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A ground-water sapping landscape in the Florida Panhandle

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Abstract

Drainage networks that have formed by ground-water sapping are developed in the highly permeable sands of the Citronelle Formation in the Florida Panhandle. The valleys resemble those formed on Hawaii, the Colorado Plateau and on Mars, but they have developed without significant lithologic controls. Drainage patterns range from trellis to dendritic depending on the effect of beach ridges and relative relief. Many of the drainage networks are not fully developed, and the adjacent uplands have been modified by marine, aeolian, and to a limited extent fluvial processes. Extension of the networks appears to be episodic, as a result of fires, hurricanes, and human activities, which damage or destroy vegetation.

1. Introduction

The recognition that some channels on Mars resemble ground-water sapping features led to a resurgence of interest in the process (Higgins 1982, 1984; Howard et al., 1988; Higgins and Coates, 1990; Uchupi and Oldale, 1994). The box canyons of the Colorado Plateau received particular attention (Laity and Malin, 1985; Howard et al., 1988) as did Hawaiian valleys (Kochel, 1988; Kochel and Baker, 1990) and New Zealand gullies (Pillans, 1985; Schumm and Phillips, 1986). A series of experimental studies provided additional information on the development of channels formed by sapping (Kochel et al., 1985, 1988; Gomez and Mullen, 1992; Howard, 1990). In a major review, Higgins (1982) defined the erosional process that formed these channels as spring sapping because a point-source spring was involved. This is in contrast to seepage erosion, which occurs where the ground-water discharge is less concentrated.

As the infiltration capacity of a terrain increases, the role that surficial runoff plays in the development of drainage networks decreases. Carlston (1963) showed that drainage density increases with peak discharge, and it is inversely related to baseflow discharge. One can argue that high discharge produces high drainage density, or conversely that high drainage density produces high peak discharge. Nevertheless, as infiltration capacity decreases, surficial runoff increases and drainage density increases and vice versa. This supports the argument of Kirkby and Chorley (1967) that a continuum of runoff situations exists with the high drainage density of badlands being related to low infiltration and high surface runoff, whereas very high infiltration rates will produce a terrain dominated by ground-water processes (De Vries, 1974, 1976).

Studies by Dunne and Black (1971) in Vermont led to the conclusion that spring sapping was an important process during snowmelt. Dunne (1980) summarizes this literature and provides an explanation of the process. He begins his discussion by assuming a tilting that "brings a smooth land surface of permeable rock above sea level". The flow of ground-water through the tilted material and its emergence leads to erosion and development of a drainage network (Fig. 1). Because the medium through which flow occurs is not homogene-

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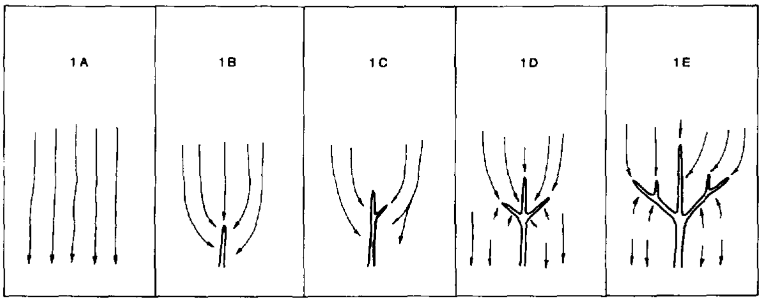

Fig. 1. Evolution of a ground-water sapping drainage network. Arrows depict groundwater flow patterns (after Dunne, 1980).

ous, zones of preferential permeability will concentrate flow and cause erosion where the flow outcrops. The inception of erosion concentrates more flow and accelerates the erosional process. As the network develops and tributaries form, however, the ground-water flow patterns of Figs. 1A, B, C are disrupted (Fig. 1D), as the development of new tributaries captures flow to the down-dip channels. Under these circumstances, the downdip channels stagnate. In addition, if a pattern of preferential ground-water flow occurs, the final drainage pattern will deviate from the standard dendritic pattern.

In the literature on sapping valleys in the Colorado Plateau and Hawaii, the characteristics are listed as follows (Kochel and Piper, 1986; Howard, 1988; Kochel and Baker, 1990):

1. light-bulb shape of basin
2. basin-area to canyon-area ratio is low
3. low drainage density
4. dendritic drainage pattern
5. theater or cirque-like valley heads
6. steep valley walls and flat valley floors
7. relatively constant valley width
8. structural control of valley alignment and planform
9. long main valleys with short stubby tributaries
10. high tributary junction angles (55°–65°)
11. hanging tributary valleys

In the southwestern United States, sapping occurs most frequently where a massive sandstone overlies a shale, and ground-water movement is concentrated along joints, faults and folds. The process of sapping in basalt and sandstone involves weathering and weakening of the rocks (Stearns, 1936; Howard, 1990, p. 261).

Experimental studies (Kochel et al., 1985, 1988; Howard, 1990) showed that valley-head erosion occurs by episodic headwall slumping, and the gradient of the experimental channels downstream of the sapping head is directly controlled by the slope of the water table in homogeneous sediments (Fig. 2). This suggests that impermeable zones are not required for development of the sapping channels. In addition, as the main channel elongates, tributaries that form up-gradient capture ground-water flow, and they prevent down-gradient channels from developing or enlarging (Kochel et al., 1985).

The five longitudinal profiles developed during Howard's experiments (Howard, 1990) (Fig. 2) show the effect of relief and water-table elevation on rates of valley formation. The top three profiles (#3) that were developed in coarse sand show that the channels approached the head of the experimental box in about 36,000 seconds, when the height of the water table was 30.5 cm. It took about 18,000 seconds, when the water table height was 33 cm, and 11,000 seconds when the water table height was 35.6 cm. The lower two profiles that formed in medium sand show a similar relation. However, the finer sand appears to be less erosive because, although the water table was higher than in the #3 experiments, it took much longer for the channel to approach the head of the box. The overhang, especially in the lowest profile, suggests that capillary cohesion was important. Obviously, resistance to erosion will retard channel extension. Following extension, sapping valleys in some experiments (Gomez and Mullen, 1992) and in the Colorado Plateau widen (Laity, 1988). Apparently, when the lengthening ceases, lateral seepage into the deep valley dominates, and a long period of valley widening follows. Also, because the Colorado Plateau valleys form along permeability boundaries, the longitudinal valley profile is relatively straight (Laity, 1988, p. 69), and it is controlled to a large extent by dip of the beds.

