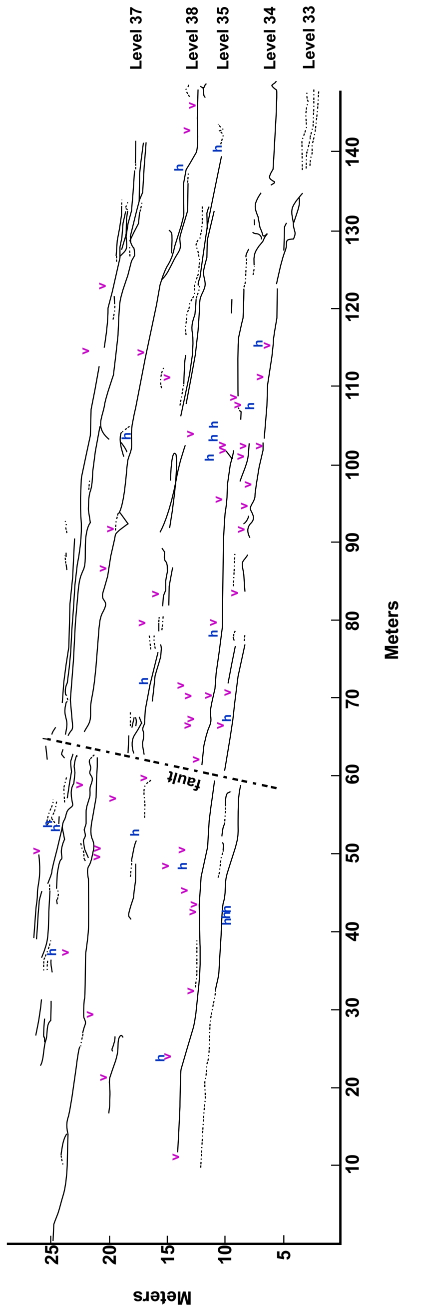

Figure 17. A plot of organic levels 33 to 37 in the Specimen Creek Petrified Forest. Note the irregularity and complexity of these levels. Symbols: v = vertical trees; h = horizontal trees. Modified from the diagram in: Coffin HG. 1983. Origin by Design. Washington DC: Review and Herald Publishing Assn., p 142.

island of St. Vincent at the rate of 0.5 m per 1000 years.[27] Some levels in Yellowstone with large trees (up to 5 m in diameter) would represent soil development well over 1000 years duration if the trees are in growth position. The mixed flora of the Yellowstone fossil forests suggests a climate closer to the tropics than to that of Mt. Shasta.

The tentative results from the study of clay suggest that no significant passage of time was involved in the formation of the organic levels of Yellowstone.

G. ABSENCE OF ANIMAL FOSSILS

Despite much study of the Yellowstone Petrified Forests, no animal fossils have been found. Why are animal remains absent from the plant fossil-bearing levels of Yellowstone? Because forests would be expected to harbor a wide variety of animals, some of which would be buried by the successive mud slides, the absence of animal fossils has been a mystery. Volcanic activity could have caused larger forest animals to flee elsewhere, but flight cannot be used as an explanation for the absence of all animal remains because many animals could not or would not leave their forest habitats. Land snails, some amphibians and reptiles, many insects, arachnids, and worms would not escape burial. Immature members of many types would be unable to flee. In addition, bones, eggs, teeth, scales, molted skins, castings, droppings, burrows, etc., would qualify as evidence of animal life. None of these have been found in the fossil forest organic levels during a century of research. Considering that delicate plant parts are excellently preserved, animal remains should also have been preserved if they were present. Only one exception is known. Remains of termites have been found in chambers within the petrified wood.[28]

If the petrified trees are standing where they originally grew and if the organic levels are the growing surfaces still intact and undisturbed, the absence of animal fossils is difficult to explain. If, however, the trees and the organic debris making up the soil levels were transported by water, the separation of animals from the plants before burial is much easier to explain.

