Fossilized forests of the Lower Carboniferous Horton Bluff Formation, Nova Scotia

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ABSTRACT

The Hurd Creek and Blue Beach members of the Horton Bluff Formation (Tournaisian) at Horton Bluff on the Bay of Fundy contain several forested levels. Evidence for standing trees is found in the form of moulds and casts of the base of trunks and in preserved decay hollows. The casts and hollows are preserved as sandstone/siltstone fills surrounded by shale, primarily within horizons of green shale. These shales are paleosols that cap progradational cycles formed by the infilling of mud-dominated brackish bays. The moulds are found in a sandstone/siltstone bed exposed on the wave cut platform. Abundant fossilized plant debris indicates the presence of *Lepidodendropsis* and of pterophytes, and potentially of *Asterocalamites*.

At least four forested levels have been identified in the Horton Bluff Formation. An 11-meter (horizontal distance) section of sandstone/siltstone exposed on the wave-cut platform contains 163 standing tree fossils spaced tens of centimetres apart. These trees range from 3 to 35 cm in diameter. A prominent 117-meter (horizontal distance) green shale observed in two dimensions contains 13 exposed casts and 8 exposed decay hollows, at the time of field work. The casts narrow upwards at approximately 58° from vertical, and have a maximum width and height of 88 cm and 22 cm, respectively. The decay hollows show more variation in their dimensions. An additional fossilized horizon with decay hollows is seen further along the cliff.

The fossilized forests at Horton Bluff may be the oldest well-preserved forests in Nova Scotia. Similar structures could potentially be identified at previously overlooked locations, such as in older rocks with poor vegetative preservation. Additionally, an understanding of the vegetative cover in the late Devonian and early Carboniferous could lead to further understanding of the paleo-environment and ecology at that time.

Key words: Horton Bluff Formation, stump casts, decay hollows, stump moulds, fossilized forests, paleo-environment

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Chapter 1: Introduction

1.1 Objective and General Statement

Horton Bluff has long been known as a region with an interesting and diverse geological history. The interpretation of the depositional environment of the Carboniferous Horton Bluff Formation has changed over the years as new information has been brought to light, but the moniker "forested" has yet to be applied to the strata. Extensive evidence for the presence of vegetation exists in the fossil record in the form of bark imprints, megaspores and root traces. Little work has been done on the species composition or the abundance of the vegetation.

This project endeavors to determine if the Horton Bluff area was periodically densely forested, or if the plant fossils are the products of sparse vegetation. This will be achieved by a close examination of the sedimentary record for evidence of trees. Structures such as tree casts, tree moulds and decay hollows in fine-grained sandstone/siltstone beds have been identified at Horton Bluff, and are described in detail in the subsequent chapters.

The tree structures can be used to investigate the extent of forestation in the Blue Beach and Hurd Creek Members of the Horton Bluff Formation. Little research has been conducted at Horton Bluff on the standing vegetative structures. An accurate and detailed description of these structures will allow comparison of the features found at Horton Bluff with those in other rock units and this could lead to new discoveries of fossilized trees or forests. This type of evidence is significant in older rocks where few trees seem to be preserved when compared to younger rocks. Identification of ancient forests leads to a more accurate description of the rock record.

Vascular plants are first documented in the fossil record in the Early Devonian (Willis and McElwain, 2002). The Tournaisian Horton Bluff Formation contains vascular plant fossils from approximately 50 Ma after the documented evolution of these plants. Well-preserved fossil evidence from the older rock record is rare, and so the identification of standing forests in Early Carboniferous rocks provides further clarification on propagation of the vascular plants over the 50 Ma of their earliest existence. An understanding of the extent of vegetative cover of the land can lead to inferences concerning atmospheric composition and the development of the carbon cycle over time (Elick et al, 1998; Willis and McElwain, 2002).

1.2 Geographic Setting of Horton Bluff

The study area belongs to the Horton Bluff Formation, which is Upper Devonian to Lower Carboniferous in age (Williams *et al.*, 1985, Martel and Gibling, 1995). The Horton Bluff Formation, a component of the Horton Group, has been divided into four members: the lowermost Harding Brook Member, the Curry Brook Member, the Blue Beach Member and the uppermost Hurd Creek Member (Martel and Gibling, 1995). The research was conducted on the Blue Beach and Hurd Creek Members exposed at Horton Bluff, on the southwestern coast of Nova Scotia, along the Minas Basin (Figs. 1 and 2). Faulting along the Cobequid-Chedabucto Fault that runs to the north of the Minas Basin (Figure 1) is partially responsible for the deformation of the Blue Beach Member (Martel and Gibling, 1995). These rocks have also been buried and heated in the regular process of lithification, a minor additional cause of deformation.

