THE INFLUENCE OF SOIL MOISTURE ON SITE IN TOM SWAMP I, HARVARD FOREST

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1. Water Relations as a Primary Factor in Site Differentiation on the Harvard Forest. The broad patterns of vegetational types at the Harvard Forest are correlated with major features of relief, exposure, and drainage. Thus recent workers (Raup and Carlson, 1941; Spurr, 1950; Stout, 1952) have emphasized that forest types in which black oak, white oak, and red maple are prominent occur commonly on exposed ridges and hilltops. Protected ravines and lower parts of north-facing slopes, on the other hand, are often characterized by the presence of much hemlock and beech. Red oak, white ash, red maple, and white pine are the most abundant trees of such intermediate sites as long gentle slopes. Red maple is also very common in forested swamps; white ash and yellow birch may be associated with it in such situations. Larch and black spruce, together with red maple and hemlock, are found in the more open bogs.

Correlated with these topographical features are physical factors which may influence the growth and development of plants. Rasche (1953), for example, has found striking differences in temperature between hilltops and valley bottoms in Petersham. On one summer night in 1948 the temperature at Harvard pond was 18^0 F. lower than that at Prospect Hill, only 3.1 miles away and 627 feet higher on the slope of a prominent north-south ridge. It is to be expected that rates of evaporation and transpiration may be relatively low on cool lower slopes and valley bottoms. Ridges and hilltops, exposed to sun, relatively warmer air, and desiccating winds, might be predicted with confidence to be relatively dry habitats. Furthermore, rain water running off ridge tops or draining through the ground may accumulate at lower elevations before ultimately passing into streams. Consequently, hilltops probably are less abundantly supplied with ground water than lower slopes and bottoms. These considerations are summarized in the common observation that on the Harvard Forest hilltops are dry; valley bottoms are moist or wet; and slopes are intermediate in moisture content. Since major vegetational types are also correlated with topography, the inference is obvious that differences in available moisture may be of primary importance in influencing their distribution on the Harvard Forest.

The suggestion that water relations might also be important in the differentiation of subtypes within major forest types of the Harvard Forest was made by Stout (1952). Previous investigators had described and attributed to historical accident the patchwork distribution of red oak and white ash on a gentle west-facing slope of the Tom Swamp tract. By digging several deep pits within the different local types of vegetation, Stout found important differences in the subsoils. Where white ash was the primary species, he found within 18 inches of the surface of the ground a compact layer of soil capable temporarily of perching a water table. Under stands of red oak, on the other hand, this compact layer was found generally at depths of 22 inches or more. Extending his observations to other parts of the Harvard Forest, Stout discovered that his compact layer was very widely distributed indeed, being absent only on some dry hilltops and sandy outwash plains. He was also able to confirm the relationship between the depth to the compact layer and the distribution of dry and moist types of vegetation.

Stout observed further that variations in depth to the compact layer were related to certain previously overlooked microtopographical features. By careful examination he found that many of the long gentle slopes of the Harvard Forest really consist of sets of terraces, the relatively steep fronts of which are often banked with boulders and stones. On or immediately behind such terraced fronts the depth to the compact layer of subsoil was always considerably greater than some distances back from them. By an ingenious application of theories of periglacial frost action, Stout was able at one stroke to account for the distribution of terraces and variations in depth to the compact subsoil. According to these ideas, which have been repeatedly confirmed in observations made near existing retreating glaciers, solufluction and loess deposition are exceedingly common phenomena at glacial fronts. It has been demonstrated that freezing soil can absorb considerable amounts of water. Upon melting, this soil is converted into a viscous liquid which slowly creeps down gentle slopes. Alternating freezing and thawing also shatter boulders, and expansion and contraction of the underlying earth may cause the resulting fragments slowly to migrate peripherally, forming stone rings. If the migration is not equal in all directions, stone ellipses and stripes may result. Stone stripes and boulder fields similar to those found at high latitudes or on the tops of high mountains of the temperate and tropical zones are not uncommon at the Harvard Forest. Stout has produced convincing evidence that many of the stone-banked terraces of the Harvard Forest have indeed resulted from solufluction.

Dust storms and deposition of loess are also much in evidence along the fronts of existing retreating glaciers. Stout argued that the relatively uniform layer of fine sandy loam which blankets the Harvard Forest, covering the compact layer of soil where the latter is present, may in part be loessial in origin. Thus Stout derived the Petersham subsoils from glacial till modified by congeliturbation; the compact layer is appropriately called the tight till. The overlying loose layer is loess, probably ultimately to be derived from silt deposited on glacial outwash streams, and this, too, has been modified by the action of frost since its original deposition. Thus by appealing to mechanisms of periglacial frost action, Stout at one stroke accounted for the existing microtopography, the loose and compact layers of soil, and for the distribution of existing sites and corresponding forest types on the Harvard Forest.

It is not always possible to distinguish surficial loams from underlying tills except where the latter are sandy or gravelly or very compact. Obliteration of sharp boundaries between loess and till is believed to have been caused by congeliturbation and windthrow. The presence of many stones and boulders in the surficial loams may be explained in the same manner.

2. <u>The Study Area</u>. Since Stout's work was a pioneer venture, it was necessarily extensive, and as he himself realized, his studies were made mostly in stands of complex history. The purpose of the work reported in the present paper was to investigate intensively on a relatively small area the relationships between subsoils, topography, groundwater, and vegetation. An area ideally suited for such a study should possess the following five attributes: (1) It should contain good examples of frost forms, such as boulder fields and stone-banked terraces; (2) A tight till should be present on at least part of the area; (3) It should be covered with a stand of virgin timber or old-growth woods, the previous cultural treatment of which was known to be simple and uniform throughout the area. A large number of tree species in the canopy layer would be desirable; (4) It should be representative of an important site-type of economic importance to the Harvard Forest and the surrounding area; (5) It should be about ten acres in size.

A small part of the northwestern corner of Compartment I of the Tom Swamp tract, which fulfilled these stringent requirements in all respects but one, was chosen as the area for this study. The vegetation, unfortunately, had had a somewhat complicated history. An improvement cutting, the boundaries of which were somewhat vaguely defined, was made in 1908-9. About three cords and three thousand board feet of large-toothed aspen were removed per acre. In 1914-15 three thousand board feet of scattered chestnut were cut in anticipation of its being killed by the blight. Following the hurricane of 1938 several up-rooted pine logs were salvaged and 87 cords of fuelwood were cut from leaning and fallen trees. It is, of course, probably impossible to determine how much influence such activities have had on the composition of this stand. Most of the area, however, appears always to have been in woods.* It contains some of the finest large trees of white pine and red oak on the Harvard Forest, many of which are 60 to 70 feet tall and 15 to 20 inches in diameter at breast height. Floristically, this area is unquestionably richer in both woody and herbaceous species than any other stand of comparable area on the Harvard Forest. Thus, although the stand has probably been pastured and certainly strongly influenced by both wind and axe, it represents the nearest approach to an old-growth midslope woods available at the Harvard Forest.

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*The area is part of houselot #51 deeded to Joseph Whitcomb in 1733. In a deed of 1825 the 70 acres containing this area were described as "wood and pasture land" (Artemus Bryant to Jonas Howe, Nov. 29, 1825; 245/640). Approximately the northern half of the study area was mapped as woodland in 1850 (Raup and Carlson, 1941), and was again described as woodland in a deed of 1888 (Lott Dennis, a butcher of Orange, to Phineas Brooks. June 25, 1888. 1269/648).

The study area contains good examples of probable frost forms. The most striking of these is a boulder field which cuts across a large part of the study area (Fig. 1). Some of the stones in this field are over six feet high, and many have angular faces. Two steep-fronted terraces also were readily distinguished. The study area is topographically diverse in other respects. A small swamp, choked with a dense growth of <u>Ilex verticillata</u>, is situated near the southeastern corner of the tract. After heavy rains, an intermittent stream rushes down a small ravine near the southern boundary of the study area. To illustrate these features, a contour map of the study area was made in 1952 by W. J. Gabriel and the author (Fig. 2).

Post holes dug to depths of ten inches or more revealed the presence of a tight till over most of the area. In a few places, notably along the western border of the tract, no tight tills were found, even at depths of over 40 inches. The soils of the study area were mapped by the U. S. D.A. Bureau of Plant Industry, Soils, and Agricultural Engineering ~~Soils~~ as Charlton sandy loam (Simmons, 1939-41). There is considerable variation, however, in the depth of the melanized, highly organic surface layer of the soil, and the presence or absence of a tight till (compact subsoil) should, in the opinion of the present writer, be sufficient to throw the soils of the study area into at least two series.

Situated on a northwest-facing, long hillside of gentle slope, well drained except for occasional small swales, the study area is typical of a very extensive type of site on the Harvard Forest. The only other important area of old-growth forest, the so-called "Barre Woods" of Slab City, was avoided, because it represented the cool, north-facing, ravine-bottom habitat type, of relatively minor importance on the Harvard Forest.

The area studied contains about 366,000 square feet (8.4 acres). It was possible to establish a rectangular grid of 56 stations spaced at intervals of about 100 feet, at which the ground water was observed frequently. Five intermediate stations were subsequently established. These 61 stations are labeled A_1, A_2, ..., E_{10}, on the topographic map.

3. Ground-water Studies. Observations on the behavior of the ground-water table constituted a major part of these studies. At each of the 61 stations a "post-hole" about 18 inches deep and 15 inches in diameter was dug. The depth from the surface of the ground to the ground-water in the hole was then measured on 29 days from November 5, 1951, to June 13, 1952. Although no attempt was made to measure the depth to the water table in other ways, it is believed that the observations accurately represent the behavior of the water in the ground near the stations. Spaeth and Diebold (1938) in south-central New York found that water-table measurements made in similar shallow wells differed in no important respect from measurements made in tube wells if the compact layer of the subsoil was not penetrated in the excavation.