H. TRACE ELEMENT PROFILES

The organic levels from which the petrified trees arise usually have a high volcanic ash content. Where did the ash come from? Spark source mass spectrometry analysis of trace elements in the bands of ash revealed pulses of ash from four source areas for the Specimen Creek Petrified Forest.[29] The four trace element profiles interfinger in an irregular manner up the sequence of 65 organic levels of Specimen Creek Petrified Forest. If these

65 ash layers (organic levels) were laid down over a long time span, the ash that was laid down thousands of years later near the end of the series of ash eruptions would have changed sufficiently to produce a new and different trace element profile. This has not been the case. Quick burial of the whole sequence seems to be required. Two of the sources for the ash appear to be Electric Peak in the northwest comer of Yellowstone Park and Lone Mountain 48 km farther northwest.[30]

I. EXAMPLES OF ORGANIC LEVELS FROM ELSEWHERE

Two examples of organic levels from Washington and Oregon add support to the proposition that organic levels like those in Yellowstone can be laid down underwater.

A road cut for Interstate 84 in the Miocene Eagle Creek formation near Cascade Locks, Oregon, exposed several levels of petrified trees, both vertical and horizontal, and bands of organic debris in volcanic breccia — a situation closely similar to that of Yellowstone. Whatever interpretation is achieved for the Yellowstone breccias will probably apply also to the breccias of this Oregon location, and vice versa (refer to Figure 13). A pronounced gradation of sediments between the deciduous leaves (seen in cross-section) is striking. Such grading is unexpected in normal undisturbed soil and suggests transport.

The extensive Ohanapecosh formation in Mount Rainier National Park, Washington, contains some organic levels, although they are less strongly developed than those of Yellowstone. Horizontal petrified trees also were noted. These breccias have been interpreted as subaqueous deposits.[31] Obviously these organic levels cannot be growth surfaces if the deposits slid into position underwater.

VI. EVIDENCE FOR TRANSPORT OF THE PETRIFIED TREES

The factors relating to the petrified trees that are of most significance for a transport model deal mainly with their position and condition, internal structure, and taxonomy.

A. THE ROOTS

Some of the petrified trees have broken roots; but when were they broken? Even if a permit to collect petrified wood within the park is obtained, excavation of stumps is not permitted; furthermore, digging is difficult in the hard rock. Consequently, to determine if the root breakage seen is pre- or post-petrification is difficult. Several examples of abrupt root terminations from Mt. Hornaday, Mt. Norris, Tom Minor Basin, and Specimen Creek strongly indicate that, at least in some cases, the tree roots were broken before the trees were buried by volcanic gravels and muds. This evidence supports the view that the trees were transported.

Small rootlets can be located at the bases of upright stumps, and this feature has been used to argue against transport.[32] Observations in Spirit Lake near Mount St. Helens and of trees uprooted by bulldozing operations show that the small roots and rootlets are usually still intact, but the larger roots often may be broken (Figure 18). The presence of small roots extending from the base of a petrified tree therefore is not evidence for an in situ interpretation unless large roots also extend unbroken. Broken and frayed large roots could be the result of changing stream currents eroding the bases of growing trees, but such activity should leave evidences in the sediments. Furthermore, erosion must be limited; otherwise, trees would be removed or toppled.

B. LACK OF DECAY

If a forest were killed by a mud flow that buried the bases of the trees, the tops of the trees would extend above the new ground surface. They would overlap a new second forest that would commence growing on the new surface. During the time of the growth of the new second forest (before it in turn was buried by another volcanic mud slide) the old first forest snags would have time to rot, to be infested with insects, and to break down. Even the tops of stumps that reached only to the root area of the second forest level (no actual overlap) would also be expected to experience decay. The soil in which the roots of the second forest grew would not be a good preserving medium for the tops of the stumps extending up from below. One of the striking features of the Yellowstone petrified trees is their good preservation (refer to Figure 11). If pieces of the petrified wood are prepared as microslides, the wood tissue may look nearly as fresh as tissue from a living tree. Seldom do they exhibit any evidence of decay and weathering. This suggests that the trees have not been subjected to these processes during the passage of time.