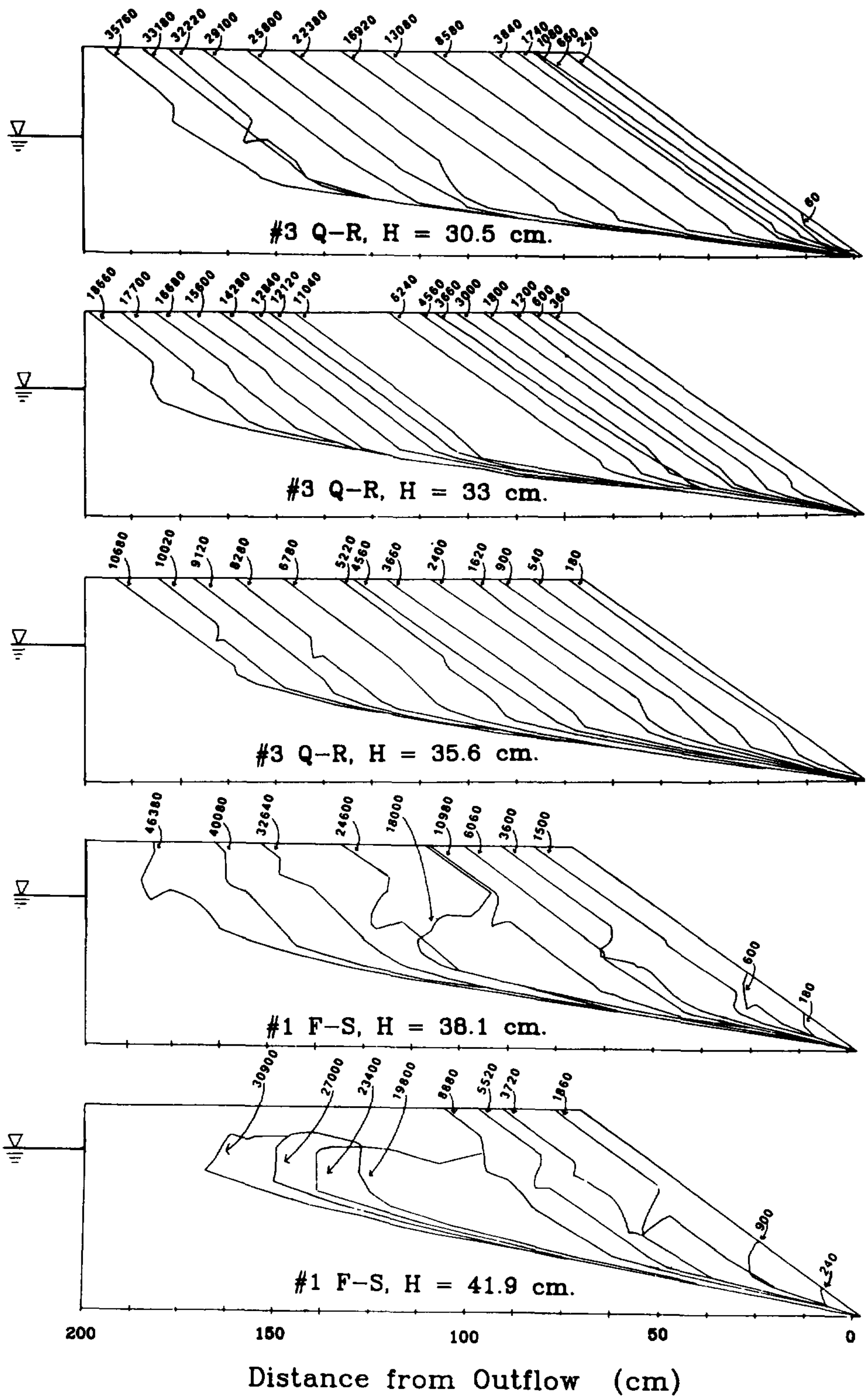

Fig. 2. Evolution of channels developed by sapping during 5 experiments. Elapsed time is given in seconds along the upper margin of each diagram. The line and triangular symbol to the left show the fixed hydraulic head relative to the outflow that was maintained during the experiment. Uniform, angular crushed quartzite was used in the experiments; #3 Q–R was a coarse sand and #1 F–S was a medium sand. H is height of water table in cm (from Howard, 1990).

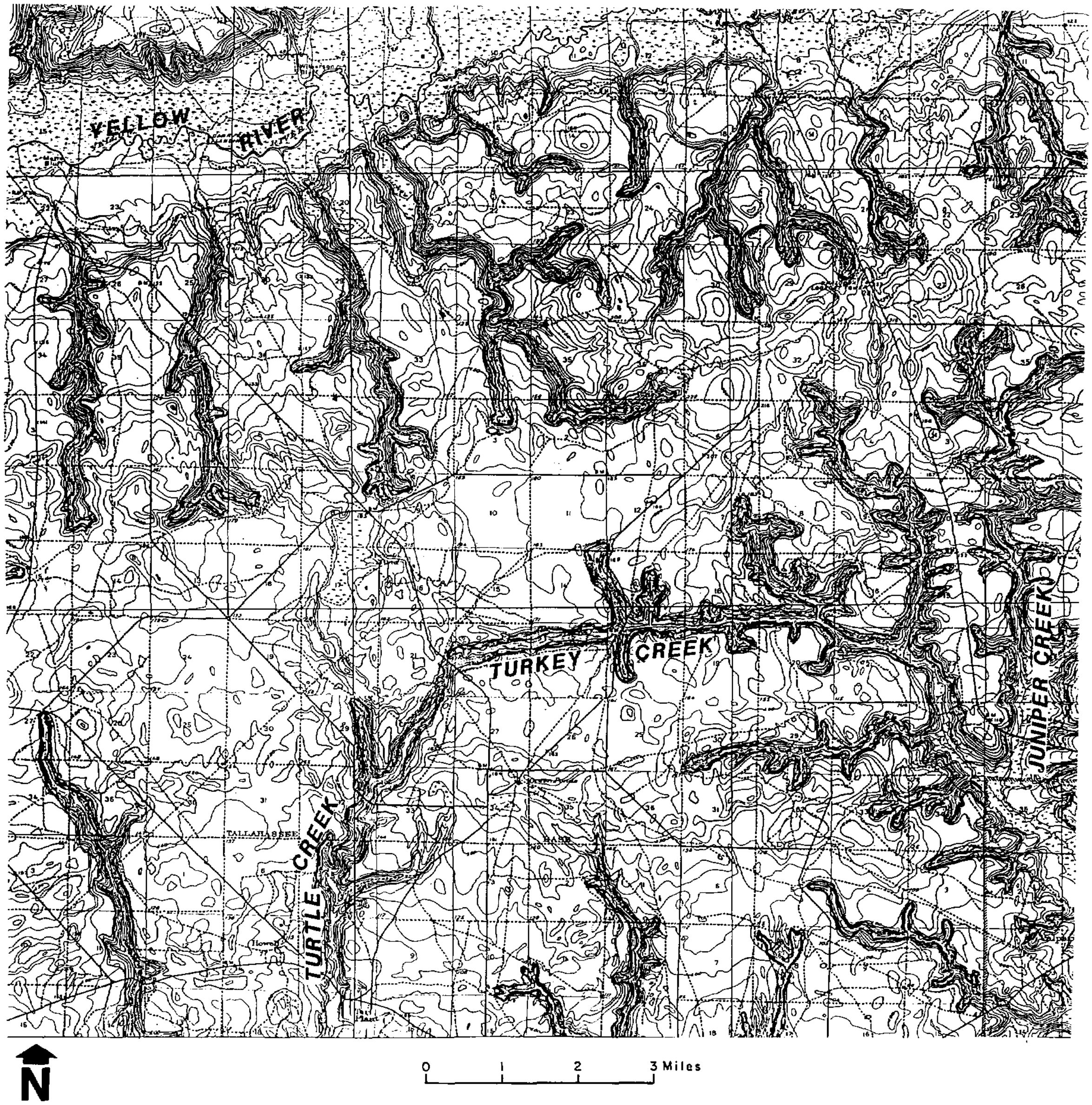

Fig. 3. Steephead valleys on Holt quadrangle, Okaloosa County, Florida, see Figs. 4 and 6 for location.

Horton (1945) demonstrated a good correlation between the log of stream length and number of streams and stream order for fluvial drainage networks. According to Kochel et al. (1985) the results of their sapping experiments were similar to Horton's relations, but "in about 50 percent of the cases there was more variation". Such variation may occur because the network is still expanding, contracting or it has stalled because of water loss or lack of erosive ability.

Geologists working in the Florida Panhandle in the early part of this century recognized that some of the landforms were unusual and that they were formed by spring sapping. Linear valleys that terminated in steep theater-heads were termed "steepheads" (Fig. 3). The first description of these features by Sellards and Gunter (1918, p. 27) is as follows: "A characteristic feature of this topography is the development of what is known locally as 'steepheads'. These steepheads are due to the fact that indurated sands and sandy clays overlie slightly indurated sands and clays and shell marls. The surface waters pass into the earth and, upon reaching the underlying clays or marl beds, emerge as springs. The indurated sandy clays near the surface stand up vertically, while the softer sands, at a greater depth where the springs emerge, wash easily. The result is the formation of a nearly vertical bluff, at the base of which springs emerge supplying small streams. This bluff or streamhead assumes in time a semi-circular form, which is the 'steephead'. The steephead thus formed is retained by the stream as it gradually extends its way back into the plateau. The depths of the steephead from the plateau is usually from 50 to 60 or more feet, depending upon the depth at which the ground water emerge as springs.''

The end result of this erosional process in the Florida Panhandle is the development of small ''box canyons'' and drainage networks that can have trellis or dendritic drainage patterns (Marsh, 1966). Numerous investigators agree that ''Ground-water percolates downward through the surficial sediments until it encounters a clay or marl. It then travels horizontally over the less permeable strata and emerges as a small spring or seep at a bluff face'' (Rupert, 1991) or ''Many of the springs at the heads of the steephead appear to be localized along extensive layers of clay or hardpan'' (Marsh, 1966, p. 7).

Although descriptions of the ecology of these valleys have appeared in national journals (Means, 1985; Nicholson, 1990), only one morphologic description of these features has appeared in a national but now defunct scientific journal (Sharp, 1938). This may explain why with increasing interest in the sapping processes, these Florida landforms have not attracted much attention. Excerpts from Sharp's description of the features on the Holt and Niceville, Florida, U.S. Geological Survey 15-minute quadrangles follow;

''One glance at the stream valleys shown on these two maps and on several adjacent quadrangles depicting the Coastal Plain of northwestern Florida will convince most observers that an unusual process of valley formation is here at work... Here the Coastal Plain surface, sloping southward from elevations a little above 200 to somewhat below 100 feet, is for the most part untouched by stream erosion. It is a coastal plain youthfully dissected by streams... These streams are sharply incised fifty to one hundred feet below the surface of the plain in irregularly trending and branching valleys, the courses of which occasionally suggest doubtful structural control. Most remarkable, however, is the abrupt ending of these valleys at their heads in steep, narrow amphitheaters locally known as 'steepheads'. The streams very often rise abruptly in the bottoms and not on the headwalls of these steepheads and are occasionally shown as originating in small ponds or swamps. Drainage lines of importance do not in general lead from the surface of the upland into the steepheads, and indeed relatively few lines of surface drainage seem to be developed upon the upland...'' ''From these observations, one is led to concur with Sellards' explanation that the steepheads are due to spring sapping, and that the valleys are formed not by downward cutting of the streams but by headward migration of the steepheads.''