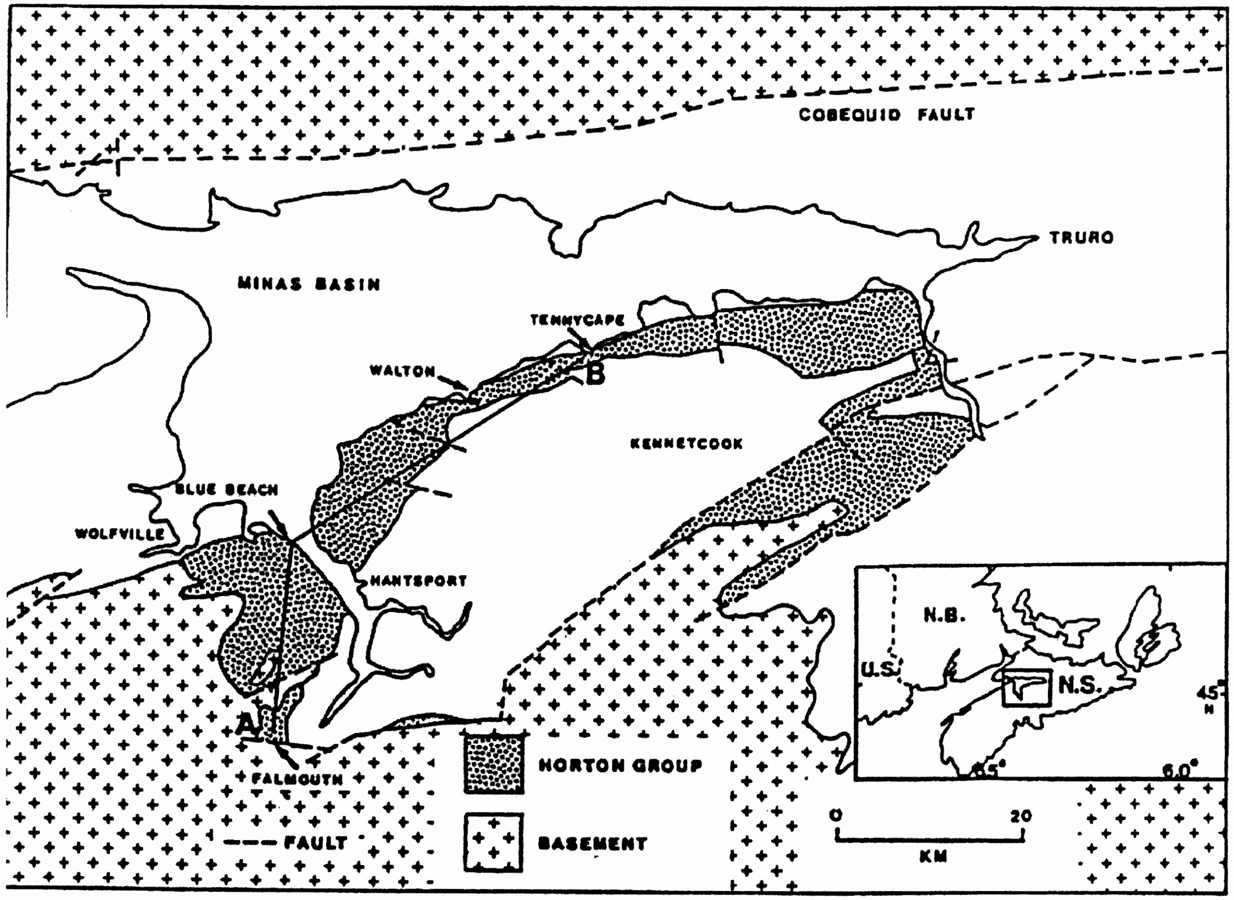
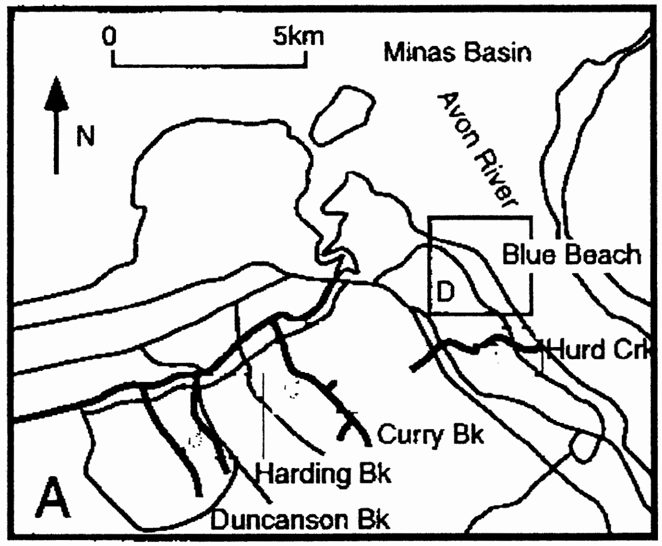
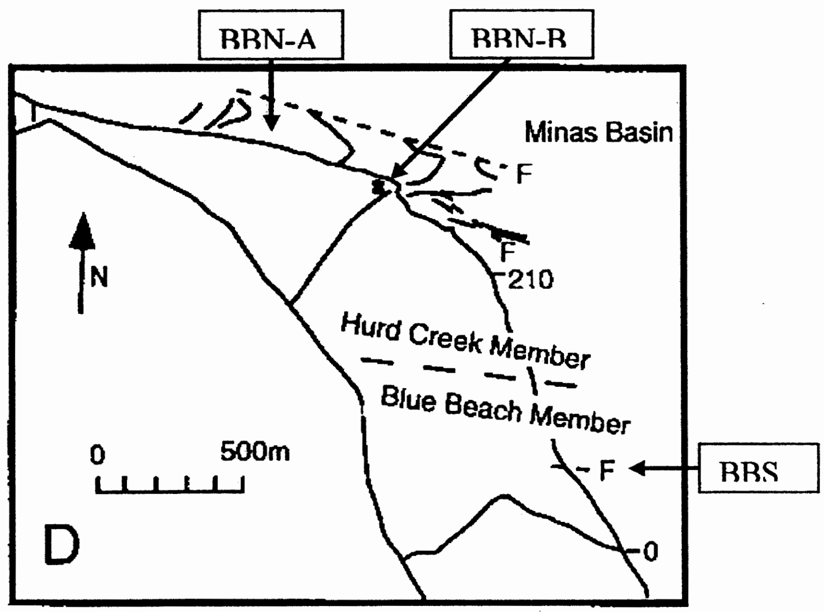


Figure 1: Geological map of southwestern Nova Scotia showing the study area at Blue Beach. The Cobequid-Chedabucto Fault is shown to the north of the Minas Basin. The Horton Bluff Formation is a subdivision of the Horton Group shown on the map. The basement rocks are composed of Meguma Group and granitic rocks to the south of the Fault, and rocks of the Avalon Terrane to the north. The inset shows the Maritime Provinces of Canada and the border with the United States of America. After Martel and Gibling, 1991.



A



B

Figure 2: Map illustrating the location of the Blue Beach study area on the Avon River, near Hantsport. The location of Blue Beach is shown by the box labeled "D" in **A**. The cliff segment of BBN-A is indicated by the top arrow in **B**, of BBN-B by the middle arrow, and of BBS by the bottom arrow. The dashed lines correspond to faults and the thick and thin solid lines correspond to roads and streams, respectively. After Martel and Gibling, 1995.

Chapter 2: Methods

2.0 Methodology

The research was conducted in the field at Horton Bluff from September to December 2002, and involved primarily photography and mapping.