C. ORIENTATION OF STUMPS AND LOGS

The parallel orientation of the horizontal logs, mentioned earlier, is better explained by water or mud transport. The dip of the beds from which the trees arise seldom exceeds 7º, which is not enough to cause all the trees to fall downhill. The dip may be due to post-deposition uplift. Prevailing winds or volcanic blasts could align fallen trees, but they would not cause the long axes of the cross-section of the upright stumps to have a similar compass alignment.

Figure 18. A tree torn out of the ground by the eruption of Mount St. Helens. Note that the large roots are broken while the small rootlets are largely intact.

The asymmetry of the cross-section of a stump, especially at its base, is usually a result of the influence of major roots that cause flare to extend for some distance up the stump. Volcanic lahars (fast-moving volcanic mud slides) or currents of water or mud could be the forces that acted on roots and trunks to produce similar alignment for both stumps and logs.

D. ABNORMAL ECOLOGY

The many petrified trees and plants in the Yellowstone area represent a diverse grouping of species. Exotic genera such as cinnamon, breadfruit, katsura and chinquapin are presently restricted to southeastern Asia. Erling Dorf accounted for this unusual assemblage by postulating a basin at low elevation (to accommodate the tropical and semitropical species) into which leaves and wood from surrounding higher elevations were transported.33 On the other hand, William Pierce suggests that gravity sliding of the Heart Mountain Thrust Fault from west to east could occur only if the area supporting the ancient Yellowstone forests was at high elevation.[34]

The mixed flora is most easily explained by the transport of trees and plant parts from different habitats and geographical locations into a flooded basin where lahars, mud flows, or turbidity currents left accumulations of sediments (Figure 19).

E. DENDROCHRONOLOGY

The results of dendrochronological research might appear at first to support an in situ interpretation. However, matching of rings from trees on different levels would be most unlikely if they are in position of growth. Arct[35] has found matching growth ring patterns for upright trees separated by one or more levels. Living forests on successive levels that are sequentially buried by volcanic mud slides could not have grown at the same time and under the same weather conditions. Sequences of wide rings (abundant rain) and narrow rings (drought) would be different. These results are a strong argument for their being allochthonous (transported from elsewhere).

F. ABSENCE OF BARK AND LIMBS

One of the first observations made when research commenced on the petrified forests was the barkless condition of both the horizontal and upright trees. Subsequent examination has revealed some thin layers of bark remaining on a few of the trees. In addition to the trees being mostly barkless, all the branches have been broken off. Even large branches, 25 cm or more in diameter, have been removed. Only scoured stubs remain on the tree trunks. Trees buried and later excavated by water erosion during the eruption of Mount St. Helens did not have all the bark or limbs removed. Trees floating for a period of time in turbulent water would more likely lose bark and branches due to softening of the bark and abrasion.