1.1. Objectives

Early in the geomorphic investigation of Eglin Air Force Base (AFB) (Resource Consultants and Engineers, 1994), the unusual patterns of the steephead drainage networks attracted our attention. Although, as noted above, many authors have mentioned these features, their presence seems unknown to those currently engaged in research on ground-water sapping processes and landforms. Therefore, we propose to describe quantitatively the Florida steephead topography and to compare it to the other field and experimental studies. Because reconnaissance field investigations did not specifically identify stratigraphic controls at the base of steepheads, an objective was to determine if, indeed, stratigraphic controls are necessary for ground-water sapping processes in high infiltration capacity and highly permeable terrain.

2. Description of study area

Steephead streams of the type described by Sellards and Gunter (1918) and Sharp (1938) occur in abundance on Eglin AFB, Okaloosa and Walton Counties, Florida where a spring-sapping landscape has formed (Fig. 4). In addition, farther east in Gadsden and Liberty Counties steephead streams drain steeply to the Apalachicola River (Fig. 5). Eglin AFB lies within the Coastal Plains physiographic province, which in the

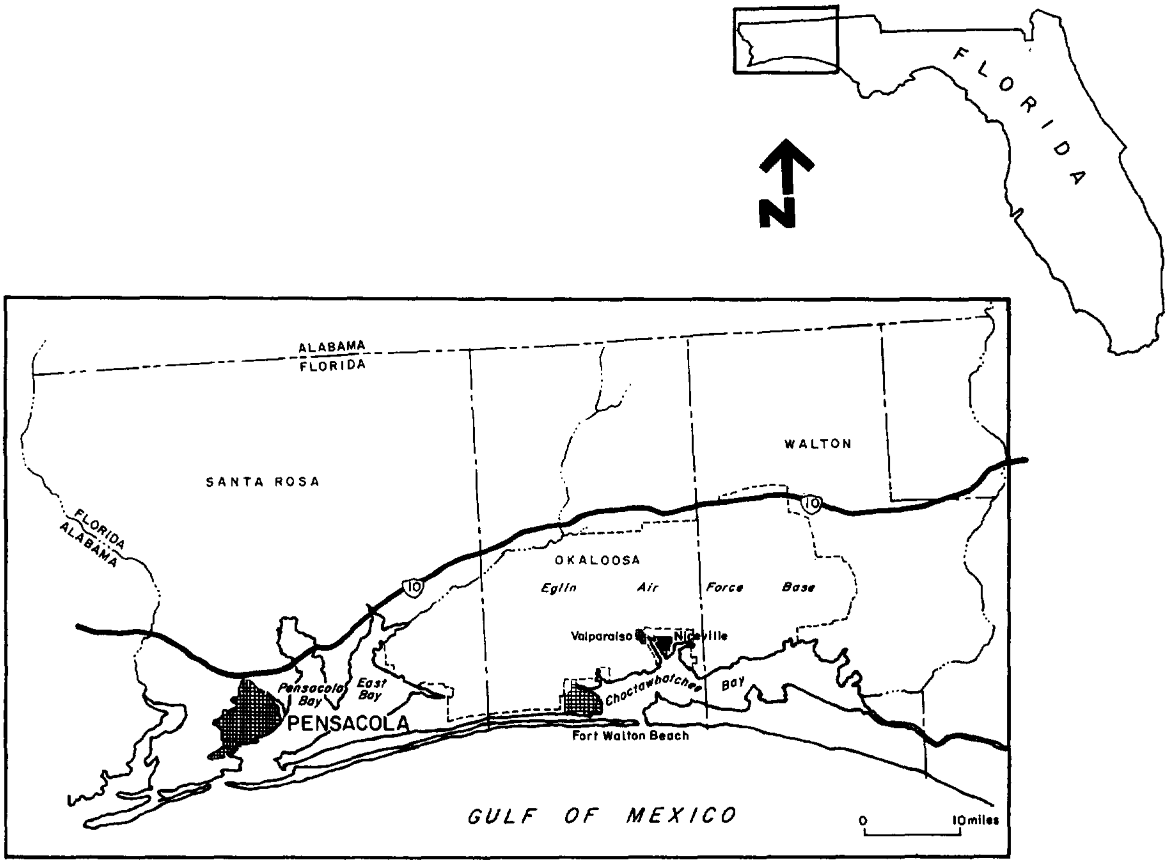

Fig. 4. Map showing Eglin Air Force Base in Santa Rosa, Okaloosa, and Walton Counties, Florida.

Florida Panhandle consists of the Western Highlands and Gulf Coastal Lowlands. The Western Highlands consist of hills of Plio–Pleistocene Citronelle Formation that slope gently southward in the study area. These hills have been modified by both stream dissection and dissolution of underlying limestones (Schmidt, 1984). Erosional relief in the highlands reaches 100 feet. Steephead streams are located in the Highlands, where the Citronelle Formation is relatively thick. Near the coast, erosion and reworking during high sea-level stands formed the Gulf Coastal Lowlands. The Gulf Coastal Lowlands generally do not exceed 100 feet above mean sea level and they are flat relative to the Highlands.

Topographic maps (Niceville, Niceville SE, Holt, Crestview South, Mossy Head, Holt SW, Valpraiso, and Spencer Flats) show depressions with adjacent highs that represent the eolian reworking of the Citronelle sands into dunes and deflation hollows. The dunes range from being nondistinct mounds to linear ridges that generally run north–south. The dunes do not appear to exert any control on channel patterns. Some dunes are located along and parallel to the upper valley margins. In other places, dune remnants indicate valley incision through a dune.

2.1. Geology

Geologic units in the Eglin area dip gently southwestward into the Gulf Coast geosyncline. The primary surficial geologic unit in the study area is the Plio–Pleistocene-age Citronelle Formation, which consists of non-marine quartz sands that contain discontinuous layers of clay or gravel. The unit blankets the upland areas of Eglin AFB, where its thickness is highly variable, because of an undulating pre-Citronelle surface and present day dissection (Schmidt, 1984). In the Rocky Creek drainage, a large portion of the Citronelle

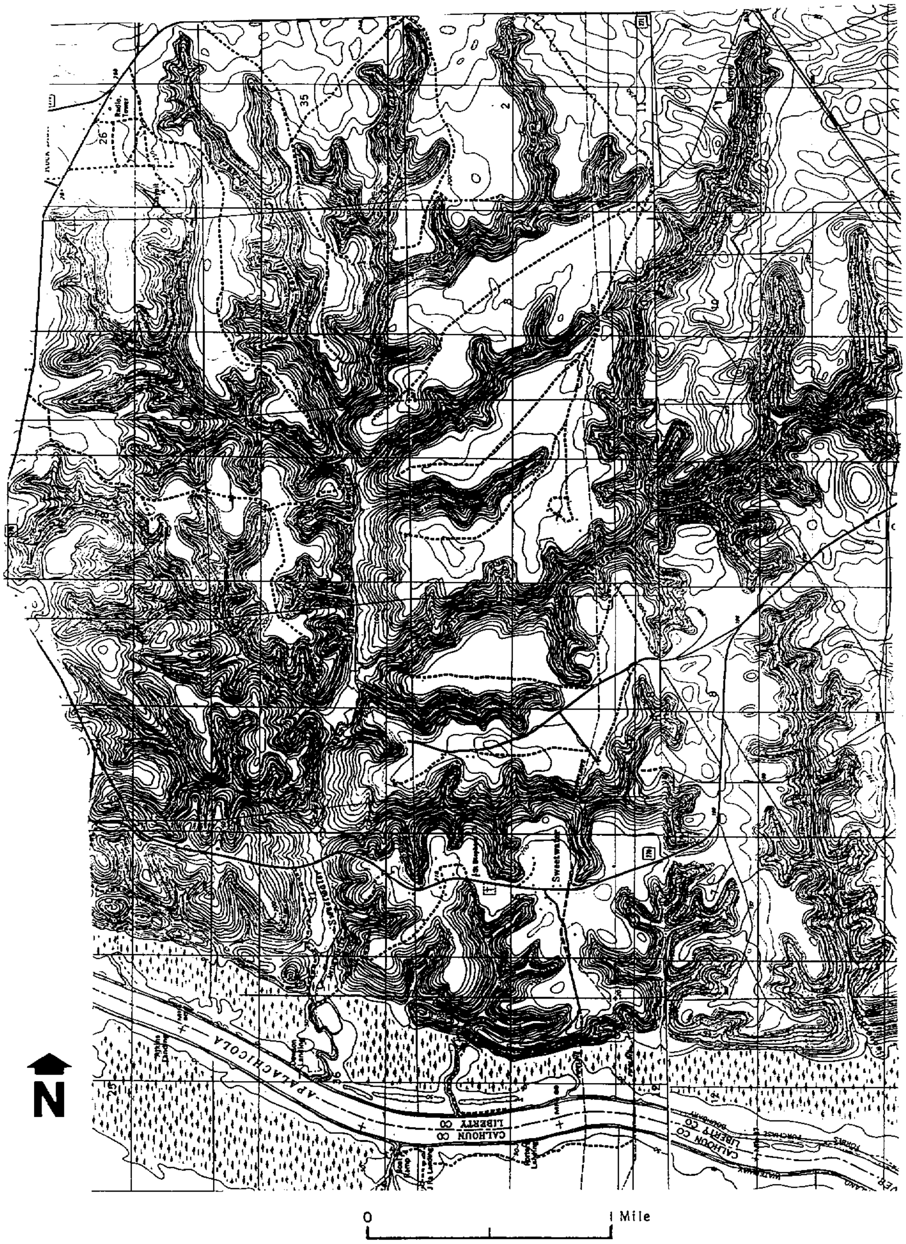

Fig. 5. Drainage network of Sweetwater Creek, a tributary to Apalachicola River on Rock Bluff and Bristol quadrangles, Liberty County, Florida.