The results of these observations are summarized graphically in Fig. 3. It is obvious that there was considerable diversity in the behavior of the ground-water tables. Holes D_7 and A_7, for example, were nearly full of water during the entire period of observation. Holes A_2, A_4, A_6, B_3, B_6, B_8, C_1, C_4, on the other hand, were always completely dry. Between these two extreme types were such intermediate stations as B_5, C_1", D_4, D_5, D_6, E_3, E_5. In order to reduce these many observations to more easily grasped relationships, the stations were classified according to the pattern of ground-water behavior as seen in the graphs. The procedure followed was simple. All stations the graphs of which nearly matched that of station A_1 were classified as belonging to the "A_1 type." Since A_2 did not fall in this category, it was considered as the type for a second class, the "A_2 type." The behavior of A_7 as indicated by its graph was considered sufficiently distinct from these two types to justify the erection of a third class typified by it. This procedure was continued systematically until each station had been accounted for. It must be emphasized again that the classification is based entirely on the appearance of the graphs, and that no attempt was made to fit the stations to an arbitrarily predetermined number of classes. The six types resulted simply because the graphs seemed to the author to fall into six natural groups. Obviously, the classification is not perfect. The A_8 type, for example, intergrades with both the A_1 and A_2 types of behavior. In the opinion of the author, however, the A_8 type is best kept distinct. Others may disagree. This simply means, of course, that in this, as in most human attempts to categorize natural phenomena a certain subjective element is unavoidable. One may ask, in fact, if any classification such as the one presented here has a logical basis in theory. Is there any a priori reason why the depth to the ground-water in any two holes should behave almost identically over the period of observation? If so, the classification has a logical basis, and an ideally correct classification must exist. If not, the classification is merely a matter of convenience, designed to reduce to some sort of order a mass of over 1700 observations which could otherwise scarcely be comprehended. In the latter instance, no ideally correct classification exists. In the opinion of the author, the phenomena here studied ideally should not be classified into discrete categories but instead should be represented as points on a continuum. Practically, however, this is difficult and hence the classificatory method of presentation is followed.

Fig. 4 indicates the average behavior of the water table in each of the six moisture classes, obtained by computing the daily mean depths to the water table within each moisture class. Where no water was observed (dry hole), the depth to the ground-water table was arbitrarily placed at 20 inches. The graphs are arranged in order of increasing wetness of site, the A_2 type being the driest and the A_7 the wettest. Included also is a graph showing the daily rainfall measured over the period of observation at Harvard Forest headquarters, about three miles from the study area.

In the fall of 1952 the author re-excavated all holes in order to determine the depth to the compact layer ("tight till"). In 46 holes this layer was readily encountered at depths of ten to 35 inches. The tight till was lacking or apparently so in 15 holes, although each of the latter was excavated to a depth of at least 30 inches. When the moisture class of a station was plotted as a function of the depth to the tight till, the resulting scatter diagram (Fig. 5) indicated a fairly close linear relationship. Where the depth to the tight till was less than 18 inches, the station invariably belonged to one of the two wettest moisture classes. On the other hand, where the tight till was 35 or more inches below the surface of the ground or where it was lacking, the station always belonged to one of the three driest categories.

These relationships may be stated in another manner. The number of days in which a station was dry (no water standing in the post hole) was plotted as a function of the depth to the tight till (Fig. 6). At the 14 stations in which the compact layer was 18 inches or less beneath the surface of the ground, the holes were dry on no more than two of the 29 days on which observations were recorded. At 15 stations no tight till was found, although the holes were excavated to depths of 30 to 46.5 inches. All such stations were dry on at least 24 days; in eight water was never recorded.

The relationship shown in Fig. 5 obviously is not perfect, indicating that the variation in behavior of the water table is not entirely to be accounted for by parallel variation in the depth to the tight till. Other factors such as degree of slope and differential internal resistence to flow of water caused by roots, stones, and boulders also influence the behavior of the ground-water table. Nevertheless, the presence or absence of a tight till and its depth below the surface of the ground certainly were of primary importance in determining the behavior of the ground-water table on the study area.

4. Vegetational Studies. Although the subject of this paper is the interrelationship of the ground-water regime and the compact layer in the subsoil, observations were also made on the tree cover of the study area. A tree species was recorded as present at a station if its crown was over the hole and its trunk was one inch or more in diameter at breast height. Small and large trees were not differentiated, nor was the abundance of the species recorded. A subjective estimate of the primary species, however, was made at each station. The frequency of occurrence of the five most common species of trees found on the study area has been plotted for each water-table class (Fig. 7). White pine was much the most frequent species at the driest

stations (A_2 type). Red maple and red oak were common at dry, intermediate, and wet stations; the former was most frequent at very wet holes, the latter at intermediate to dry sites.

Fig. 8 suggests a relationship between the depth to the tight till and tree cover. Where the compact subsoil was lacking, white pine was the most frequent species. White ash and red maple were the leading species where the tight till was within 18 inches of the surface of the ground, although white pine was again common in this situation. In excavating the pits, it was noticed that the bulk of the roots of trees did not penetrate the tight till. A compact layer near the surface of the ground might well hinder the growth of species normally producing deep roots and thus favor competing species with shallow, spreading root systems, The tight till may thus affect the composition of vegetation quite independently of any influence it may have on the behavior of the ground-water table.

Although the stand studied consisted of a mixture of about 15 species of mature trees growing on a moist slope favorable for the growth and development of hardwoods, the leading tree species was white pine. White pine was recorded as the primary species at 19 stations; its closest competitor, red oak, was the primary species at ten stations. White pine was also the most frequent species, being recorded as present at 27 stations, although red oak and red maple were almost as commonly encountered. The importance of white pine in this old stand is surprising, because in a nearby stand in the same compartment it was found uneconomical to attempt to perpetuate white pine in competition with the same species of hardwoods. At the outset it must be admitted that the white pine trees growing on the study area may be of "old field" origin, although the form of the trees and what little is known of the use-history of the study area makes this unlikely. On the other hand, when the distribution of white pine over the study area is considered, it seems much more probable that the pine emerged successful in competition with the hardwoods. White pine was most frequent at stations of the A_2 (dry) type, and where the tight till was lacking. Although it appears to be competitive with the hardwoods on somewhat moister sites as well, white pine is pre-eminently a species of relatively dry sites and perhaps develops best in fairly light soils which permit its roots freely to grow in all directions. It would appear that white pine can be grown with profit in the region of Petersham if careful attention is paid to the site. Many foresters have become discouraged with the species because it is not competitive on all sites, but this would hardly seem to be a fair test of its potentialities.

White ash appears to be the economic species best suited to very moist and wet sites where the compact layer of soil is relatively near the ground surface. Although red maple is more frequently present and dominant in such situations, it is, with rare exceptions, valuable only as firewood. Where white ash was the primary species (three stations) the compact layer was less than 22 inches from the surface of the ground. It would appear, therefore, that white ash can be grown profitably in moist pockets, swales, and along the banks of streams, providing competition from red maple is reduced.

On intermediate sites red oak was the most frequent species. Growing on the study area were several handsome specimens which well illustrated the potentialities of the species in the Petersham area. Black and white birches were also common. The importance of black birch in the forests of Petersham seems very generally to have been underestimated. Locally the tree has been used only for cordwood.

5. The Nature of the Tight Till. Determining the depth to the tight till was not always a simple task of digging until a uniform, easily recognized, compact layer was reached. No compact layer was found in almost 25 percent of the holes excavated. In a few (A_8, C_1'', E_3) a fairly tight layer was found, which was recorded as "weakly developed." Such situations, however, were exceptional. At the majority of stations an unmistakable tight till was readily found which differed from the overlying sandy loams chiefly in degree of compaction and in color. For charting profiles of trenches and pits, the blade of a jackknife was jabbed point-first into the side of the pit

at several places. The tight till was charted as the layer of soil penetrated with difficulty by the knifeblade. Commonly, especially in very wet places, the tight till could be distinguished from the dark surficial layer by its light, blue-gray color. Where the surficial loam was reddish brown, the tight till was usually a somewhat yellowish gray, suggesting that it had been less thoroughly oxidized than the overlying layers. To summarize, the tight till is a layer of earth two to four or more feet thick distinguished from over-lying layers by its more compact consistence ~~structure~~ and by differences in color.

The texture of the tight till is not noticeably different to the touch from that of the overlying loam, and Goodlett (unpublished) in a large number of careful siftings found no important differences in proportions of sand and silt between the two layers. This fact, together with the observations of intergradations in compactness between an easily recognized tight till in many stations and its apparent complete lack in others, make plausible the hypothesis that the tight till may be a developed horizon--a hardpan--a compacted subsoil derived from the same parent material as the overlying horizons. According to this interpretation, stations at which the tight till is lacking are places in which a hardpan never developed, because conditions were unfavorable for its development. Where conditions were slightly more favorable, doubtful "tight tills" developed. At station C_1" a compact, grayish layer

mechanical analysis

about six inches in thickness encountered at a depth of 32.5 inches was recorded as a tight till. Deeper digging revealed compact gravel in the bottom of the pit, but this latter could not be classified as a tight till. In hole A_4 a thin, weakly developed compact layer was found at a depth of 25 inches, but this gave way to looser soil beneath, and no other compact till was encountered to a depth of 40 inches. To summarize, at seven stations the compact layer was recorded as "doubtful" or "weakly developed." In the 61 holes excavated, almost all possible degrees of compactness were found.