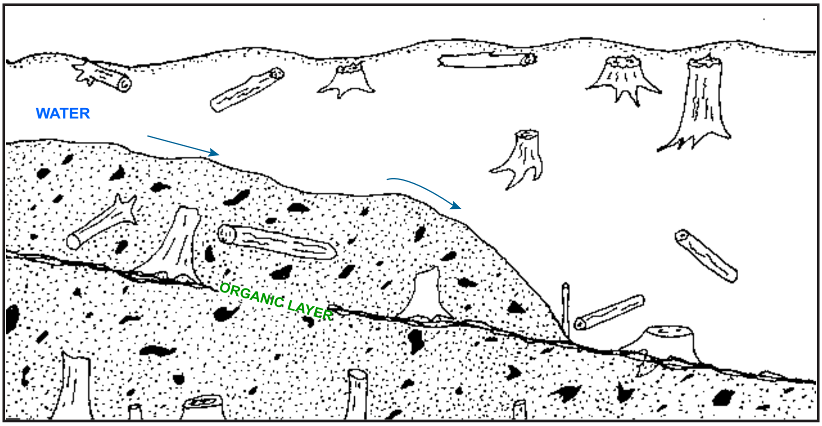

Figure 19. A sketch of a model for the rapid burial of trees (both upright and horizontal), and organic debris, by underwater volcanic mud slides (coarse-grained turbidites). Modified from the illustration in: Coffin HG. 1983. Origin by Design. Washington DC: Review and Herald Publishing Assn., p 151.

VII. A MODERN CASE HISTORY

A. THE ERUPTION OF MOUNT ST. HELENS

On May 18, 1980, Mount St. Helens in the state of Washington erupted with a roar heard 300 km away and a force equal to 500 Hiroshima atomic bombs.[36] Enough ash and rock were moved to provide a ton for every person on Earth. A blast of ash-charged superheated gas was flung northward, killing 61 humans and thousands of animals.[37] Millions of trees in 600 km^2 of prime forest were blown down or killed.[38]

The eruption that removed nearly 400 m from the top of the beautiful mountain was triggered or preceded by a 4.9 magnitude earthquake.[39] The immediate result of the jolt was a massive avalanche down the north face which had been bulging at a rate of 1.5 m per day for several weeks.[40] The eruption following the slide eviscerated the mountain, leaving a crater 600 m deep. A resort lodge and thirty cabins were pulverized and buried under 90 m of sediments.

The forests in the area north of the mountain were devastated. Huge trees, some of them 2 m or more in diameter, were felled like matchsticks (Figure 20). The areas closer to the mountain showed blast destruction without much regard for the topography, although trees on the south-facing slopes were more completely destroyed or removed than those on the north-

Figure 20. The eruption of Mount St. Helens snapped and uprooted thousands of trees, some of great size.

facing slopes. When the incandescent blast began to lose speed farther from the mountain, it funneled down the valleys, leaving the trees on the tops of the surrounding hills untouched.

B. RIVER TRANSPORT OF UPRIGHT STUMPS

Associated with the St. Helens eruptions, trees and stumps have been transported upright to new locations. Mud slides and turbid floods down the North Fork of the Toutle River have deposited and buried trees in an upright position. Many erect stumps in various stages of burial have been scattered on some of the mud flats and gravel bars (Figure 21).[41] One huge stump over 2 m in diameter and 13 m tall sits on the toe of the 24-km-long debris flow.

Figure 21. Stumps of trees previously logged were torn out of the ground by volcanic activity associated with the eruption of Mount St. Helens, transported down the Toutle River, and dropped upright onto the scoured floor of the river. Note that some of the upright stumps are partially buried. This photograph first appeared in: Coffin HG. 1983. Origin by Design. Review and Herald Publishing Assn., p 149.

C. SPIRIT LAKE

Before the eruption of Mount St. Helens, Spirit Lake, located at the base of the mountain on the north side, was a beautiful gem among virgin forests with the majestic mountain as a backdrop. The lake probably originated during similar past eruptions of the mountain when the floor of the north

Figure 22. A portion of the log raft on the surface of Spirit Lake near the base of Mount St. Helens. Note the trees floating upright off Eagle Point. Upright trees are in the log mat also, but not as obvious as those in the open water. This photograph first appeared in: Coffin HG. 1983. Erect floating stumps in Spirit Lake, Washington. Geology 11:298-299. Reprinted with permission of the Geological Society of America.

fork of the Toutle River Valley was raised by volcanic debris. This natural dam impounded the water that became Spirit Lake.