Formation has been eroded; therefore, its thickness increases to the west from 75 to 100 feet in the Rocky Creek drainage, to over 175 feet in the Live Oak drainage (Fig. 6). The formation ranges in color from brown and red to purple and orange-yellow. Local limonite lenses, commonly referred to as hardpans, are present in Citronelle Formation. The hardpan is generally located over clayey sand horizons where vertical permeability is reduced. The low permeability clayey sand and hardpan layers affect ground-water flow patterns because of anomalously low hydraulic conductivities. Investigation of the distribution of the clayey-sand horizon that is extensive throughout the study area indicates that it is a paleosol that is discontinuous, and its

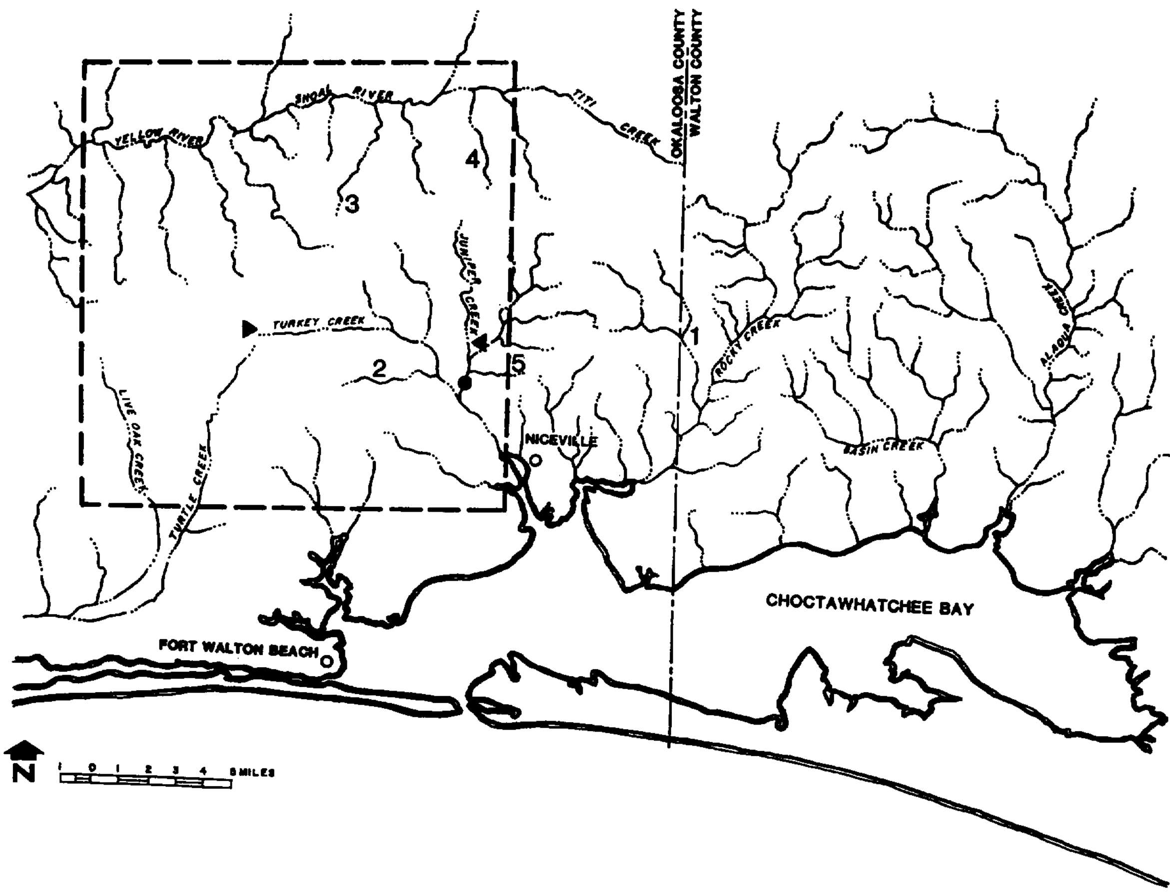

Fig. 6. Map showing drainage networks, Eglin Air Force Base, Florida. Rectangle shows limit of Fig. 3. Large dot shows location of Juniper Creek gaging station. Numbers indicate creeks plotted on Figs. 12 and 13 and referred to in text as follows: (1) Little Rocky Creek, (2) Rogue Creek, (3) Turkey Hen Creek, (4) Silver Creek, and (5) Nine Mile Creek. Triangles show location of drilling sites.

location is not determined by stratigraphy or elevation (Brown et al., 1994).

The uppermost surface of the Citronelle Formation has been reworked by eolian activity and by marine processes during high sea level stands. Consequently, the unit is capped by a clean, white, well sorted sand. Infiltration capacity of the Citronelle sands ranges from 8 to 12 inches per hour (Overing and Watts, 1989). The Miocene-age Pensacola Clay confining bed underlies the Citronelle Formation in the study area. The steephead streams of Eglin AFB formed in thick sequences of Citronelle Formation above the Pensacola Clay.

2.2. Ground-water hydrology

Ground-water resources in the study area are located primarily within the surficial sand-and-gravel aquifer and the underlying Floridan aquifer. The surficial sand-and-gravel aquifer consists of the Citronelle Formation and overlying marine terrace deposits; it thickens to the southwest, reaching its maximum thickness of 1200 feet at Mobile Bay. Where the sand-and-gravel aquifer is confined by hardpan or paleosol, artesian conditions occur. Ground-water flow through the unit is generally from areas of high hydraulic head on upland surfaces to areas of low hydraulic head in river valleys.

Under most of the Florida Panhandle, the surficial sand-and-gravel aquifer is separated from the underlying Floridan aquifer by the Pensacola Clay. The Pensacola Clay pinches out to the northeast, however, so that in central and eastern Walton County, the sand-and-gravel aquifer directly overlies the Floridan Aquifer.

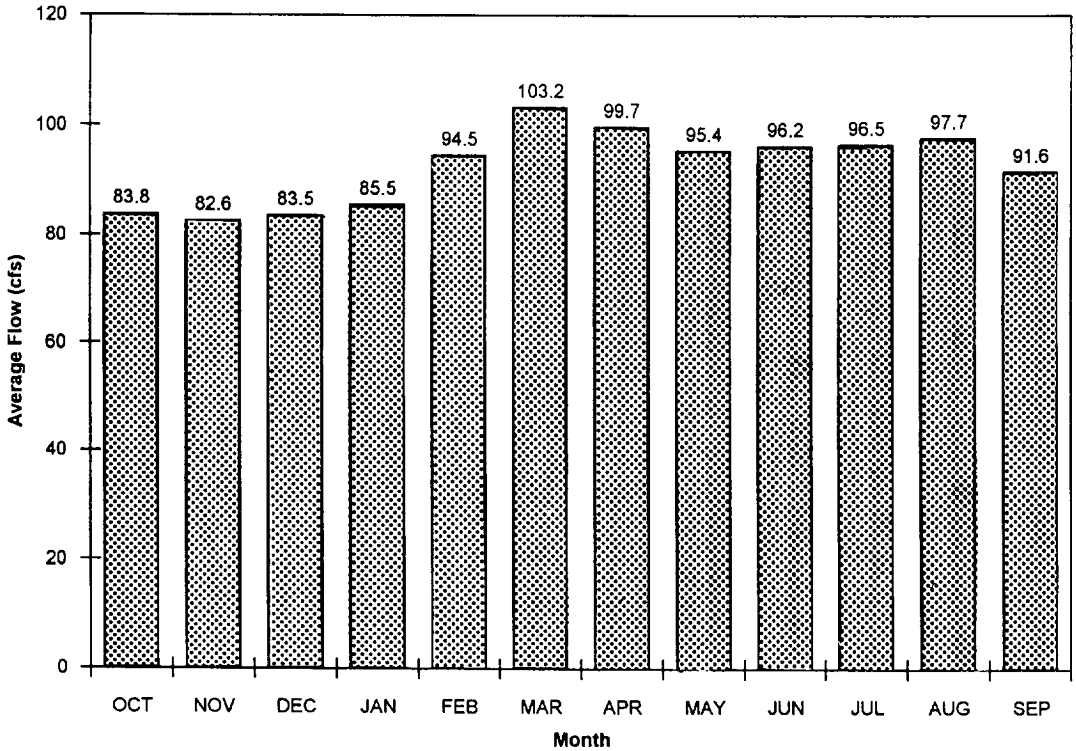

Fig. 7. Average monthly discharge for water years 1967–1974 and 1978–1991, Juniper Creek at Highway 85 gage.

2.3. *Surface-water hydrology*

Eglin AFB contains many small perennial streams, which originate in the gently rolling sand hills of the Western Highlands. The eastern portion of the Base is drained by streams that generally flow south, crossing the Coastal Lowlands and terminating in Choctawhatchee Bay (Fig. 6). The western portion of the Base is drained mainly by streams that flow generally north into the Yellow River and its tributary, Shoal River.