The structures of interest occurred in cliff sections approximately 117 meters and 60 meters long in the BBN-A and BBN-B cliff segments, respectively (Fig. 2). These cliffs were sequentially photographed at a constant distance of 10 meters from the base of the cliff, using a digital camera. The resulting pictures overlapped by approximately 20%, and were stitched together using Adobe PhotoShop©. After printing these photo-mosaic cliff sections, Mylar tracings were made in the lab, highlighting major features such as prominent sandstone beds, plant fossils and trace fossils, and the top and bottom of the cliff face. This traced information was subsequently confirmed and supplemented during a later field visit. GPS readings were taken at the northern-most end of the cliff sections, giving a position of 4995908N 403065E for BBN-A and 4995830N 403427E for BBN-B.

The individual tree fossils within BBN-A and BBN-B were also photographed and traced, adding specific details to the tracing such as their dimensions, lithologies, and any direct evidence of vegetation.

An 11-meter (horizontal distance) section of forested bedding plane showing extensive tree stump positions preserved as moulds was mapped at BBS (Fig. 2). A central reference line, divided into 0.25m lengths, with a bearing of NE-SW, was laid across the bedding plane on the wave-cut platform. The position of each tree stump mold was mapped by proceeding perpendicularly from the central line and marking its position on grid-paper. The tree density of the paleo-forest was calculated from this map.

Stratigraphic columns of the rocks exposed at BBN-A and BBN-B were generated while in the field. The cliff was visually divided into distinct units, and these units, their dimensions, the boundaries between them, and their characteristic properties were added to the corresponding photomosaics.

Chapter 3: The Horton Bluff Formation and its plant fossils

3.1 Facies and Paleoenvironment

The study area falls into the Blue Beach and Hurd Creek Members of the Famennian-Tournaisian Horton Bluff Formation. The Horton Bluff Formation was laid down in a half graben formed by faulting along the Cobequid fault or a precursor to this fault (Martel and Gibling, 1995). At the type area, near Hantsport, Nova Scotia, the Horton Bluff Formation is 525 meters thick (Martel and Gibling, 1995). Both the Blue Beach and Hurd Creek members are characterized by repeated stratigraphic cycles.

The Blue Beach member consists of asymmetric, coarsening-upward cycles of four facies (Martel and Gibling, 1995). The basal facies is a dark grey fissile clay shale, with abundant fossils and siltstone lenses. Siltstone and fine-grained sandstone interbedded with clay shale cover this shale facies. These strata contain subaerial and shallow-water sedimentary features, such as sharp-crested and planed-off wave ripples, hummocky cross-stratification, groove casts and clastic dykes of compactional or diagenetic origin. Planar-bedded siltstone layers cap this facies in most cycles. The third facies consists of disrupted green mudstone, usually interbedded with tabular-bedded siltstone. Vertical trees are found within these strata. The fourth facies consists of dolomite in the form of laterally continuous massive beds as well as nodules within disrupted mudstone. Vertical trees are also associated with this facies. The Blue Beach member cycles range from 1 to 22 meters in thickness, with an average thickness of 6 meters. These strata contain abundant fossil material including vegetative remains, disarticulated fish material, ostracodes, agglutinated foraminifera, and trace fossils (Bell, 1960; Martel and Gibling, 1995; Tibert and Scott, 1999).

The Hurd Creek Member consists of two types of stratigraphic cycle (Martel and Gibling, 1995). The first type is a coarsening-upwards sandstone dominated cycle. These cycles are up to 16 meters thick. A basal shale is overlain by any combination of planar- and lenticular-bedded siltstone and clay shale, flaser-bedded sandstone, and interbedded rippled sandstone and clay shale. These strata are in turn overlain by coarsening-upwards medium- to very coarse-grained sandstone, with planar and trough cross-stratification in sets up to 25 cm thick. The second type of cycle found in this member is a clay-shale and siltstone-dominated cycle similar to that of the Blue Beach member, and comprises only a small portion of the Hurd Creek member at the type section, but predominates in coastal sections of the study area.

The Horton Bluff Formation has long been interpreted as a fluvio-lacustrine tropical paleo-environment (Bell, 1959; Martel and Gibling, 1991), but recent microfossil assemblages have suggested a marine-influenced environment (Tibert and Scott, 1999). The Blue Beach member represents a cyclical transition from a marine environment to a terrestrial one (Martel and Gibling, 1995). The dark clay shales would have been deposited offshore, presumably oxygenated to allow the survival of scavenging organisms. The strata of facies two represent a nearshore or shoreline environment, subject to wave action. Facies three and four represent hydromorphic paleosols. The discovery of agglutinated foraminifera and a review of ostracode taxa indicate a marine component to the depositional environment, at least periodically (Tibert and Scott, 1999). The Hurd Creek member is interpreted as being deposited in a large standing body of water subjected to wave activity, with some of the strata representing deltaic distributary-channel deposits (Martel and Gibling, 1995).

3.2 Plant Material

The Horton Group contains abundant fossilized plant material, including bark imprints, megaspores and root traces, as well as protist, ostracode, fish and amphibian fossils (Calder, 1998). Bell (1960) and Calder (1998) have compiled summaries of the fossil assemblages of the Horton Group. The plant species documented regionally in the Horton Group are shown in Table 1.

Table 1. Summary of the paleo-botanical fossil assemblage of the Horton Group, according to Bell (1960) and Calder (1998).

Calder	**Bell**
Lepidodendropsis corrugatum	*Lepidodendropsis corrugata*
-	*Lepidodendropsis* sp. A
-	*Lepidodendropsis* sp. B
Lepidophyllum fimbriatum	*Lepidophyllum fimbriatum*
-	*Lepidostrobophyllum* sp.
-	*Lepidodendron* sp.
Asterocalamites scrobiculatus	*Asterocalamites scrobiculatus*
Nematophyllum sp.	*Nematophyllum* sp.
Aneimites acadica	*Aneimites acadica*
	Adiantites tenuifolius
Sphenopteridium macconochei	*Sphenopteridium macconochiei*
Sphenopteris patentissimum	*Diplotmema patentissimum*
Triphyllopteris minor	*Triphyllopteris minor*
Triphyllopteris virginiana	*Triphyllopteris virginiana*
Sphenopteris strigosa	*Sphenopteris strigosa*
Carpolithus tenellus	*Carpolithus tenellus*
	Sphenopteridium sp.