These variations in compactness of the tight till would seen difficult to explain under the hypothesis that the latter is "geological" in origin. According to that theory, the tight till represents the surface exposed by the retreating glaciers; the overlying looser sandy loam consists of material deposited by wind but subsequently modified by congeliturbation and windthrow to include some material originally deposited as till. Much variation in soils has been attributed to the vagaries of glacial deposition, but providing that the material deposited was very nearly the same over the study area, it is difficult to understand how some subsoils came to be so much more compact than others.

fragipan?

According to the hardpan theory, the "tight till" has originated since the retreat of the last Wisconsin glaciers through the action of soil-forming processes.

Since the study area contains stations at which the tight till is present, absent, and present but weakly developed, it is ideally suited for the investigation of conditions necessary for the development of "tight tills." The results of these studies may be briefly summarized. Where, because of the nature of the topography and the texture of the subsoils, water tended to collect and slowly to percolate through the soil to the permanent water table, so that the solum was nearly saturated for relatively long periods of time, hardpans tended to develop. Where the topography favored rapid runoff or a coarse subsoil allowed rapid percolation, so that the solum was excessively well drained, hardpans did not develop. The two extreme situations will be discussed separately.

a) *Tight tills well developed*. Stout in 1952 made the important observation that where the ground surface was concave, the loam overlying the tight till was relatively thin, but where the surface was convex the loam was relatively thick. Stations A_7 and D_7 were located in conspicuous concavities on our area. The latter was situated in a small swamp or swale on a terrace flat where the tight till was well developed and only ten inches from the surface of the ground. Fig. 9 indicates how water carrying particles of silt and clay may tend to accumulate in such situations. The solum through which this water slowly percolates acts as a kind of filter, screening out the suspended particles. The latter in time tend to clog the pores of the filter, with the result that ultimately water moves through the solum with increasing difficulty. The water table is thus temporarily perched. The more pronounced the clogging process, the nearer the hardpan will move to the surface of the ground. The bottoms and banks of intermittent streams and rivulets are also well supplied with water laden with silt, clay, and colloidal organic matter. Stations A_9, B_9, C_9', C_{10}, C_{13}, D_9', D_{10}, E_9' and E_{10} were located near an intermittent stream which flows in a westerly direction through the southern end of the study area. In all a well developed tight till was found, and in eight of these ten holes the depth to the tight till was 17 inches or less. A trench dug across this stream between stations E_9 and D_9 is profiled in Fig.10. The depth to the tight till was at a minimum in the stream bed, where it was only 11 inches. Farther down the stream at station C_9 the depth to the tight till was again only 11.5 inches. Similar results were obtained at the other end of the study area. The depth to the well developed tight till at station B_1', at the edge of a smaller intermittent stream, was only ten inches. Another pit was dug 30 feet upstream from station B_1'; here the depth to the tight till was 16.5 inches.

Stations C_5, D_1', D_3, E_1', and E_7, which possessed well developed tight tills within 18 inches of the surface of the ground, were not situated in obvious concavities or near intermittent streams, or other sources of water. No simple explanation of the development of these "tight tills" is offered under the hardpan theory. It should be noted, however, that at D_1' the water in the hole was perched ten inches or more above the tight till on 27 of the 29 days recorded; similar observations were made at station E_1'. Since the ground water remained well above the surface of the tight till, it would appear that factors other than the tight till alone were tending to maintain it at a high level. Local concentrations of stones, boulders, and tree roots probably tend to impede the free lateral flow of ground water and thus favor the development of hardpans.

To summarize, 12 of the 15 stations at which the tight till was within 18 inches of the surface of the ground were supplied with abundant ground water. Conversely, in almost all places known to be supplied with an abundance of water, the tight till was found at depths of less than 18 inches. Station A_9 was exceptional. Although it belonged to the A_7 moisture class, its tight till was found at a depth of 26.5 inches.

b) <u>Tight till absent</u>. Tight tills were lacking at 15 stations. At eight of these (A_2, A_3, A_6, B_1, B_3, C_1, C_2, D_1'') coarse-grained material--gravel, sand, or loose mica schist--was noted at the bottom of the pit. The remaining six holes were excavated to depths of at least 33 inches before the work was abandoned. The lack of a compact layer at the stations where a layer of coarse material was present at depth is conveniently explained under the hardpan hypothesis. After percolating through the upper solum, water moves rapidly through the layer of coarse material, flushing the upper layers of small particles. The effect is essentially that of the flower pot in the bottom of which pieces of rock or broken crockery are placed to facilitate "drainage."

These relations were studied in more detail in a deep pit excavated between stations B_6 and B_7 (Fig. 11). Under a thin melanized horizon lay a 16-inch belt of reddish sandy loam. This rested on an horizon approximately two feet thick, of yellowish, slightly compacted, fine sandy loam. Beginning at a depth of 41 inches was a belt of coarse sand and gravel varying in thickness from three to 19 inches. The latter material was underlain by apparently solid schistose rock, which occupied the entire 26 square feet of the bottom of the excavation. Although clearly no tight till was present, the yellowish horizon of this pit is, according to the theory here presented, an incipient hardpan which can be shown almost imperceptably to intergrade with the very compact "tight tills" of other stations. Under the geological hypothesis, however, the loam overlying the gravel must be considered entirely loessial in origin since it cannot be distinguished from the loams overlying nearby "tight tills." The only glacial deposit in the pit would then be the narrow belt of loose gravel overlying the mica schist. At nearby stations

(B_7, C_7, C_6, C_5, B_5, and A_7), however, "tight tills" were present in soils of approximately the same texture, color, and depth as the yellowish horizon in this pit. According to the geological theory, these compact layers must be glacial in origin. A map of the glacial deposits on our area would thus show a compact, fine sandy loam covering the eastern and southern parts of the study area but passing abruptly into sand and gravel between B_6 and B_7, the latter phase continuing to station A_6. Such a map would make degree of compactness the only basis determining whether a soil horizon was glacial or loessial in origin. Under the hardpan theory, the entire solum is glacial in origin (no loess is hypothesized). It is assumed that open channels under the ice may locally have been filled with glacio-fluvial deposits of coarse materials, but over these and the rest of the area was deposited a relatively uniform fine sandy loam, dispersed throughout which were numerous stones and boulders.

Both geological and hardpan theories have been discussed elsewhere, but no general agreement about the origin of compact tills is evident. The U. S. Soil Survey in its Manual (1951) recognizes a group of "very compact horizons, rich in silt, sand, or both, and usually relatively low in clay, /which/ commonly interfere with water and root penetration. When dry, the compact material appears to be indurated, but the apparent induration disappears upon moistening." Such layers, termed "fragipans" because of their brittleness, are apparently identical with the "tight tills" of the Harvard Forest. The Survey Manual states that "it has not yet been generally agreed whether fragipans are merely an expression of extreme compaction or are reversably indurated." Jahns, in a U. S. Geological Survey report (1953), probably expressed the views of most geologists in stating that the unstratified blanket of silt and fine sand present in all parts of the Ayer Quadrangle (east-central Massachusetts) is "evidently of windblown origin." He recognized two kinds of till underlying the windblown material. The younger was generally "bouldery, loose, and poorly compacted" and was most commonly pearl gray in color, although pale reddish brown and tan tills were also present. The older till, which was darker in color and distinctly more compact, was characterized by a "closely spaced parting that splits its fine-grained portions into thin chips on freshly exposed surfaces." Since brittleness and compactness are also characteristic of fragipans, it would appear that these tills might be interpreted as hardpans by some.

It is the opinion of the present author that on the Harvard Forest at least the hardpan theory is probably correct, although the evidence is by no means complete. Further investigation is needed on the microscopic structure of the "tight till." Are the pores in the soil actually clogged with very small particles which have moved down from overlying layers with the percolating ground water? The writer observed in one pit vertical streaks of colored material extending from the loose loam into the tight till. The phenomenon may be more general. Are the loose loam and the tight till mineralogically identical, as required by the hardpan theory? The distribution of the tight till throughout New England and adjacent states should be investigated. The writer has noted a typical tight till in a grave excavated in 1953 in Scituate, Massachusetts, where this compact layer is apparently well known to farmers. If the tight till is the result of a soil-forming process, it should occur wherever climate and parent material of the soil closely resemble those obtaining at Petersham. Until these points have been more thoroughly investigated, the true nature of the tight till will not be understood.

6. Applications. The investigations reported here of the physical factors related to site differentiation are of interest in view of a recent grouping of soils into six "soil-drainage classes" by the U. S. Soil Survey (1951). Although it is encouraging to find that the primary importance of soil moisture is becoming widely recognized, it is to be hoped that future classificatory schemes will be placed on a strong observational basis. Much survey work on soil moisture is based on degree and depth of soil mottling, but the relationship between mottling and moisture needs much more clarification. It is argued that a mottled soil indicates reduction of iron compounds. This in turn is an indication of oxygen lack and consequently

of considerable moisture. It is true that Spaeth and Diebold (1938) demonstrated the correctness of this argument in a study made in south-central New York State, but more extensive investigations are needed. A satisfactory soil-drainage classification must be based ultimately on the behavior of the water itself, not on putative indicators of its behavior. In science deductive arguments may suggest but do not prove relationships. In the absence of supporting data, therefore, any classification of soils based on degree and depth of mottling must be considered at best doubtfully valid.

It appears quite evident, however, that site moisture has had an important influence on the distribution of major species of trees on the study area. It may also have influenced profoundly the development of its soils. This is not to suggest that the vegetation of the study area can be comprehended through the study of a single environmental factor, however important. In fact, if the whole habitat were thoroughly understood, the vegetation growing on it would always remain an enigma to the degree that chance events might have determined the establishment of individual plants on sites to which they were not perfectly suited.