The channels on Eglin AFB are consistently characterized by a bed of well sorted sand and very little suspended load. The channel beds contain ripples and dunes. Where overbank flow and surface runoff occur, the water in the channels becomes tea colored because of the incorporation of organic compounds in the runoff. Near the steepheads or where flow is derived predominantly from springs, the water is clear.

Flow records from the U.S. Geological Survey gage on Juniper Creek at Highway 85 provide a general description of streamflow of Eglin AFB. Average monthly flows for the Water Years 1967–1974 and 1978–1991 are relatively constant throughout the year (Fig. 7), being lowest in November (82.6 cfs) and highest in March (103 cfs). Average annual discharge for the period 1967 through 1991 was 92.5 cfs, which represents a unit runoff of 3.4 cfs per square mile. Significant variability in average flows occur from year to year, with the lowest recorded average flow of 65.7 cfs in 1967 and the highest recorded average flow of 127 cfs in 1991. The annual flow-duration curve for the Juniper Creek gage (Fig. 5) at Highway 85 shows that the median flow is between 80 and 90 cfs with minimum flows above 40 cfs. The relatively high minimum flows show that the basin has a relatively large groundwater storage.

3. Steephead streams of Eglin Air Force Base

Steephead streams dominate the landscape of the western portion of Eglin AFB (Figs. 3, 4). The channels are generally linear with right angle tributary junctions. Stream valleys characteristically have steep walls and flat bottoms. The heads of the valleys are theater-shaped and steep, and springs emerge from the base of

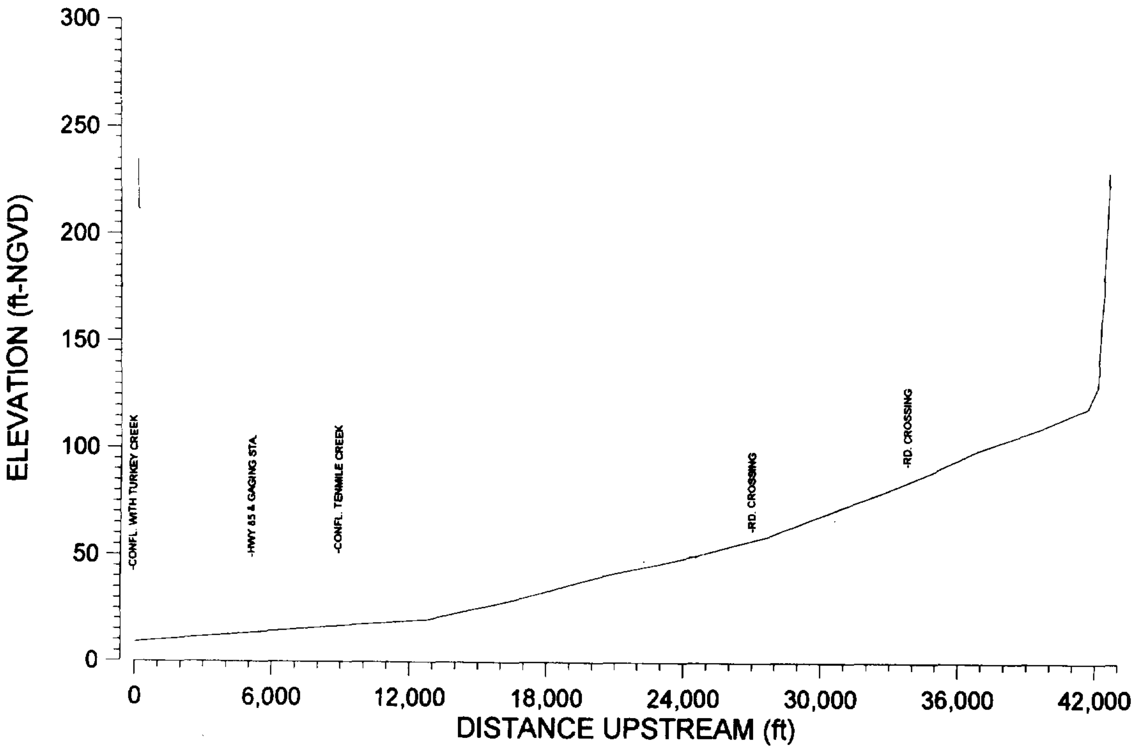

Fig. 8. Longitudinal profile of Juniper Creek. Abrupt steepening of the profile is the steephead.

these valley headwalls. Several springs may be present at a single steephead. The steephead springs are all located within the Citronelle Formation.

Water surface profiles constructed for numerous channels on the Eglin AFB using both 1956 (5-foot contour) and 1973 (10-foot contour) topographic maps can be used to roughly represent channel profiles. The profiles of the longest streams are typically concave, steepening in the upstream direction (Fig. 8). On the figure, the head of the stream appears to be near vertical, but this segment represents a steephead.

Steephead streams in the Turkey Creek drainage form a distinct trellis-type drainage pattern that extends in a predominantly east–west direction, with smaller north–south components (Figs. 3, 6). The Turkey Creek trellis pattern has been attributed to beach ridges, beach terraces, fault offset, and minor grain size variations in the Citronelle Formation (New World Research Inc., 1990). Some of the smaller drainage networks resemble those that are controlled by joints in the Colorado Plateau (Campbell, 1973), but this explanation is probably not valid for the unconsolidated Citronelle sands, although zones of relatively high permeability may control channel development.

Another explanation has been advanced to explain the trellis appearing drainage pattern. Beach ridges form generally parallel to the coast, and they provide ready made drainage divides between the east–west trending channels. According to Winkler and Howard (1977), the beach ridge topography is emphasized by the incised trellis drainage. They state that "when first examined, the drainage appears joint controlled. However, the overall pattern is one of subparallel concave to seaward arches like those that characterize beach ridge plains". Gremillion et al. (1964) appeal to barrier island and lagoon topography as the control on the streams that develop on the sites of the lagoons.

Although the Eglin AFB landscape of the Florida Panhandle is dominated by ground-water sapping processes, field observations reveal that surface runoff does occur during high intensity precipitation. As a result, some shallow linear depressions extend the drainage networks into as yet basically undissected drainage areas (Fig. 9). This secondary drainage pattern extends

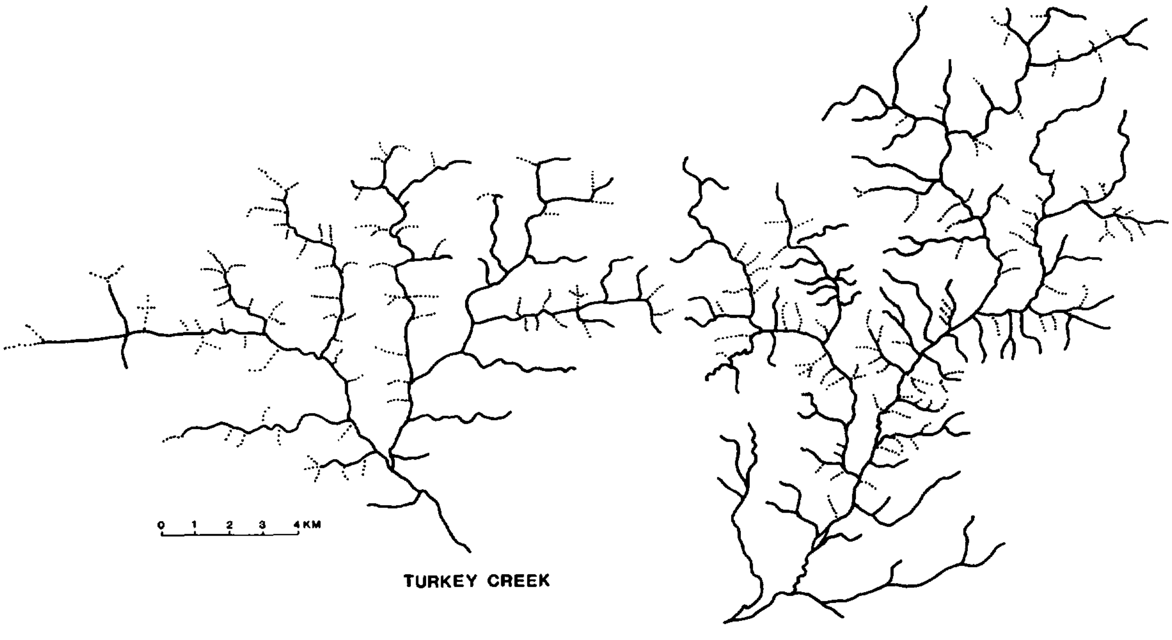

Fig. 9. Steephead channels (solid lines) and secondary fluvial extensions (dashed lines), Turkey and Rocky Creeks.

the main steephead streams (Fig. 9). These smaller drainage features are commonly present as depressions leading to the steephead valley walls. Many of these drainages are V-shaped in contrast to the U-shaped theater heads of the steephead valleys. These ephemeral-stream patterns indicate areas where channelized surface runoff occurs intermittently.