These two lists show certain discrepancies within the species assemblages. These are most likely accounted for by the age of the Bell classification scheme. Plants identified as a certain species by Bell, in 1960, have been re-classified as either a new species or genus, such as with the change of *Sphenopteris* to *Diplotmema*, or that multiple species have been amalgamated as one species. Some of the species names have been corrected since the Bell classification, such as *Lepidodendropsis corrugatum* to

Lepidodendropsis corrugata. Some of the items on the Bell list are likely spores, which were not accounted for in the Calder list. The variations of *Lepidodendropsis* in the Bell list have been reclassified as *Lepidodendropsis corrugatum* in the later Calder list.

The most likely constituents of the fossilized forests of the Horton Bluff Formation discussed in this paper are *Lepidodendropsis, Asterocalamites,* Progymnosperms or Pteridospermales (seed ferns) (J. Calder, pers. comm.). The identification of these plant species in Horton Bluff Formation is based on drifted plant material. The standing trees, however, show poor tissue preservation and so species identification is difficult. *Lepidodendropsis* is well documented within the formation. This early, branched lycopsid originated in the Upper Devonian (Stewart and Rothwell, 1993), and was rooted by a "lobed, corm-like rhizomorph" termed a *Protostigmaria* (Fig. 3) (Calder, 2001). This rhizomorph consisted of two lobes separated by a furrow in smaller plants, with the number of lobes increasing to as many as 13 in larger plants, with rows of root scars extending from between the furrows (Stewart and Rothwell, 1993). *Lepidodendropsis* is documented as dominating the coastal regions and the floodplains of Tournaisian swamps in Virginia (Schekler, 1986). Willis and McElwain (2002) classify the habitat of *Lepidodendropsis* as "tropical everwet".

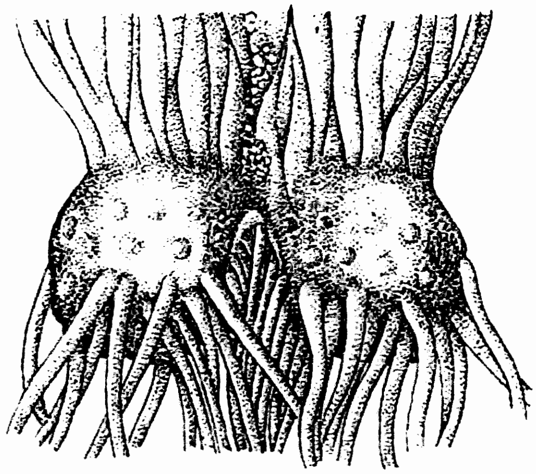


Figure 3: Diagram of a *Protostigmaria*, the rhizomorph of *Lepidodendropsis*. This rhizomorph shows two lobes and numerous smaller roots extending from the lobes. After Stewart and Rothewell, 1993, Figure 11-30.

The now extinct class of Progymnospermopsida, the ancestors of gymnosperms, is unified by two characteristics: the presence of cambium and woody tissue made of secondary xylem, allowing the plants to grow to large heights, and heterospory, the evolutionary ancestor to seed production (Calder, 2001, Willis and McElwain, 2002). Some of these trees grew up to 8 meters tall, with diameters of over 1.5 meters (Willis and McElwain, 2002). These plants were anatomically similar to gymnosperms, but reproduced by spores (Willis and McElwain, 2002). As the foliage of progynmosperms was comparable to fern fronds (Willis and McElwain, 2002), this class could include some of the *Adiantites*-like foliage found in the Horton Bluff Formation (J. Calder, pers. comm.).

Seed ferns (order Pteridospermales) of the class Gymnospermopsida (Calder, 1998) are another possibility for the tree structures seen at Horton Bluff. These plants are documented as occupying a similar habitat to *Lepidodendropsis*, a "tropical everwet" environment (Willis and McElwain, 2002). Pteridosperms were among the first plants to reproduce via pollen generation and seed production, and had fern-like foliage (Willis and McElwain, 2002). The majority of pteridosperms had arborescent forms, reaching a height up to 10 meters, and stem-base diameters of 0.5 meters in some species (Willis and McElwain, 2002).

The evolution and diversification of vascular plants, particularly during the Devonian resulted in larger plants, more successful reproductive strategies and wider distributions, including adaptation to unstable high-energy environments (Elick *et al.*, 1998; Willis and McElwain, 2002). These changes also included a shift towards horizontal growth habit, because of inter- and intraspecific competition for resources such as light, space, and nutrients, and because of the development of vascular tissue (Elick *et al.*, 1998). Major climatic changes occurred simultaneously with this proliferation of vascular plants. The Devonian Earth changed from a warm planet with high concentrations of atmospheric CO_2 to a colder planet with rapidly declining atmospheric CO_2 concentrations during the Carboniferous (Willis and McElwain, 2002). This decrease in the global temperature and atmospheric CO_2 has been attributed to the diversification and proliferation of plants (Elick *et al.*, 1998, Willis and McElwain, 2002). The increase of plant cover and the decrease in atmospheric CO_2 would have resulted in increased soil stability, soil acidity and soil organic matter concentrations (Elick *et al.*, 1998). These changes in the soil would have led to a subsequent increase in silica weathering, altering the compositions of the lithosphere, hydrosphere and atmosphere (Elick *et al.*, 1998). The increased success of plants corresponds to anoxic events in the Devonian oceans and sediments (Elick *et al.*, 1998).

Chapter 4: Evidence for Standing Trees in the Horton Bluff Formation

4.1 BBN-A: Tree casts and hollows

Two primary types of structures were observed, both related to the former presence of trees. These structures were related to trees on the basis of the fossilised plant material found in the vicinity, the root traces attached and near to the structures, and the similarities between the structures within the cliff face. All of the structures shared common structural characteristics, and occur along the same stratigraphic horizon. These characteristics, the stratigraphic context, and the interpretation of their formation are given in subsequent sections.