Most trees seen in rivers are rootless logs floating horizontally. Opportunities for observations on significant numbers of floating logs with roots have been few. In casting about for a modern (if local) example, I thought of Spirit Lake. The eruption of Mount St. Helens tore thousands of trees out of the ground and threw many of them into Spirit Lake. When the north face of the mountain collapsed into Spirit Lake, water surged scores of meters up surrounding hills and washed many trees into the lake. A huge floating mat of logs and debris now covers nearly half of the lake surface (Figure 22). It consists of plant material ranging from chips of bark to trees with trunks nearly 2.5 m in diameter. Many of the trees still retain their root systems. Research on this log raft has thrown light on the flotation characteristics of trees.

D. RESEARCH IN SPIRIT LAKE

Our research began at the lake in September 1982, two and a half years after the eruption. We noticed many stumps upright in the water (Figure 23).

Figure 23. A small sample of the log raft on Spirit Lake. The upright trees in the foreground are lightly grounded in shallow water, whereas those in the background are floating free.

Some of them could be seen drifting with the wind. To be certain that they were not anchored to the bottom in their original positions of growth but truly were floating or had drifted into shallow water where they were now grounded, scuba divers examined the lower ends of many of the stumps. They found that the root systems were either well above the lake bottom (truly floating) or that they were lightly grounded on the bottom.[42] The latter could be pushed around and when tilted would swing back into vertical position. Some stumps that had sunk were standing upright on the bottom, their tops well below the surface of the water. Others floated or sat on the bottom mud with tops protruding above the water surface (Figures 24 and 25).

We wondered how many floating stumps and logs had already sunk to the bottom. To answer that question, we chose to utilize side-scan sonar. Although scuba divers had verified that stumps were sitting erect on the bottom, quantitative measurements were not possible by this method because of the size of the lake, the depth of the water, the darkness below certain depths because of water turbidity, and other factors.

Using side-scan sonar, transects covering slightly under 1% of the lake bottom yielded 154 vertical stumps and 95 prostrate logs.43 A sonograph reveals light areas or reverse shadows when objects block sound transmission (Figure 26). The vertical light streaks are sonar shadows cast by erect trees. Confirmation of these sonar results was obtained by divers at specific sites and by observing the sonograph recordings of vertical stumps whose protruding tops revealed their locations. Extrapolation to the entire lake bottom gave approximately 19,500 erect stumps and about 12,000 horizontal logs. The submerged stumps and logs range in height from less than 1 m to more than 20 m.

Figure 24. A large erect stump sitting on the bottom of Spirit Lake that extends within a meter of the surface of the water. This stump is representative of thousands that are sitting upright on the bottom of Spirit Lake. This photograph first appeared in: Coffin HG. 1987. Sonar and scuba survey of a submerged allochthonous "forest" in Spirit Lake, Washington. Palaios 2:179-180. Reprinted with permission of the Society of Economic Paleontologists and Mineralogists.

Figure 25. Floating tree trunks with tops protruding above the surface of Spirit Lake. In time they likely will sink upright and disappear into the depths if the water is sufficiently deep.

Figure 26. Side-scan sonograph showing several erect trees in a 75 m length on the bottom of Spirit Lake. The vertical streaks are sonar shadows cast upon the bottom of the lake by upright stumps. Scattered wood debris is also visible. This illustration first appeared in: Coffin HG. 1987. Sonar and scuba survey of a submerged allochthonous "forest" in Spirit Lake, Washington. Palaios 2:178-180. Reprinted with permission of the Society of Economic Paleontologists and Mineralogists.

After the completion of a safety tunnel that lowered the lake surface approximately 7 m, submerged upright stumps in the process of being buried became visible. Underwater examination via scuba divers also verified this observation.