3.1. Steephead formation

The description of the process of steephead formation as described by Sellards and Gunter (1918) has persisted in the literature, and it appears to be generally accepted. Steepheads form because of ground-water erosion of thick sand sequences, and they migrate with time because of undermining of the headwall (Fig. 10). To date, however, we have not found actual data that indicate that the lithologic controls on ground-water discharge are as described. The existing interpretations require that an impermeable layer be present at the point of spring emergence. However, previous experiments (Howard, 1990) indicate that these drainages can be formed in homogeneous sediments (Fig. 2). While in the field, we probed stream beds at steepheads with metal rods to try and locate impermeable horizons beneath the springs and found none to depths of 2 m. In addition, the longitudinal profile (Fig. 8) does not contain significant breaks of slope that would indicate lithologic controls, although paleosol and hardpan layers can have a local effect on the channels.

Following the completion of the geomorphic studies (Resource Consultants and Engineers, 1994), a drill rig became available, which permitted limited subsurface investigations. Drilling was undertaken at the head of the Rogue Creek steephead and a Juniper Creek tributary steephead (Fig. 6) to a depth below the base of the steepheads. Neither the clayey-sand paleosol nor hardpan was encountered in the holes. Therefore, the absence of the paleosol and hardpan at the base of the steepheads indicates that the low-permeability horizons do not affect steephead development at all locations.

The steephead streams appear to have been stable for most of Holocene time, but they may migrate on the order of an inch or two per century (New World Research, Inc., 1990). Radiocarbon dates from Blue Pond, located within a steephead, indicate a migration rate for that feature that is somewhat higher, approximately 28 inches per century (New World Research, Inc., 1990). Nevertheless, some steepheads are in a phase of relatively rapid erosion and extension. Commonly, the eroding steepheads have clay pits, road crossings, or clear-cut areas in the headward portions,

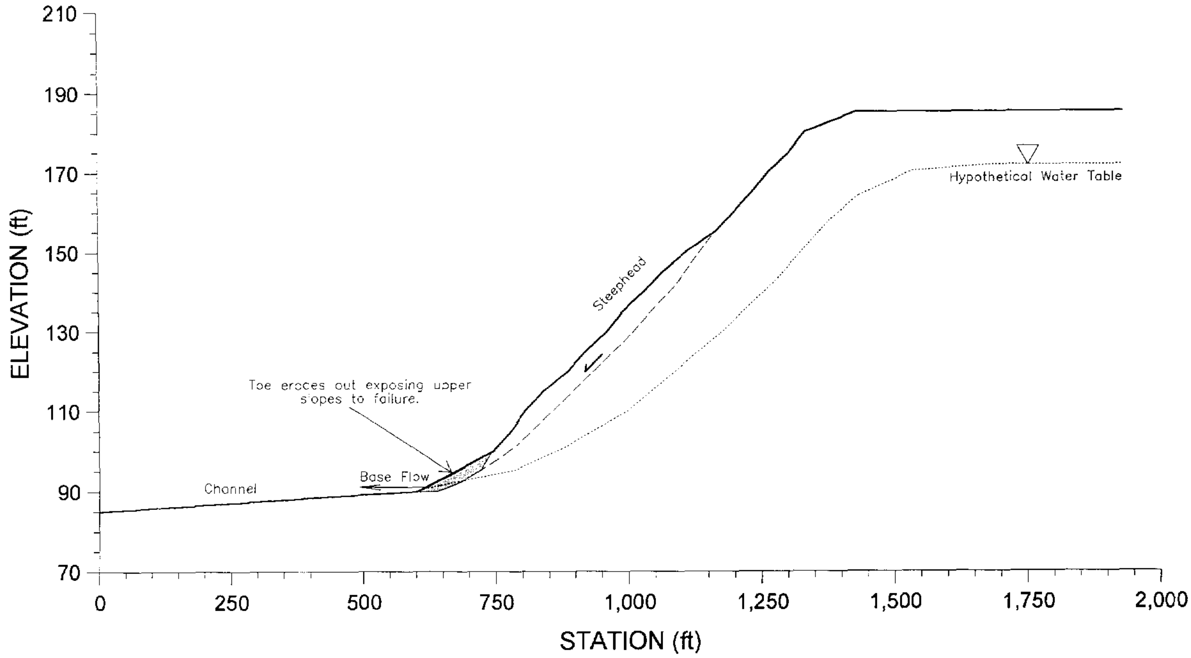

Fig. 10. Longitudinal profile of typical steephead.

which serve to increase surface runoff into the steephead and which result in gullying of the steephead wall. This appears to occur naturally as well where the upland above the steephead is burned. Historic burn cycles required for maintenance of open pine forests have been estimated at two to six years; frequent fires were required to selectively promote long leaf pine seedlings while excluding other tree species. This suggests that natural steephead migration is episodic in nature, and that it may be related to forest fires. Clear evidence of a recent burn was found at one active steephead.

In order to develop an understanding of the evolution of a sapping valley, we can consider two extreme cases. If a sapping valley has formed and the water table falls to a level below the bottom of the valley, the valley and steephead will cease to evolve, and the dry valley will be modified by mass movement. However, if the water table were to rise, seepage erosion would cause collapse of the valley walls and the steephead itself, and a wide valley would result. In both cases, the steephead valley would lose its characteristic form. Therefore, in order to maintain its characteristic morphology, the floor of the sapping valley must follow the slope of the water table, as was the case in the experimental studies (Fig. 2). Hence, the slope of the valley floor should reflect the average slope of the water table.

3.2. Geologic and hydrologic controls of drainage network development

Where the Citronelle Formation is thick and relatively coarse grained, as in the Turkey Creek watershed, infiltration rates are high and steephead streams dominate the landscape. As the unit thins and fines to the east, as in the Rocky Creek watershed, patterns reflecting more frequent surface runoff or high valley wall springs become more dominant (Fig. 9).

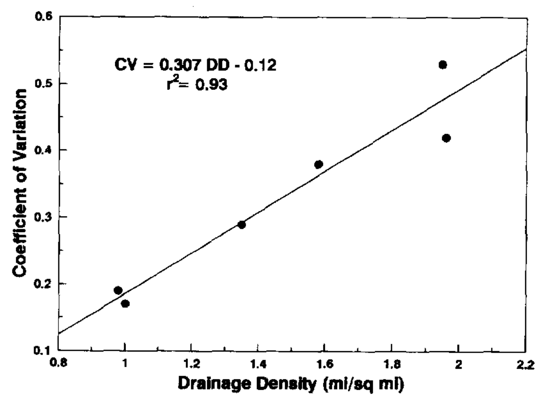

Fig. 11. Relation between coefficient of variation of mean daily discharge at gaging stations and drainage density of upstream watershed.

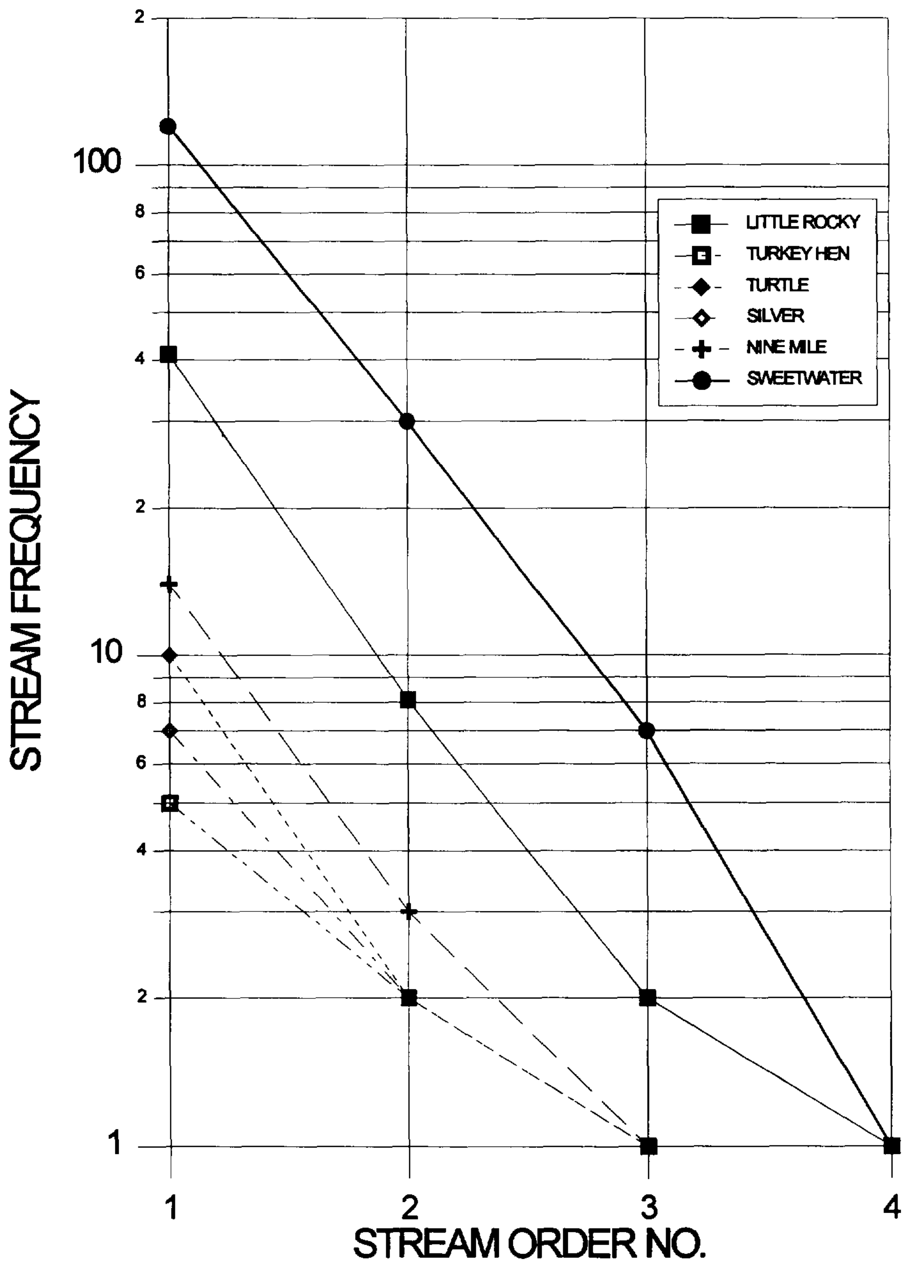

Fig. 12. Relation between stream frequency and stream order number for Eglin Air Force Base streams and Sweetwater River.