4.1.1 Stratigraphic context- tracings and columns

The tree casts and decay hollows at BBN-A are found along two primary horizons in the cliff face, a sandstone layer at the top of Unit 2, as well as Unit 3a. A detailed photo-mosaic of this cliff face can be seen in Figure 4. This photo-mosaic illustrates the position of the tree casts, the decay hollows, and other biogenic features of a similar scale visible at the time of field work. Subsequent visits to the field area showed the dynamic nature of the eroding cliff face, with the destruction some of the identified tree structures, and the uncovering of new features. The photographed cliff section is 117 meters long horizontally along the beach.

The cliff face was divided into distinct lithologic units, shown in Figures 4 and 5 that correspond to the four facies within the cycles. The tree casts were found in Unit 3a, a 40 cm-thick shale and fine-grained sandstone/siltstone unit. This unit contains organic matter, principally plant remains. Root structures, bark traces and carbon remains are common. The decay scours were found in a sandstone/siltstone layer directly underneath Unit 3a. They appear as truncations in the sandstone horizon. Root traces can be found on the top of this bedding

Figure 4-A

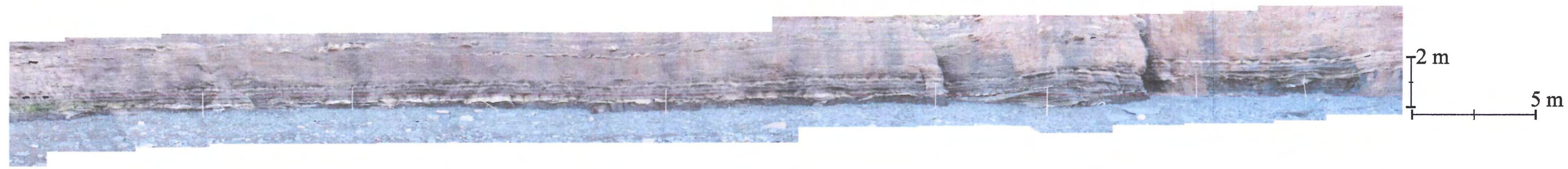
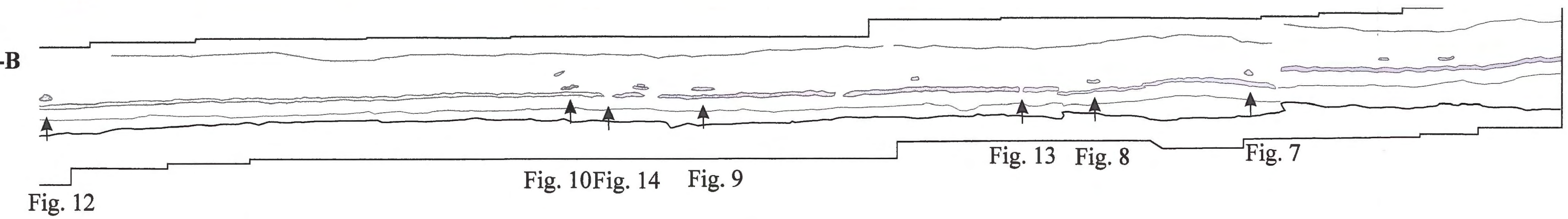
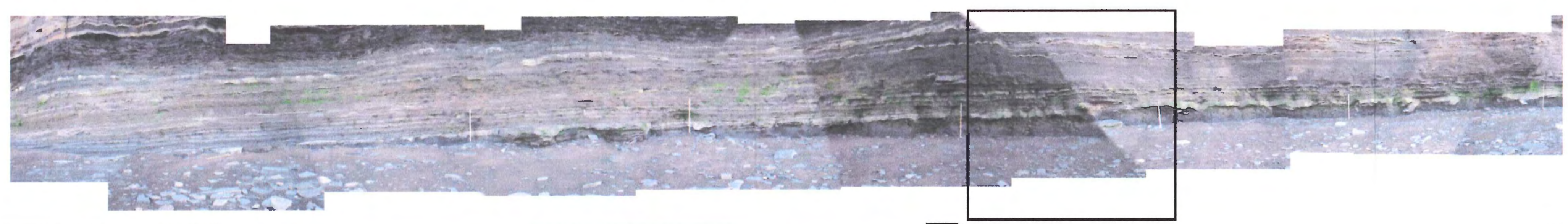
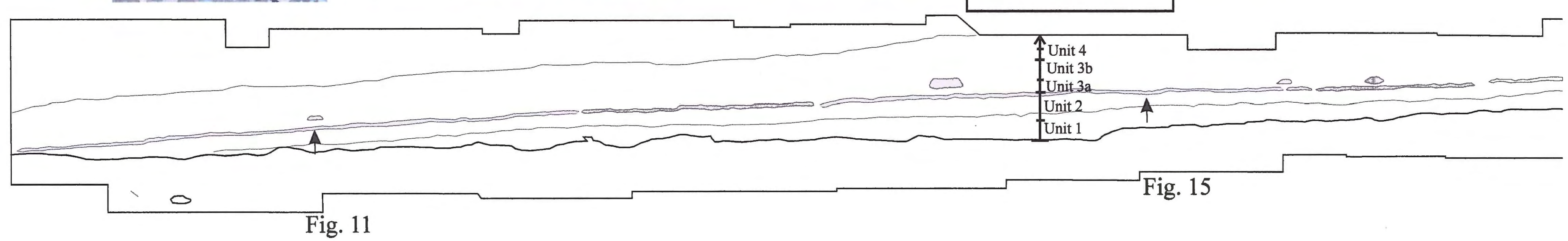