Such chance events, however, need not seriously concern the forester, who in the management of any wild stand must in any event choose among the trees already growing on the site. Accurate appraisal of the potentialities of the site is important in such cases. The forester who recognizes the importance of soil moisture may legitimately ask for practical methods of estimating the moisture class of a site. Stout's work suggested that the shape of the ground surface might be useful in estimating the depth to the tight till, and this idea is strongly supported both theoretically and observationally in this report. Where the ground surface is concave, soil moisture is likely to be high and the layer of loose loam overlying the tight till is generally thin. Where the ground surface is convex, soil moisture is usually lower and the layer of loose loam is generally thick. Foresters with a good knowledge of the local flora may find correlations between soil moisture and the ground vegetation. W. J. Gabriel and the present author recorded very marked differences in the frequency and abundance of several herbaceous species under adjacent stands of young red oak and white ash in Tom Swamp I, not far from the present study area. Students of soils may prefer to excavate post holes. If a tight till is found within 20 inches of the ground surface, the site is probably suitable for white ash. The present author, finding all these methods useful, confesses that even taken together they are not completely sufficient. A certain amount of intuition, based on the forester's experience and personality, will in his opinion always play an important part in judgments of site quality. Site evaluation, therefore, will probably always remain something of an art.

7. Summary. The depth to the ground-water was recorded at 61 stations in the western part of Tom Swamp I between November, 1951, and June, 1952. On the basis of these observations, the stations were grouped in six site-moisture classes.

The depth to the tight till was determined at 46 stations; compact subsoils were apparently lacking at 15 stations. Site-moisture class was shown to be correlated with depth to the tight till.

Although the use-history of the study area is complex, the distribution of important timber species is correlated with site-moisture class and depth to the tight till. White pine was the most frequent species on dry sites and where the tight till was lacking. White ash was most abundant on wet sites, but the less valuable red maple was a severe competitor in such situations. Red oak was the primary species at most intermediate stations, although black and white birches were also common.

The compact layer of the subsoil ("tight till") is interpreted as a hardpan, probably equivalent to the "fragipan" of the U. S. Soil Survey. It is suggested that the formation of such hardpans is favored by ample supplies of water and a uniformly fine-textured soil. Where coarse sand or gravel underlay fine sandy loams, hardpans were not encountered or were weakly developed.

Methods of site-moisture estimation are discussed.

ACKNOWLEDGMENTS

The writer is indebted to Professor H. M. Raup, Director of the Harvard Forest, for his patient guidance, criticism, and encouragement through all phases of the work. Many of the ideas presented in this paper arose during conversations with Dr. J. C. Goodlett, who maintained a lively interest in the project from its inception. The field work was done jointly with Mr. W. J. Gabriel, to whom appreciation is expressed for stimulating discussions and help in many other ways.

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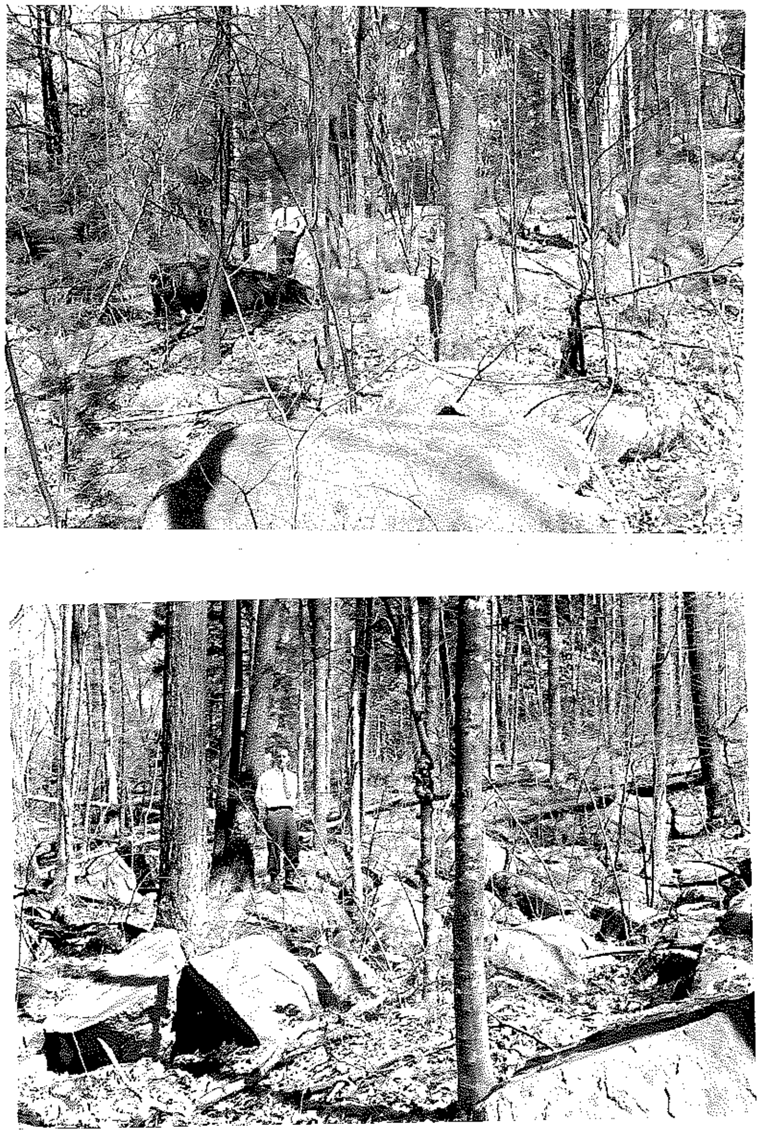


Figure 1

Boulder concentration near station B_5.

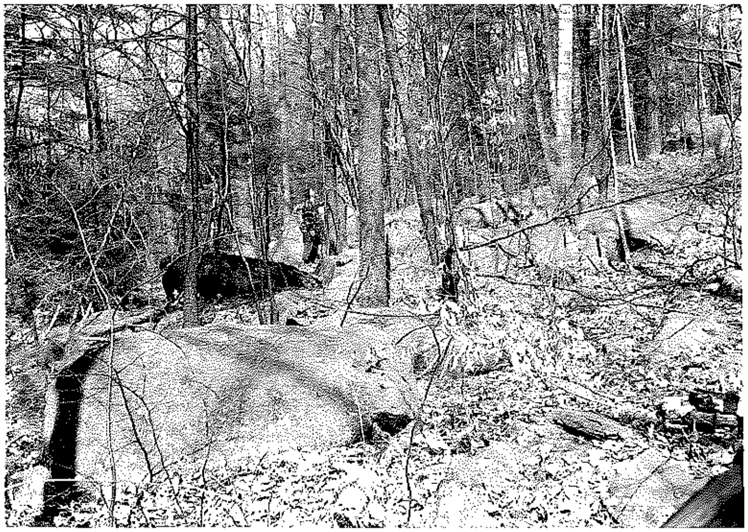
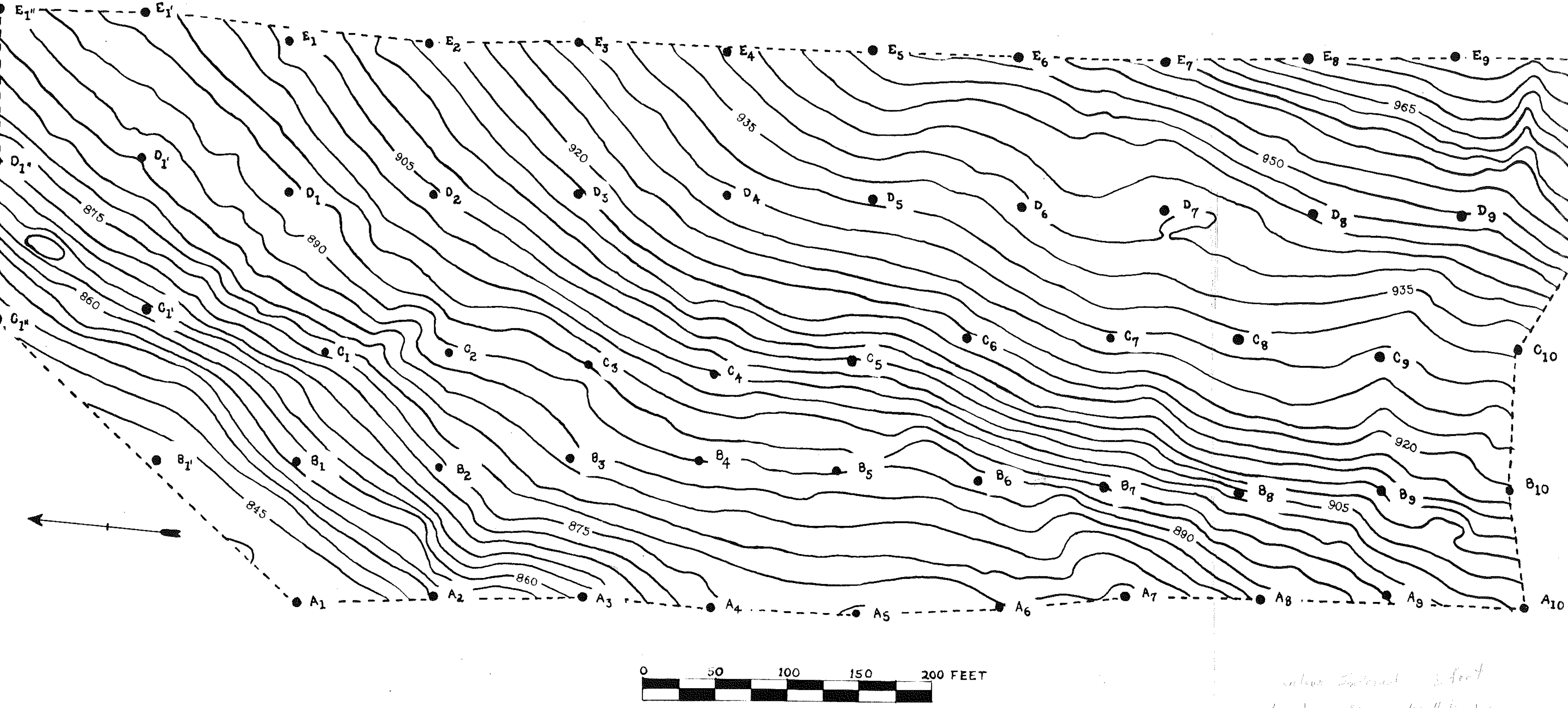


Figure 2

Map of study area. Contour interval 3 feet. Spots labeled A_1, A_2, ..., E_{10} indicate stations at which soil and ground-water studies were made. Contours drawn by W. J. Gabriel.