E. FLOTATION CHARACTERISTICS

The floating log raft in Spirit Lake also provided some insights on taxonomic sorting. Most of the stumps sitting erect on the bottom of Spirit Lake are Silver Fir, Noble Fir, and Hemlock. Douglas Fir, abundant in the surrounding forests, has only 2.2% representation. Sampling of the trees in the floating raft solved this discrepancy; 48% are Douglas Fir. Apparently this species is more buoyant and resistant to water saturation. Cedar was represented by 2.2% of logs floating in the lake; yet the surrounding forests contained a higher percentage of cedars. Sampling of the broken wood pieces along a transect on the shore gave 11% for cedar. Cedar is brittle wood, and evidently most cedar trees were shattered by the volcanic blast and associated violence.

Some of the erect trees floating in the lake or standing on the lake bottom are over 20 m tall. The argument that tall petrified stumps must be in position of growth does not apply to a flotation scenario.

The flotation of organic matter (including trees in an upright position) as illustrated in Spirit Lake at the base of Mount St. Helens provides a model for interpreting the upright petrified trees of Yellowstone. Trees and plants will float vertically when there is sufficient water and time. The research at Spirit Lake helps explain the presence of the organic layer at the level of the roots. Saturated organic debris sinks to the lake bottom to produce a layer of organic matter. Upright floating trees also have dropped out of suspension onto the bottom of Spirit Lake in a spacing pattern similar to that of growing forests (Figure 27). They are not jumbled together in log jams as might be expected.[44]

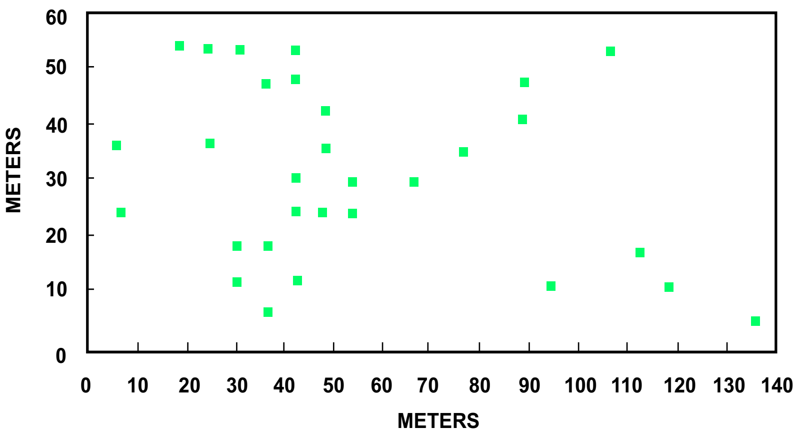

Figure 27. Spacing of erect stumps on the bottom of Spirit Lake. The plot represents a continuous 140 by 60 m area of lake bottom. (Note that the right half is a continuation from the top of the left half.)

Some have argued that Spirit Lake is not a good analog for the Yellowstone Fossil Forests, because the large number of logs accumulating on the bottom of Spirit Lake is very different from the more scattered fossil logs and stumps in Yellowstone. However, one important difference between the two deposits is that Spirit Lake has not had adequate sediment input to bury the sinking logs and stumps. If the 1980 Mount St. Helens eruption had been followed by a series of volcanic breccia flows into Spirit Lake, spaced long enough apart to bury successive sets of logs and stumps as they sank, it would likely have produced a deposit very similar to the Yellowstone Fossil Forests.

VIII. ALLOCHTHONOUS MODEL

A. ALLOCHTHONOUS ORGANIC LEVELS

The normal accumulation of organic debris and the subsequent formation of humus and true soil that proceeds relentlessly on modern growth surfaces do not readily account for several of the phenomena seen in the organic levels of Yellowstone. These are specified below.

1. The absence or thinness of organic matter on levels with abundant and large trees.
2. The sorting of organic and inorganic matter.
3. The lack of a typical soil profile.
4. The multiplicity and complexity of the organic levels.
5. Lack of agreement between leaves and pollen and the dominant wood types.
6. The absence of clay, or, when present, uncorrelated to the organic levels.
7. The absence of evidence of animals expected in typical forest plant-animal associations.
8. The evidence from the study of the trace elements of the volcanic ash, associated with the organic levels, for repeated eruptions during a short span of time of insufficient duration to support the growth of a superimposed series of forests.