Figure 4-B







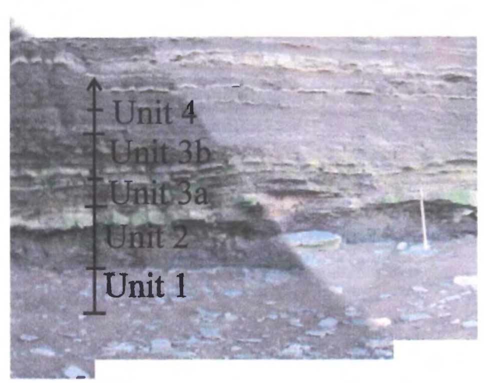
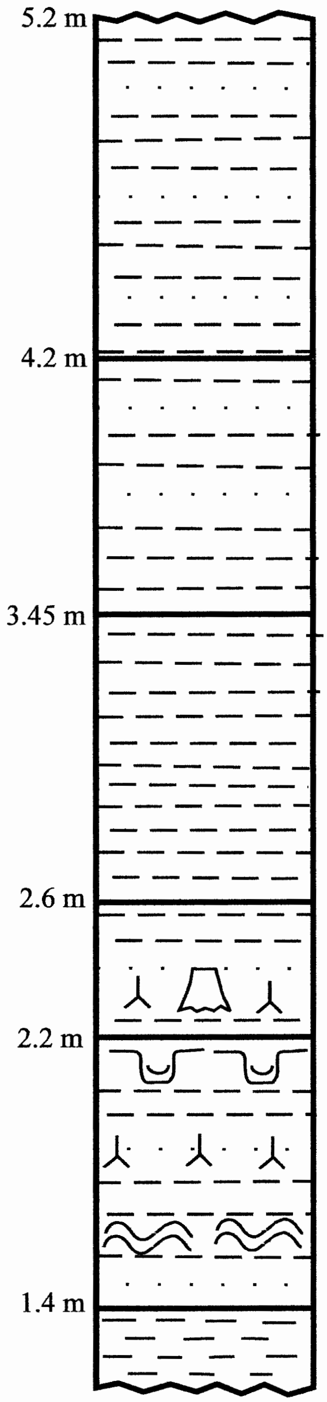


Figure 4-C

Figure 4: Cliff section of BBN-A. **A:** Photo mosaic of the cliff face in which the tree casts and decay hollows were found. The left edge of the top portion aligns with the right edge of the lower portion of the photo-mosaic. The scale varies somewhat along the photo-mosaic, and can be determined from the meter-stick propped against the cliff at intervals. An approximate average scale is shown on the right. The shale layer where the tree casts and decay scours are located occurs directly above the shaded sandstone horizon shown in **B**. All the decay hollows and tree casts are found along the same shale/sandstone horizon. The location of the scours and casts seen in figures 6 through to 14 is illustrated



Unit 4b: Interbedded green shale and fine-grained sandstone/siltstone (10%). A carbonate layer approximately 20 cm from the top of the unit consists of 20 cm of continuous nodular material. This unit is overlain by black shales with minor sandstone.

Unit 4a: Interbedded green shale and discontinuous sandstone/shale. The approximately 30% sandstone fills low-angle channel features such as gullies.

Unit 3b: Thin silty layers of "chippy" medium-gray shale. Consists of 90% fine-grained material and 5% sandstone/siltstone.

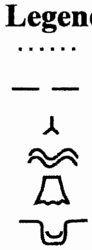
Unit 3a: The main forested level, consists of approximately 90% medium gray shale, with 10% discontinuous sandstone.

Unit 2: Interbedded sandstone/siltstone(40%) and grey shale (60%). Sheet-like bedding, with large clastic dykes, plant material, and wave ripple forms in the sandstone/siltstone. The six planar-lenticular beds found above the bottom-most 25cm thick, massive sandstone/siltstone bed range from 10 to 15 cm in thickness. Deposited as flood sheets.

Unit 1: Incompletely exposed well-stratified platy grey shale with minor sandstone. No obvious roots or plant material.

Figure 5: Stratigraphic column of the cliff face exposed at BBN-A. Unit 3a contains the tree casts and decay hollows of interest in the paper. These strata represent a marine transgressive and regressive environment. A photograph of the cliff exposure used to generate this column is found in Figure 4 .

Legend



Sandstone
Shale
Roots
Wave ripples
Tree casts
Decay hollows

surface, presumably in connection with the overlying treed horizon. These roots tend to spread horizontally, and range from less than 5 mm to 1.5 cm wide.

4.1.2 Detailed tree occurrences

Close up photographs and interpretive diagrams for six tree stump casts, one tree trunk cast and two decay hollows can be seen in Figures 6 to 14. The position of these structures within the cliff face is shown by arrows in Figure 4. Many of the tree casts show similar features, including curved bases, flared sides and bark traces on the outer surface. The curved bases can be seen in Figures 6 to 10. Some of the stump casts show more intense deformation underneath the casts then in the surrounding strata, in the form of deformed lamina and increased fracturing. All of the tree casts in the close-up photographs (Figs. 6-11) demonstrate the flared sides. The sides of the casts taper upwards from the base at an angle between 56-58° from vertical. Figure 10 shows this form nicely. Black organic bark traces on the outer surfaces of the tree casts can be seen in Figures 6, 7, 10 and, in particular, Figure 11.

The casts range in minimum diameter from 37 cm to 88 cm. These diameters are minimum diameters only, due to incomplete exposure of the tree structures in the cliff face. The widest cast (88 cm) is shown in Figure 8. The height of the casts, or the level up to which the infilling was preserved ranges from 6.5 cm (Fig. 8) up to a maximum of 22 cm.

Figure 6 shows a rougher outer surface than the casts in Figures 7-11. The other casts appear smooth in comparison.