Fig 2
[illegible]

Figure 2



Contour Interval 5 feet
based on survey by [illegible]

Figure 3

Results of ground-water studies. The depth to the compact layer of subsoil at each station is indicated in parentheses. Asterisk (*) indicates pit was excavated to depth indicated without encountering a compact layer. In the graphs, ordinates indicate depth to ground-water table. Dry holes are arbitrarily represented as if depth to ground water had been 20 inches.

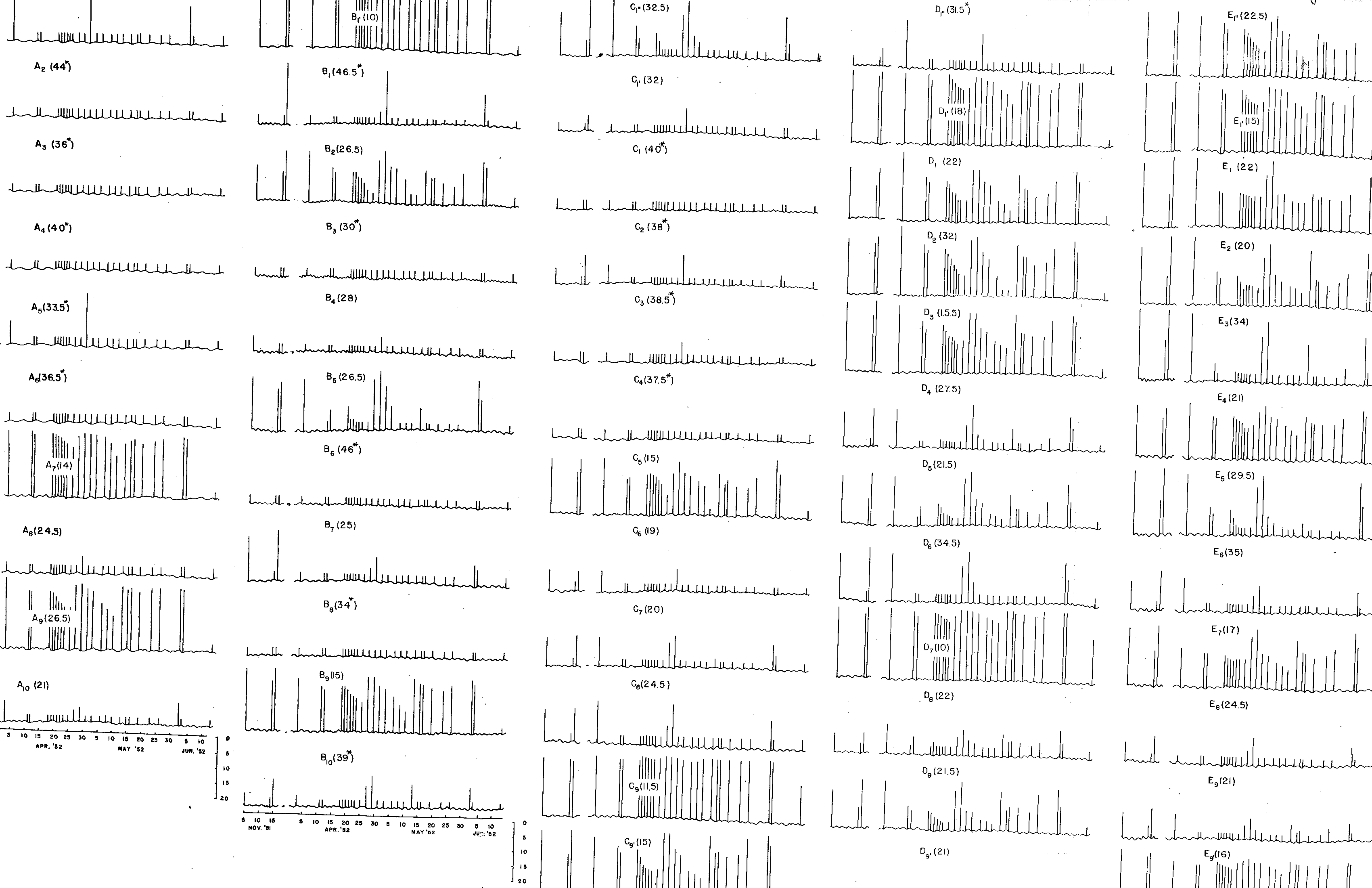

A_2 (44*)
A_3 (36*)
A_4 (40*)
A_5(33.5*)
A_6(36.5*)
A_7(14)
A_8(24.5)
A_9(26.5)
A_{10} (21)
5 10 15 20 25 30 5 10 15 20 25 30 5 10
APR. '52
MAY '52
JUN. '52
0 5 10 15 20
$B_{1'}$(10)
B_1(46.5*)
B_2(26.5)
B_3 (30*)
B_4(28)
B_5 (26.5)
B_6 (46*)
B_7 (25)
B_8(34*)
B_9(15)
B_{10}(39*)
5 10 15 5 10 15 20 25 30 5 10 15 20 25 30 5 10
NOV. '51
APR. '52
MAY '52
JUN. '52
0 5 10 15 20
$C_{1''}$ (32.5)
$C_{1'}$ (32)
C_1 (40*)
C_2 (38*)
C_3 (38.5*)
C_4(37.5*)
C_5 (15)
C_6 (19)
C_7 (20)
C_8(24.5)
C_9(11.5)
$C_{9'}$ (15)
$D_{1''}$ (31.5*)
$D_{1'}$ (18)
D_1 (22)
D_2 (32)
D_3 (15.5)
D_4 (27.5)
D_5(21.5)
D_6 (34.5)
D_7(10)
D_8 (22)
D_9(21.5)
$D_{9'}$ (21)
$E_{1''}$ (22.5)
$E_{1'}$ (15)
E_1 (22)
E_2 (20)
E_3(34)
E_4 (21)
E_5 (29.5)
E_6(35)
E_7(17)
E_8(24.5)
E_9(21)
E_9(16)

Figure 4

Average behavior of ground water in the six moisture classes. Daily rainfall in inches for period of record was measured at Harvard Forest headquarters, about 3 miles from study area.