As previously noted, soils have a significant effect on the runoff characteristics of streams in the study area. Infiltration rates in coarse grained soils of the Citronelle sands are as high as 12 inches per hour. These soils generally become finer in an easterly direction. Changes in soils and infiltration rates across Eglin AFB have resulted in a corresponding change in drainage density. Drainage densities were calculated (ratio of channel length to drainage area) for subbasins of the Turkey and Rocky Creek drainages, and for several streams that flow northward to the Yellow and Shoal Rivers. Drainage density increases easterly across Eglin AFB, which is consistent with an increase in fines in that direction. The small watersheds that drain

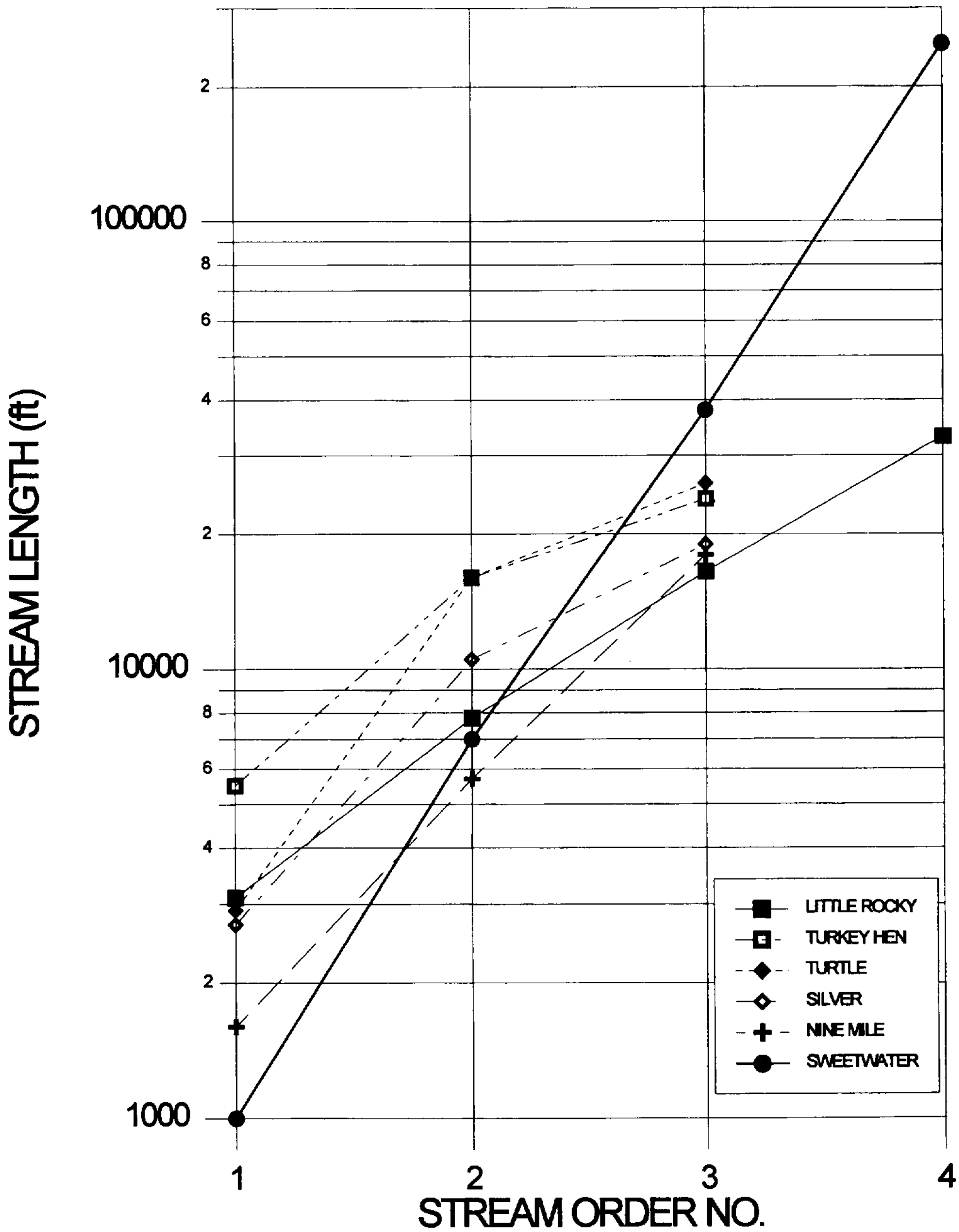

Fig. 13. Relation between average stream length and stream order number for Eglin Air Force Base streams and Sweetwater River.

directly southward to the coast have the highest overall drainage density, averaging 1.80. The Rocky Creek watershed has the next lowest average of 1.77, followed by the Turkey Creek watershed at 1.53, and the northerly draining watersheds, at 1.27. Finer soils increase the frequency of surface runoff which in turn results in a higher drainage density.

The hydrologic effect of the increased frequency of surface runoff and the higher drainage density is greater variability in streamflow. For example, runoff in the Alaqua Creek basin is considerably more variable than that in the Juniper Creek basin. The coefficient of variation (standard deviation divided by the mean) of recorded mean daily flows for the Juniper Creek gage is 0.38 compared to 0.88 for the Alaqua Creek gage. When the coefficient of variation for discharge at several gaging stations is plotted against drainage density (Fig. 11), a strong positive relation results, which illustrates the difference between the low variability of discharge of the steephead streams and the large variability of discharge in streams where surface runoff is more dominant.

3.3. Drainage network analysis

Horton (1945) developed a stream ordering scheme that permitted analysis of drainage networks. Unbranched tributaries are first-order streams, and junction of two first-order streams form a second-order stream and so on. Because of this branching, relations exist between stream frequency, channel length, and drainage area for streams of each order, which are manifested as straight lines on semi-logarithmic paper. However, when these relations are developed for some of the Eglin AFB streams, instead of straight lines, the stream frequency plots are concave and stream length plots are convex. This suggests that too many first-order streams occur in the spring-sapping networks (Fig. 12) and that the first order streams are too short (Fig. 13). During experimental investigations, such departures from straight-line plots were identified as being typical of as yet incomplete drainage networks (Schumm et al., 1987). In addition, the bifurcation ratio, a ratio of the number of stream of one order to the number of streams of the next highest order is very high for some of the Eglin AFB streams. The ratio between first and second order streams is usually about 3 to 4, but the ratio for Little Rocky Creek is 5, for Rogue Creek it is 6, and for Parrish Creek it is 14 (Fig. 6). No attempt was made to define drainage areas for these steephead streams as no obvious drainage divides could be located on the upper surface. Therefore, drainage density was not determined, although it would be low in comparison to networks formed by fluvial processes (Berger and Aghassy, 1984).

These deviations from the normal relations suggest that spring-sapping networks have anomalous Horton-type relations and that these criteria could be used for identification of such networks elsewhere. However, spring-sapping (steephead) networks have also developed east of the Apalachicola River (Fig. 5), and there the major drainage network, Sweetwater Creek, conforms to the Horton relations (Figs. 12, 13).

The Sweetwater Creek drainage basin is about 5.2 miles long and relief is 210 feet (Fig. 5), whereas Rocky Creek is about 8.8 miles long and relief is 200 feet. Hence, the ability to erode in the Sweetwater Creek drainage system is much greater than on Eglin AFB. The conclusion is that departures from the Horton relations reflect drainage networks that are incompletely developed. This either means that further development by headward elongation and tributary development can be expected or more likely, the networks have stabilized under present climatic conditions, although the excavation of clay pits near steepheads and forest fires could reactivate steephead processes.

4. Discussion

The steephead drainage networks of the Florida Panhandle have formed as a result of a combination of highly permeable soils and abundant ground water. Nevertheless, the ground-water landscape is compound. The steephead streams have formed only portions of the landscape. Most of the area remains essentially unmodified and shows evidence of past eolian (dunes, deflation depressions) and marine (beach ridges, terraces) processes. Hence, the ground-water sapping landscape is composed of both relict and active components. The relict portions of the landscape exist because very high infiltration rates of the surface materials and relatively low relief have limited surface erosion.