A cast of a 20 cm-wide tree trunk is shown in Figure 12. This trunk casts is different from the stump casts in that it occurs below Unit 3a, the paleosol layer. The trunk cast is preserved as shale surrounded by sandstone/siltstone, whereas the stump casts are preserved as sandstone/siltstone surrounded by shale. The trunk cast occurs in the same horizon as the decay

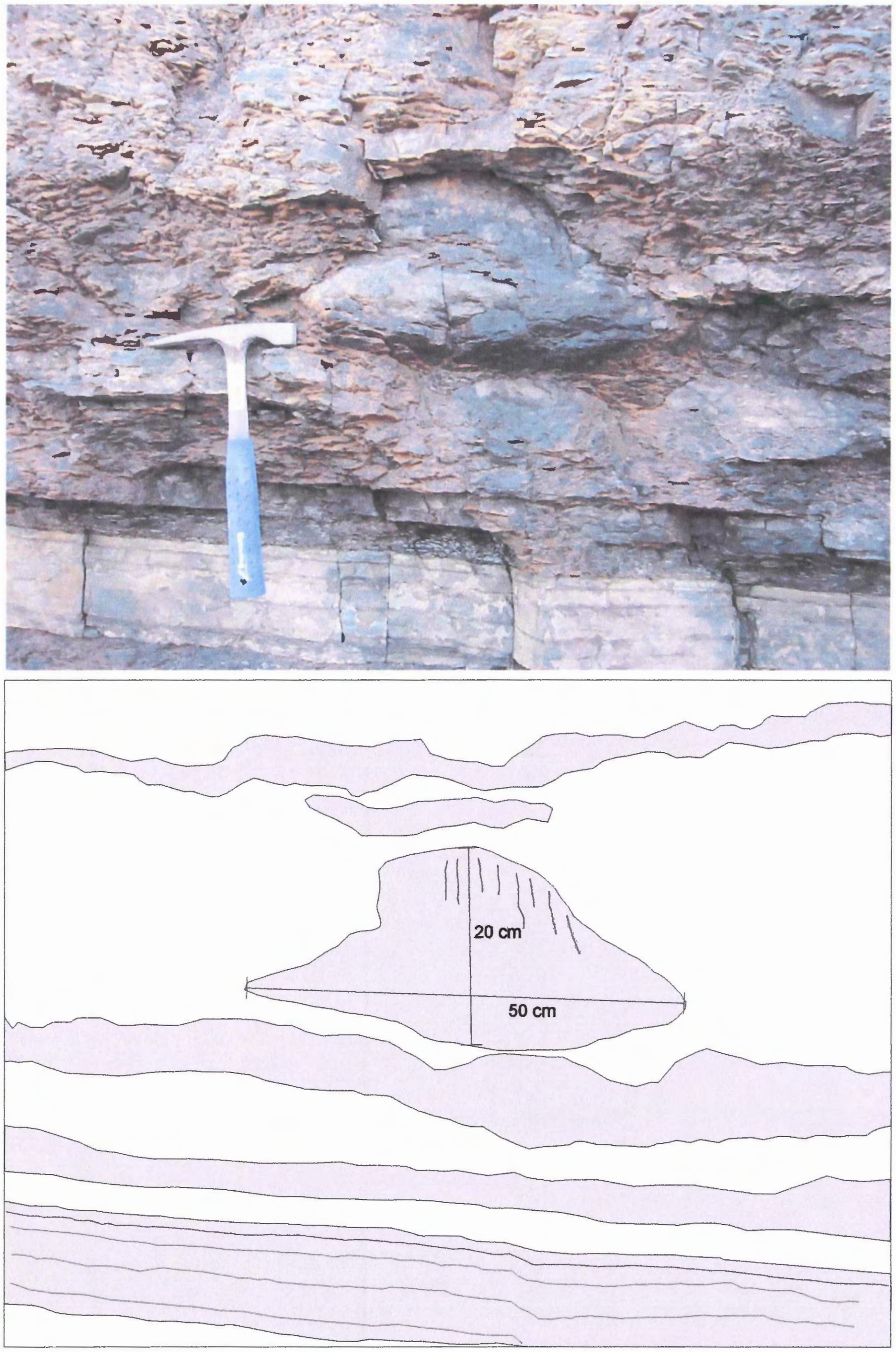


Figure 6: Tree stump cast found in the cliff face at BBN-A. The tree cast shows the curved base and downward-flaring sides characteristic of all the tree casts. Bark lineations are seen on the outer surface of the cast. Black organic matter is found on this surface and in the surrounding rocks. The tree cast is preserved as a fine-grained sandstone/siltstone within dark shale corresponding to a poorly developed palaeosol. The scale is consistent between the two diagrams. The diameter given is a minimum value only, due to incomplete exposure in the cliff face.