Figure 4

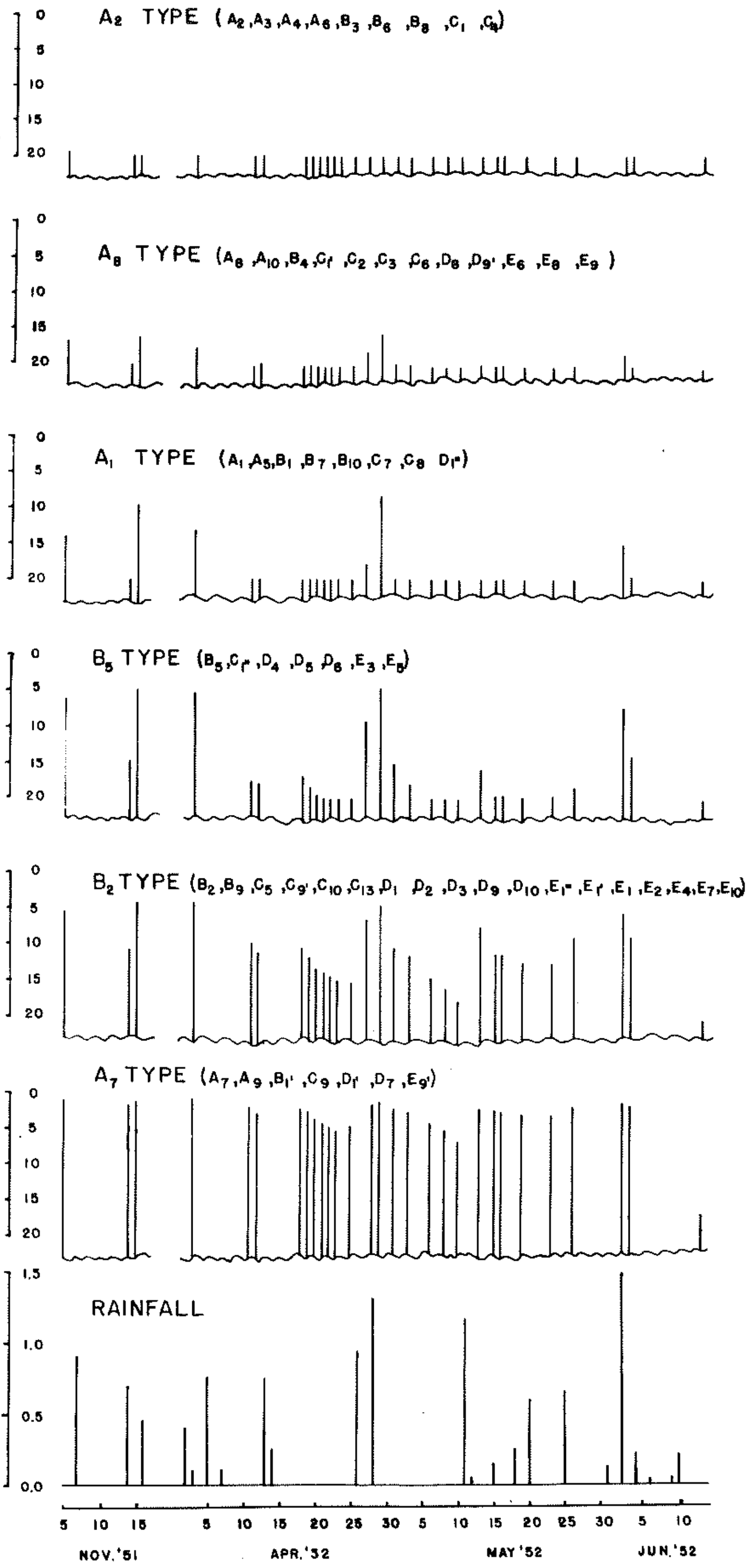

A2 TYPE (A2, A3, A4, A6, B3, B6, B8, C1, C4)
A8 TYPE (A8, A10, B4, C1', C2, C3, C6, D8, D9', E6, E8, E9)
A1 TYPE (A1, A5, B1, B7, B10, C7, C8, D1")
B5 TYPE (B5, C1", D4, D5, D6, E3, E5)
B2 TYPE (B2, B9, C5, C9', C10, C13, D1, D2, D3, D9, D10, E1", E1', E1, E2, E4, E7, E10)
A7 TYPE (A7, A9, B1', C9, D1', D7, E9')
RAINFALL
0
5
10
15
20
0.0
0.5
1.0
1.5
5
10
15
5
10
15
20
25
30
5
10
15
20
25
30
5
10
NOV.'51
APR.'52
MAY '52
JUN.'52

Figure 5

Site-moisture class plotted as function of depth to the compact layer of subsoil. A_1, A_2, ..., A_{10} indicate stations at which soil and ground-water studies were made. Asterisks (*) indicate pit was excavated to depth indicated without encountering compact subsoil.

Figure 5

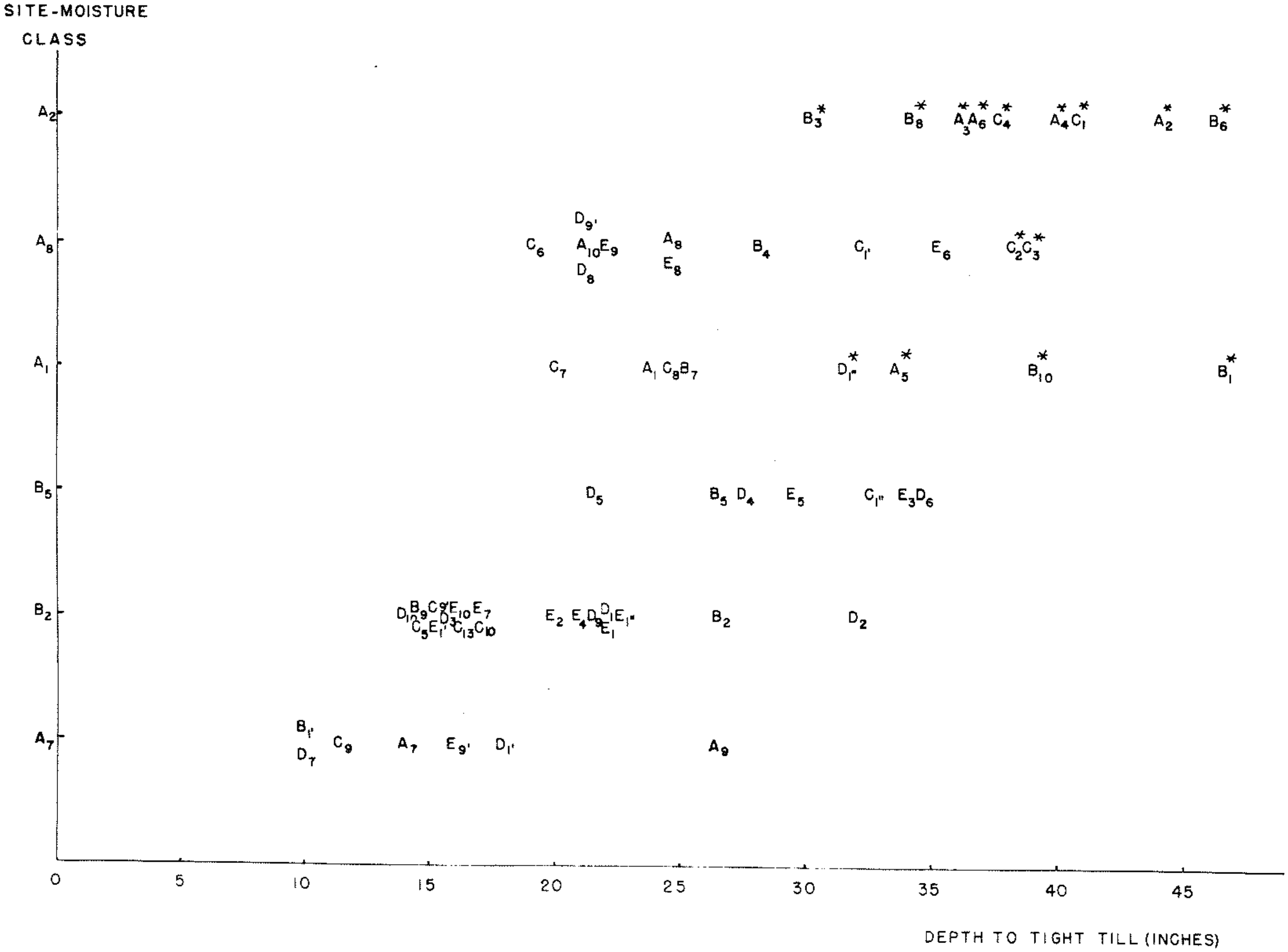

SITE-MOISTURE CLASS
A2
A8
A1
B5
B2
A7
0
5
10
15
20
25
30
35
40
45
DEPTH TO TIGHT TILL (INCHES)
B3*
B8*
A3*
A6*
C4*
A4*
C1*
A2*
B6*
D9'
C6
A10
E9
D8
A8
E8
B4
C1'
E6
C2*
C3*
C7
A1
C8
B7
D1"*
A5*
B10*
B1*
D5
B5
D4
E5
C1"
E3
D6
D12
B9
C9
E10
E7
C5
E1'
D3
C13
C10
E2
E4
D9
D1
E1"
E1
B2
D2
B1'
D7
C9
A7
E9'
D1'
A9

Figure 6

Site-moisture class plotted as a function of depth to the compact layer of subsoil. Note that wells in which compact layer lay within 18 inches of the surface of the ground were dry on no more than 5 of the 29 days on which observations were recorded.

Figure 6

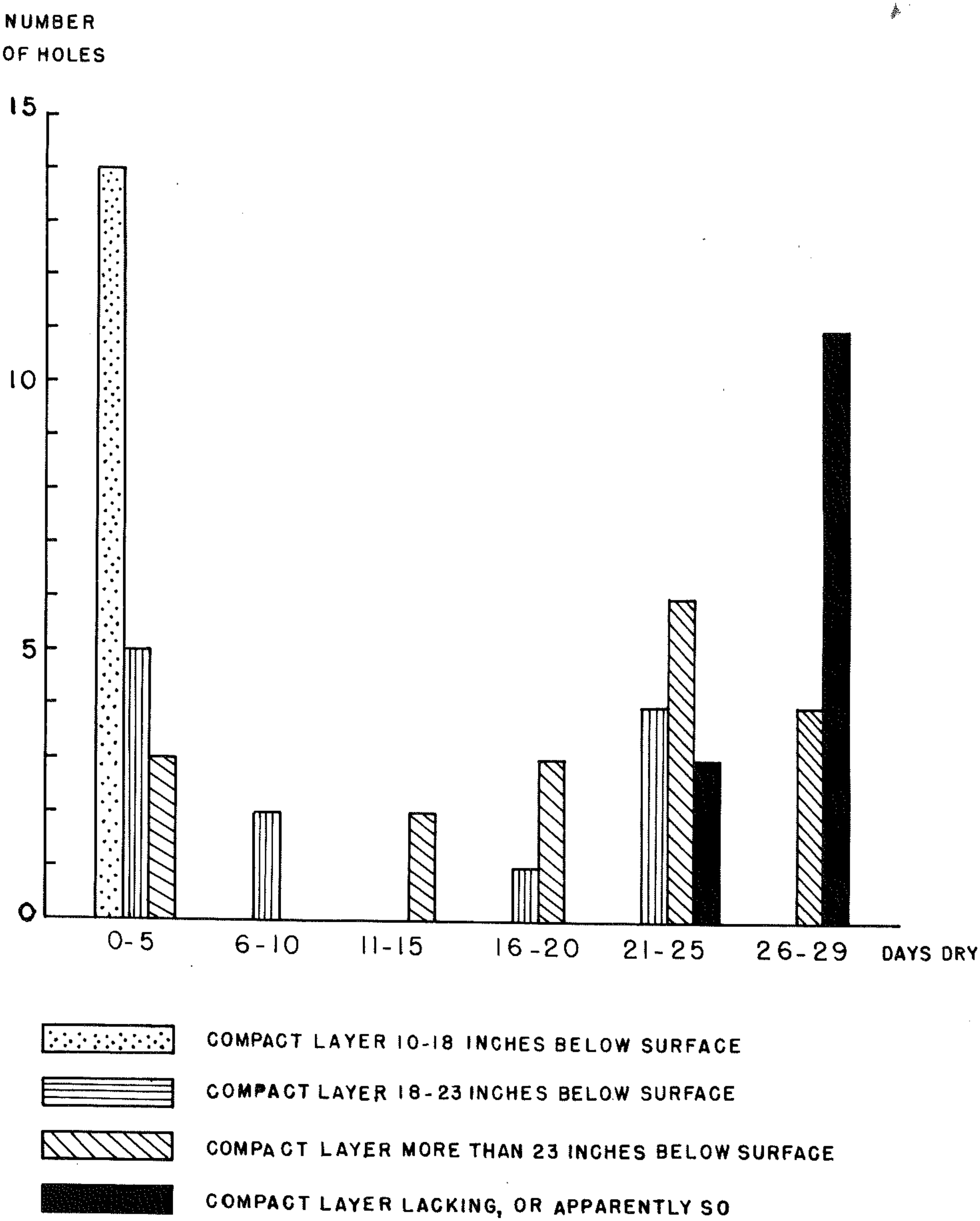

NUMBER
OF HOLES
15
10
5
0
0-5
6-10
11-15
16-20
21-25
26-29
DAYS DRY
COMPACT LAYER 10-18 INCHES BELOW SURFACE
COMPACT LAYER 18-23 INCHES BELOW SURFACE
COMPACT LAYER MORE THAN 23 INCHES BELOW SURFACE
COMPACT LAYER LACKING, OR APPARENTLY SO

Figure 7

Frequency of occurrence of 5 most common tree species on study area plotted as a function of site-moisture class.