The steephead valleys conform to most of the characteristics of sapping valleys, as summarized in the Introduction, with the exception of items 1, 2, and 8. For example, in the Juniper Creek drainage, structural control is probably replaced by topographic control by beach ridges. Also, items 4 and 11 are less obvious in the relatively homogeneous Citronelle sands. Nevertheless, the drainage networks contain some unusual patterns. First and second order tributaries on the upslope side of a main tributary are much longer than those on the downslope side, and asymmetrical growth of tributaries is usual (Fig. 5). The headward intersection of two valleys (Fig. 3) is a feature not expected in a fluvial landscape. The long Turkey Creek valley has captured the ground-water supply to Turtle Creek, and a steephead valley is forming that will extend north of the junction.

The lack of conformance of the sapping valleys to Horton's relations (Figs. 11, 12) apparently results from incompletely developed drainage patterns, as in the Rocky and Juniper Creek basins. Nevertheless, the patterns can conform where the drainage network is more fully developed, as in the Sweetwater system (Figs. 5 and 12). The most common cause of the stalling of steepheads is capture of ground-water by other streams (Fig. 1).

The experimental studies of spring-sapping channels appear to reproduce very well the conditions of steephead stream development and evolution. Perhaps of most importance is the lack of impermeable zones in the experimental material (Fig. 2). Hence, it is not necessary to have an impermeable zone for steephead-stream development. In the Colorado Plateau valleys, the strata dip downstream and provide a continuous impermeable layer, whereas in the Citronelle Formation, local horizontal layers provide spring water at only a few locations. The Florida steephead streams do not require stratigraphic variability.

Finally, as in the experiments, movement of the steepheads is probably episodic. The steephead walls are densely vegetated, and episodes of movement may be associated with fires which remove vegetation, kill trees, and produce a situation susceptible to mass movement and steephead advance. Obviously, human activities that deliver water to the steephead or that weaken the vegetative cover will also induce steephead erosion and advance. Steephead advance may also occur during prolonged wet periods.

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References

Berger, Z. and Aghassy, J., 1984. Near-surface groundwater and evolution of structurally controlled streams in soft sediments. In: R.G. LaFleur (Editor), Groundwater as a Geomorphic Agent. Allen and Unwin, Boston, pp. 59–77.

Brown, J.W., Patrick, D.M. and Albertson, P.E., 1994. Pedogenic origins of Citronelle Formation hardpans: Examples from the Florida Panhandle with Mississippi applications. J. Miss. Acad. Sci., 39(1):49.

Campbell, I.A., 1973. Controls of canyon and meander forms by jointing. Area, 4: 291–296.

Carlston, C.W., 1963. Drainage density and streamflow. U.S. Geol. Surv. Prof. Pap., 422-C: 8 pp.

De Vries, J.J., 1974. Ground-water Flow Systems and Streamnets in The Netherlands. Rodopi, N.V., Amsterdam, 226 pp.

De Vries, J.J., 1976. The ground-water outcrop-erosion model: Evolution of the stream network in the Netherlands: J. Hydrol., 29: 43–50.

Dunne, T., 1980. Formation and controls of channel networks. Prog. Phys. Geogr., 4: 211–240.

Dunne, T. and Black, R.D., 1971. Runoff processes during snowmelt. Water Resour. Res., 7: 1160–1172.

Gomez, B. and Mullen, V.T., 1992. An experimental study of sapped drainage network development. Earth Surf. Process. Landforms, 17: 465–476.

Gremillion, L.R., Tanner, W.F., and Huddlestun, P., 1964. Barrier and Lagoon sets on high terraces in the Florida Panhandle. Southeastern Geol., 6: 31–36.

Higgins, C.G., 1982. Drainage systems developed by sapping on Earth and Mars. Geology, 10: 147–152.

Higgins, C.G., 1984. Piping and sapping, development of landforms by ground-water outflow. In: R.G. LaFleur (Editor), Groundwater as a Geomorphic Agent. Allen and Unwin, Boston, pp. 18–58.

Higgins, C.G. and Coates, D.R. (Editors), 1990. Ground-water geomorphology, the role of subsurface water in earth-surface processes and land forms. Geol. Soc. Am. Spec. Pap., 252: 368 pp.

Horton, R.E., 1945. Erosional development of streams and their drainage basins: Hydrophysical approach to quantitative morphology. Geol. Soc. Am. Bull., 56: 275–370.

Howard, A.D., 1988. Introduction: Groundwater sapping on Mars and Earth. NASA, SP-491, pp. 1–5.

Howard, A.D., 1990. Case study: Model studies of ground-water sapping. In: C.G. Higgins and D.G. Coates (Editors), Geol. Soc. Am. Spec. Pap., 252: 257–264.

Howard, A.D., Kochel, R.C. and Holt, H.E., 1988. Sapping features of the Colorado Plateau. NASA Spec. Publ., 491: 108 pp.

Kirkby, M.J. and Chorley, R.J., 1967. Throughflow, overland flow and erosion. Int. Assoc. Sci. Hydrol. Bull., 12: 5–21.

Kochel, R.C., 1988. Role of ground-water sapping in the development of large valley networks on Hawaii. In: A.D. Howard et al. (Editors), NASA Spec. Publ., 491: 100–101.

Kochel, R.C. and Baker, V.R., 1990. Case study: Ground-water sapping and the geomorphic development of large Hawaiian valleys. In: C.G. Higgins and D.R. Coates (Editors), Geol. Soc. Am. Spec. Pap. 252: 245–257.

Kochel, R.C. and Piper, J.F., 1986. Morphology of large valleys on Hawaii Evidence for groundwater sapping and comparisons for martian valleys. J. Geophys. Res., 91: E175–E192.

Kochel, R.C., Howard, A.D. and McLane, C., 1985. Channel networks developed by ground-water sapping in fine-grained sediments: Analogs to some Martian valleys. In: M. Woldenberg (Editor), Models in Geomorphology. Allen and Unwin, London, pp. 313–341.

Kochel, R.C., Simmons, D.W. and Piper, J.F., 1988. Ground-water sapping experiments in weakly consolidated layered sediments, A qualitative summary. In: A.D. Howard et al. (Editors), NASA Spec. Publ. 491: 84–93.

Laity, J., 1988. The role of ground-water sapping in valley erosion on the Colorado Plateau. NASA Spec. Publ., 491: 63–70.

Laity, J.E. and Malin, M.C., 1985. Sapping processes and the development of theater-headed valley networks in the Colorado Plateau. Geol. Soc. Am. Bull., 96: 203–217.

Marsh, O.T., 1966. Geology of Escambia and Santa Rosa counties, western Florida Panhandle. Fla. Geol. Surv. Bull., 46: 140 pp.

Means, D.B., 1985. The canyonlands of Florida. Nature Conserv. News, 35(5): 13–17.

New World Research, Inc., 1990. Eglin Air Force Base Historic Preservation Plan, Dept. of Investigations No. 192.

Nicholson, R., 1990. Chasing Ghosts. Natural Hist., 12/90: 8–13.

Overing, J.D. and Watts, F.C., 1989. Soil survey of Walton County. U.S. Dep. Agriculture, Soil Conservation Service, 234 pp.

Pillans, B., 1985. Drainage initiation by subsurface flow in South Taranaki, New Zealand. Geology, 13: 262–265.

Resource Consultants and Engineers, 1994. Geomorphic investigation of Eglin Air Force Base, Florida. Unpubl. Rep. 92-904, 193 pp.

Rupert, F.R., 1991. The geomorphology and geology of Liberty County, Florida. Fla. Geol. Surv. Open-File Rep., 43: 9 pp.

Schmidt, W., 1984. Notes on the geology of Walton County. Fla. Geol. Surv. Open-File Rep, 3: 34 pp.

Schumm, S.A. and Phillips, L., 1986. Composite channels of the Canterbury Plain, New Zealand: Amartian analog? Geology, 14: 326–329.

Schumm, S.A., Mosley, M.P. and Weaver, W.E., 1987. Experimental Fluvial Geomorphology. Wiley, New York, 413 pp.

Sellards, E.H. and Gunter, H., 1918. Geology between the Apalachicola and Ocklocknee Rivers. Fla. Geol. Surv. 10th Ann. Rep., pp. 9–55.

Sharp, H.S., 1938. Geomorphic notes on maps, "Steepheads and spring sapping in Florida — Holt and Niceville Quadrangle, Florida," J. Geomorphol., 1: 247–248.

Stearns, H.T., 1936. Origin of the large springs and their alcoves along the Snake River in southern Idaho. J. Geol., 44: 429–456.

Uchupi, E. and Oldale, R.N., 1994. Spring sapping origin of the enigmatic relict valleys of Cape Cod and Martha's Vineyard and Nantucket Islands, Massachusetts. Geomorphology, 9(2): 83–95.

Winkler, C.D. and Howard, J.D., 1977. Plio–Pleistocene paleography of the Florida Gulf Coast interpreted from relict shorelines. Gulf Coast Assoc. Geol. Soc. Trans., 27: 209–420.