B. ALLOCHTHONOUS TREES

The main factors that support the transport of the trees seen in the Yellowstone Petrified Forests are summarized below.

1. Large roots that can be traced to upright trees are broken or terminate abruptly.
2. The good preservation of tree wood. Decay is seldom seen.
3. The parallel alignment of logs and stumps appears to require their transportation by a moving force such as water or mud.
4. The variety of habitats and climatic preferences seen by the great taxonomic diversity of trees and plants suggests transport.

5. Matching growth rings for trees on different levels requires contemporaneous growth elsewhere and subsequent transport to a new location.

6. Battered and barkless trees are better explained by transport in violent water than by growth in situ.

IX. CONCLUSION

The evidence presented here provides a basis for additional detailed research that could be done. Such research would be beneficial for our understanding of these unique fossil deposits. Offhand, the in situ model would appear to be the simplest and most natural explanation, but closer examination uncovers features that are difficult to explain for trees in growth position. A transport model involving the flotation of trees and organic debris in a body of water, as illustrated in Spirit Lake, gives a better fit to the data as observed in the Yellowstone Petrified Forests. We propose that the Yellowstone Petrified Forests provide an example of catastrophic deposition.

ACKNOWLEDGMENTS

I wish to thank Donald Jones and John Boyd who assisted greatly in plotting some of the Yellowstone sites. I am thankful to Lanny Fisk who gave many helpful suggestions and assisted with field studies and subsequently went on to make significant contributions to the Yellowstone research. I am indebted to Ivan Holmes and Clyde L. Webster, Jr., for important contributions in geochemistry; the former for the x-ray diffraction studies of Specimen Creek Fossil Forest organic levels and the latter for trace element research. Steve Austin gave assistance at Spirit Lake with the side-scan sonar research and underwater photography for which I am grateful.

GLOSSARY

Basalt — an extrusive molten rock, dark in color and often exhibiting columnar jointing.

Breccia — rock consisting of angular broken fragments cemented together.

Caldera — a large crater produced by explosion or collapse at the summit of a volcano.

Cambrian — a period (the earliest) in the Paleozoic Era.

Conglomerate — rock composed of rounded fragments of heterogeneous size and composition cemented together.

Cretaceous — a period in the Mesozoic Era.

Ecology — the study of the relationships of organisms to one another and to their environment.

Eocene — an epoch in the Cenozoic Era.

Formation — a clear-cut unit of rock usually with uniform texture and composition.

Genera (singular, genus) — a unit of classification above the species but below the family.

Geologic column — the total vertical sequence of strata considered to have been laid down during geologic time. Creationists consider the geologic column largely to be the result of a worldwide flood.

In situ — in natural position; not transported or moved.

Lahars — mud slides full of volcanic debris.

Miocene — an epoch in the Cenozoic Era.

Mississippian — a period in the Paleozoic Era.

Oligocene — an epoch in the Cenozoic Era.

Organic — any matter consisting of, or produced by, living organisms.

Palynology — the study of fossil pollen.

Petrification — the process of becoming hard like rock.

Precambrian — all time or deposits before the Cambrian.

Sedimentary — composed of particles; consisting of sediments.

Species — a unit of classification below the genus. Animals and plants able to interbreed are usually considered in the same species.

Stratigraphy — the study of stratified rocks as they relate to Earth's crust.

Taxonomy — the study of the relationships and the classification of organisms.

Thrustfault — a fault that has resulted from one mass of rock being thrust onto another.

ENDNOTES

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23. Coffin 1983, Fig. 11.7 (see Note 20).

24. DeBord 1979 (see Note 12).

25. See the Acknowledgments section for appreciation expressed to Ivan Holmes and Clyde Webster, Jr.

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