7

Figure 7

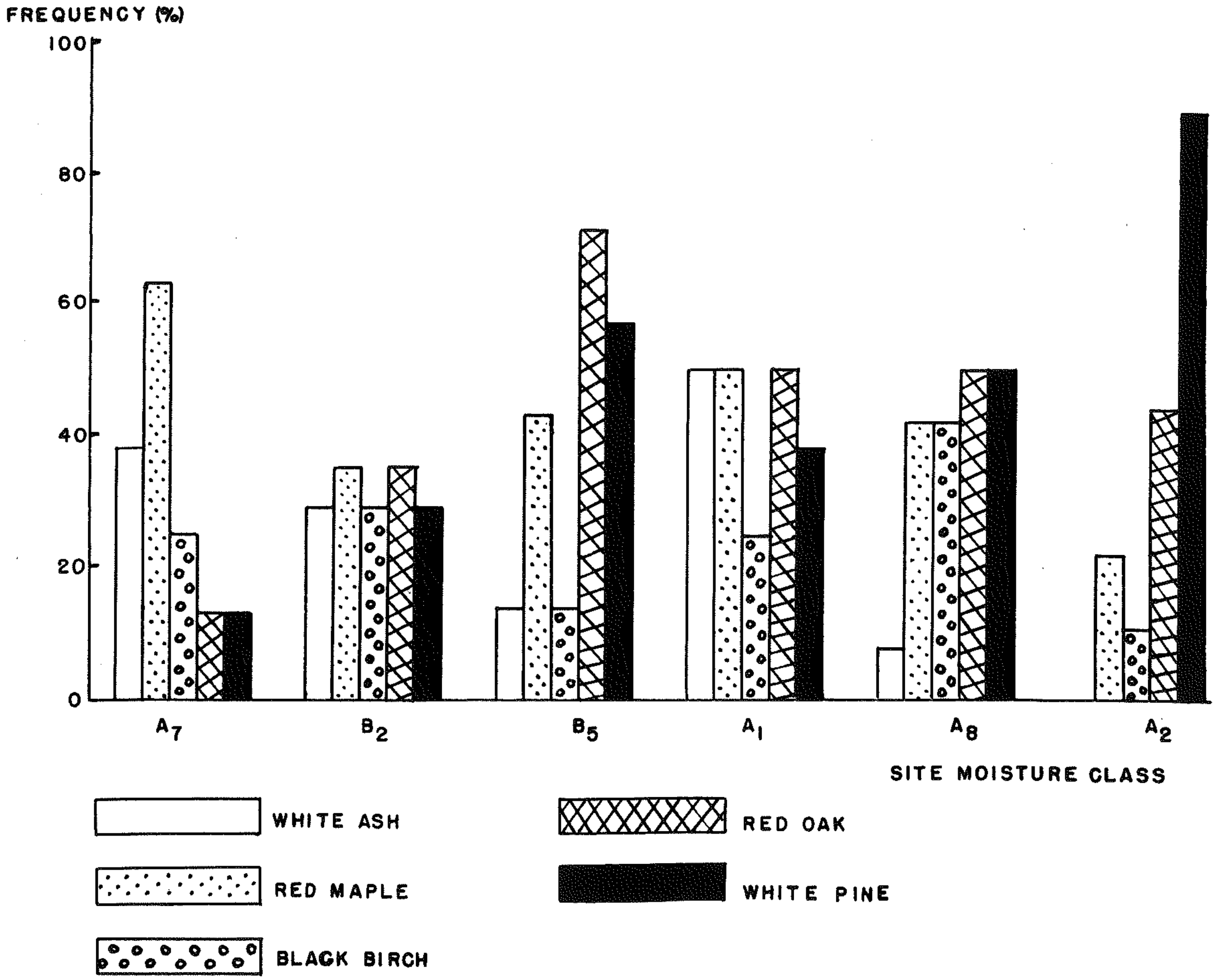
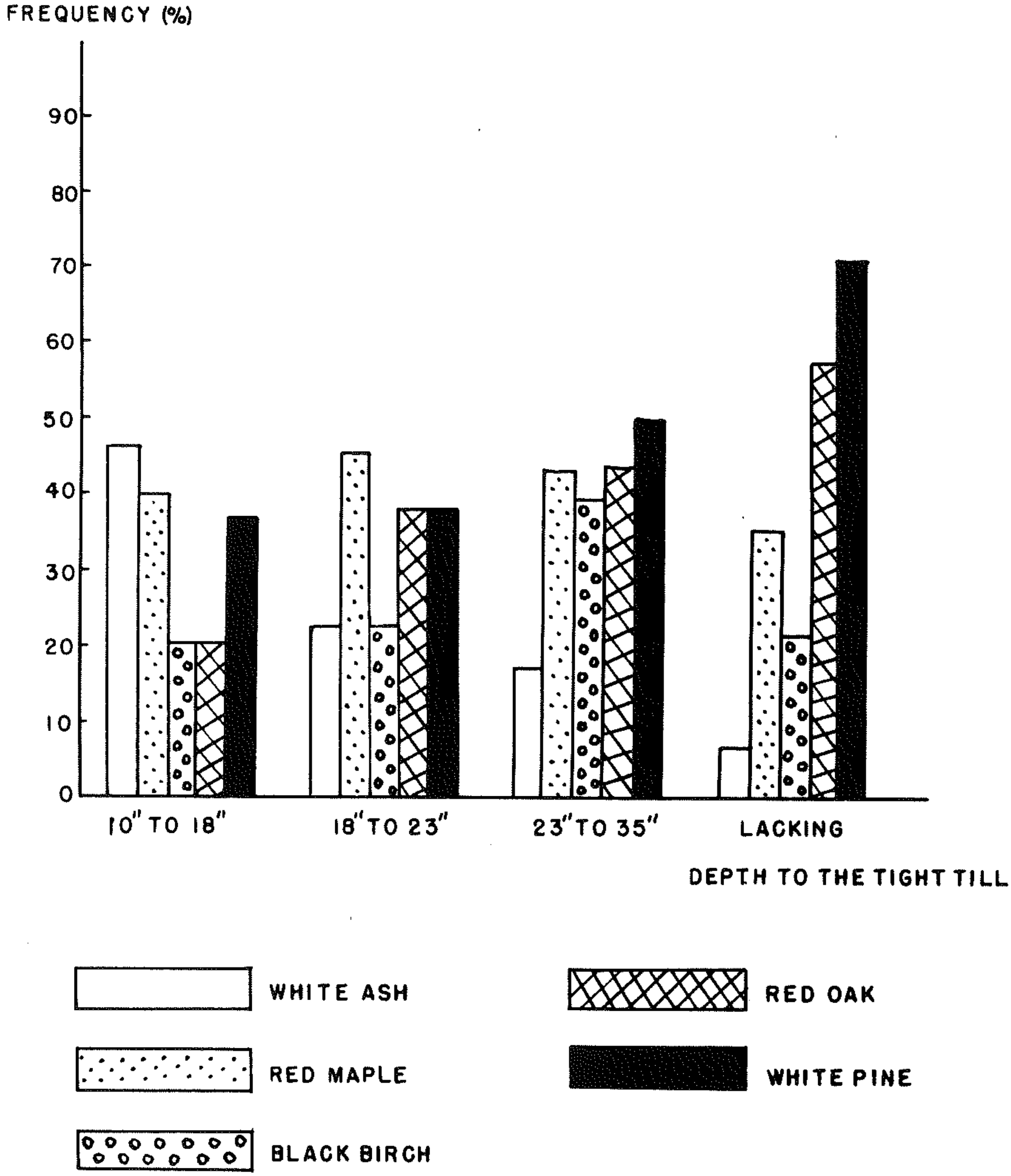

FREQUENCY (%)
100
80
60
40
20
0
A_7
B_2
B_5
A_1
A_8
A_2
SITE MOISTURE CLASS
WHITE ASH
RED MAPLE
BLACK BIRCH
RED OAK
WHITE PINE

Figure 8

Frequency of occurrence of 5 most common tree species on study area plotted as a function of depth to compact layer of subsoil.

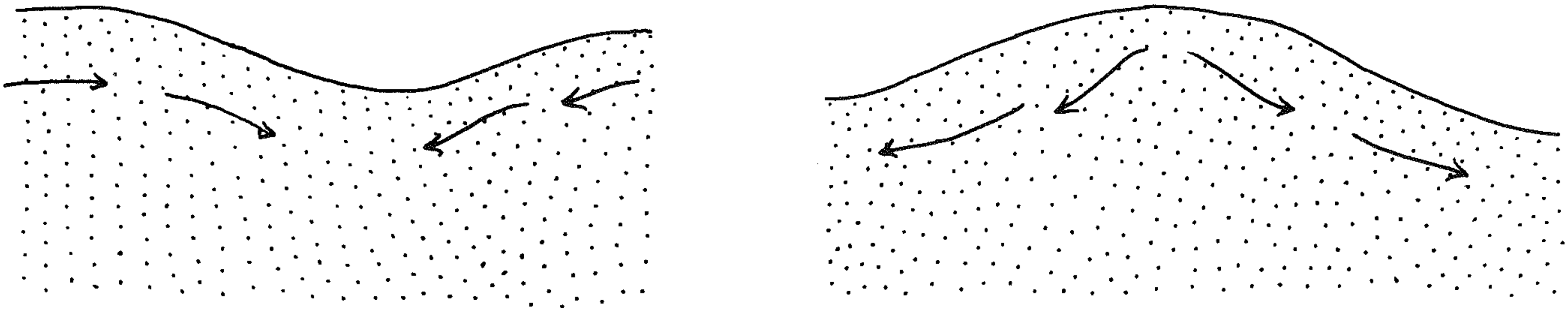
Figure 8



FREQUENCY (%)
90
80
70
60
50
40
30
20
10
0
10" TO 18"
18" TO 23"
23" TO 35"
LACKING
DEPTH TO THE TIGHT TILL
WHITE ASH
RED MAPLE
BLACK BIRCH
RED OAK
WHITE PINE

Figure 9

Influence of shape of surface of ground on direction of flow of ground water.



GROUND SURFACE CONCAVE

GROUND SURFACE CONVEX

ARROWS INDICATE PROBABLE DIRECTION OF FLOW OF GROUND WATER

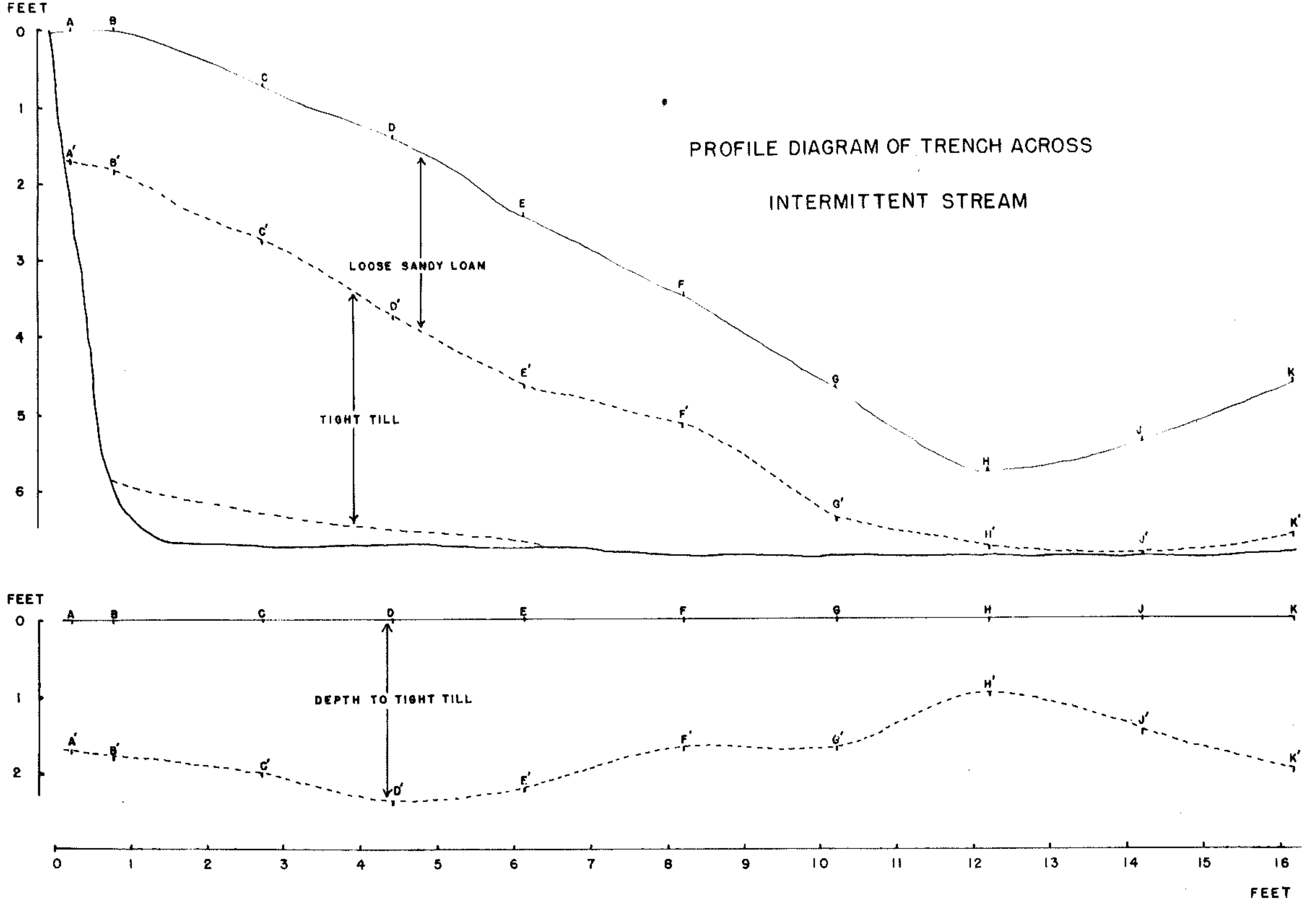
Figure 7

Figure 10

Profile diagram of a trench dug across ravine in south end of study area. Depth to compact layer of subsoil is least in streambed.

Fig 10
Hathaway

Figure 10

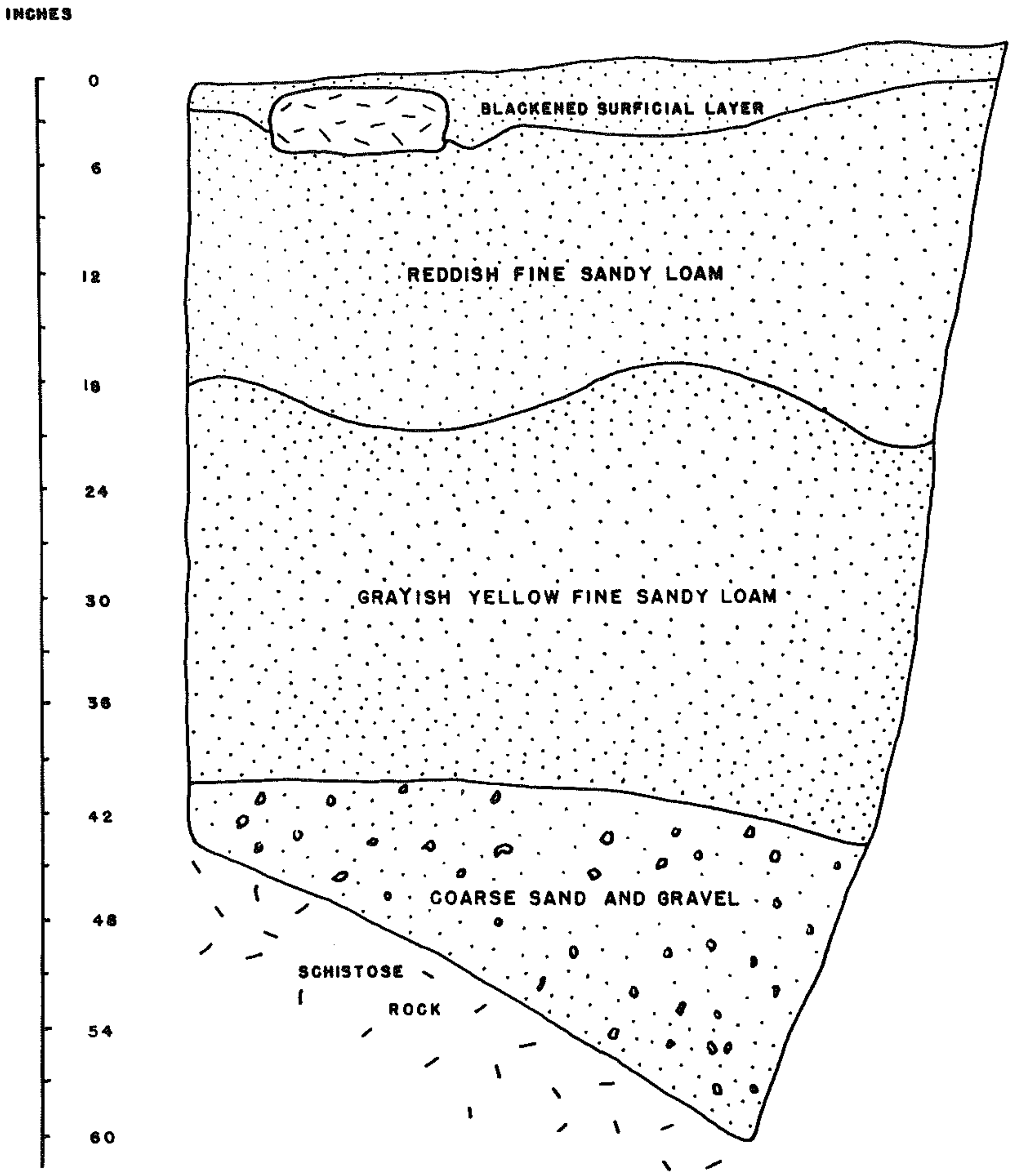


PROFILE DIAGRAM OF TRENCH ACROSS INTERMITTENT STREAM

Figure 11

Profile diagram of pit between stations B_6 and B_7. Note layer of sand and gravel at depth of 40 inches and absence of compact subsoil.

Figure 11



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