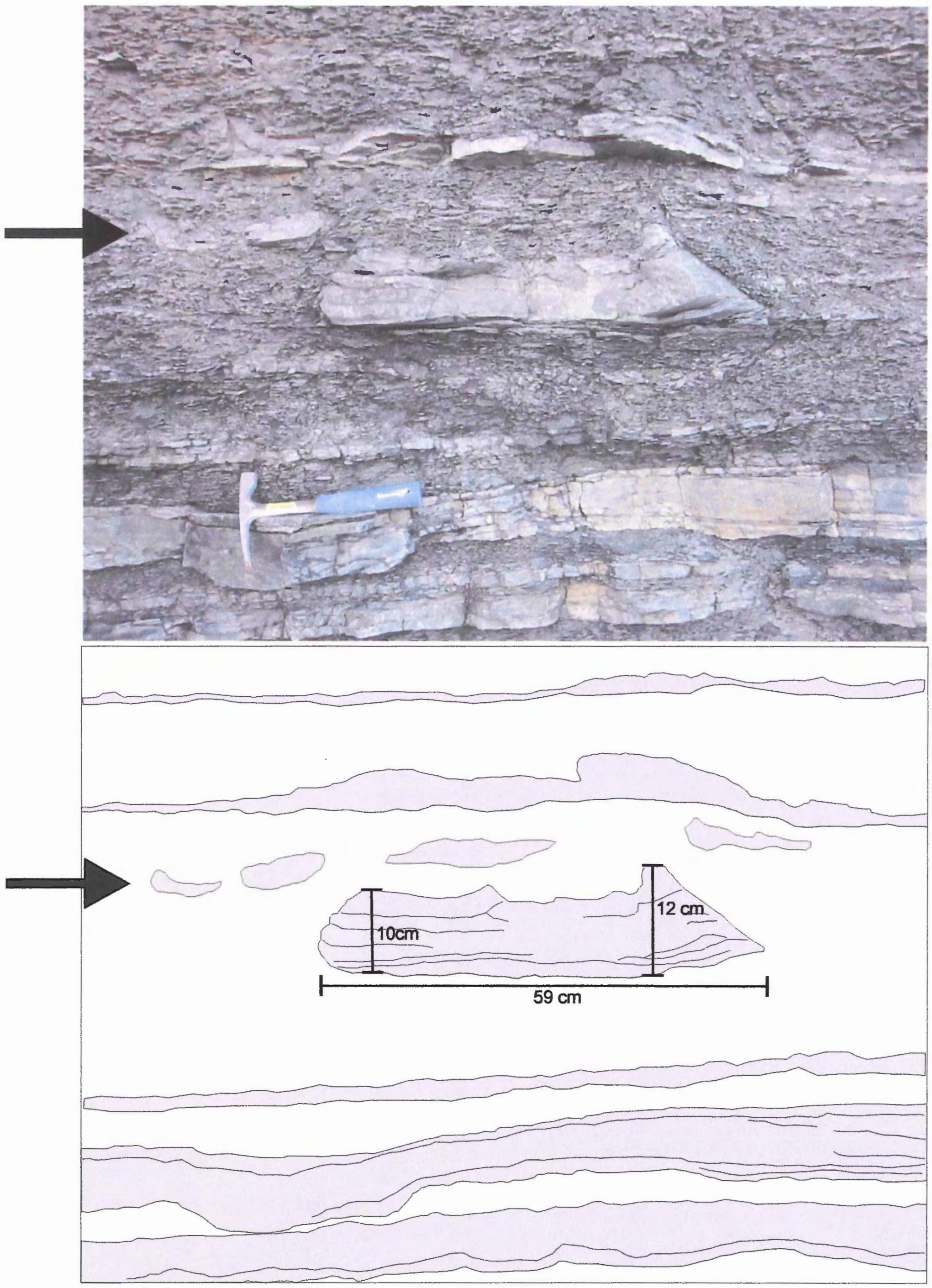


Figure 7: Tree stump cast found at BBN-A, as a sandstone/siltstone unit within dark shale. The base flares inwards at an angle of 58° from vertical. The underlying shale laminae are more intensely deformed directly underneath the tree cast than where laterally adjacent to it. Bark imprints are found on the right-most outer surface seen in this picture. The given diameter of the tree cast is a minimum diameter, as the cast was only partially exposed. The overlying incomplete sandstone layer(indicated by the arrow) is a probable source for the sandstone infilling the casts. The scale of the photograph and the interpretive diagram are the same.

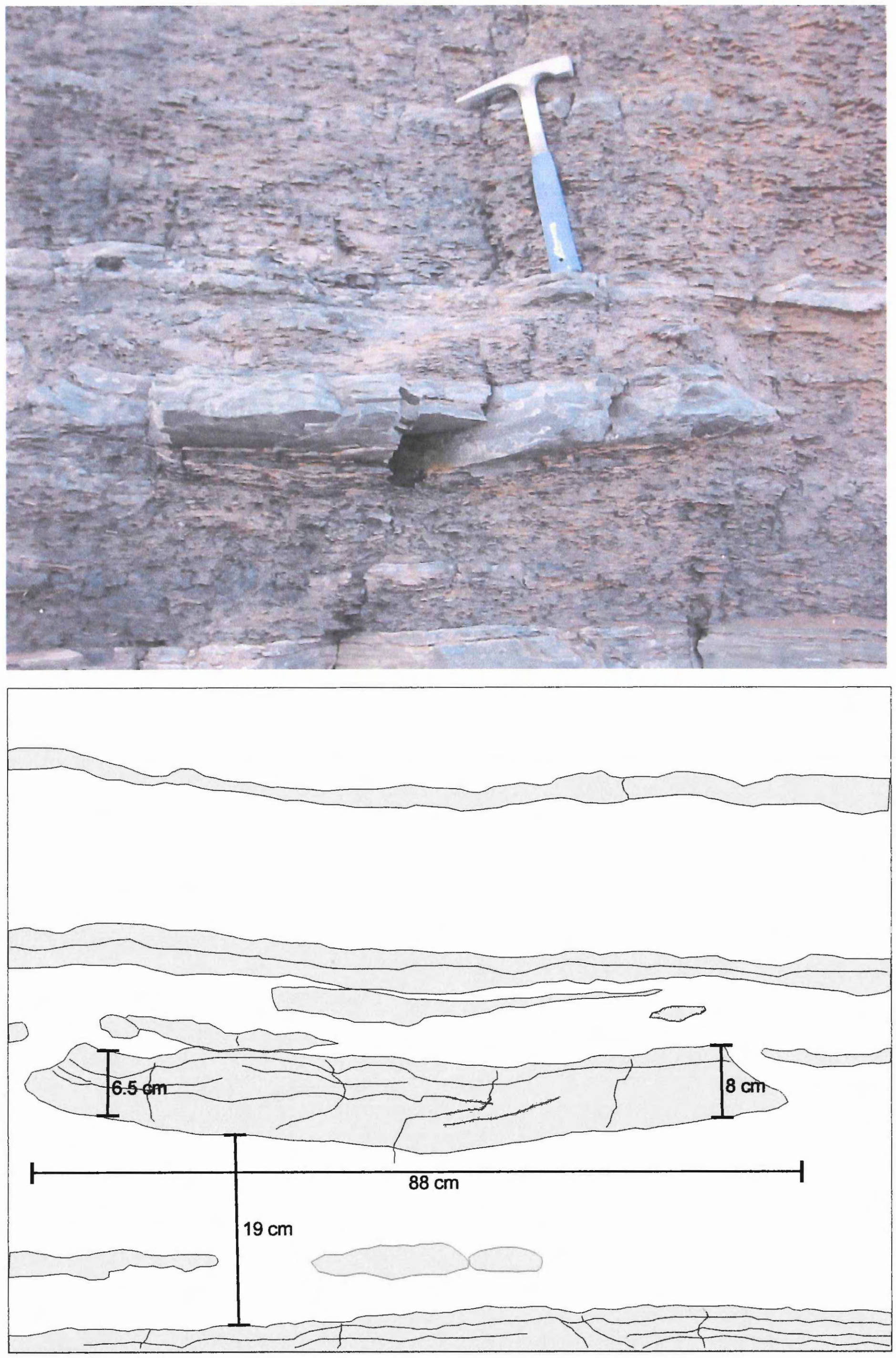
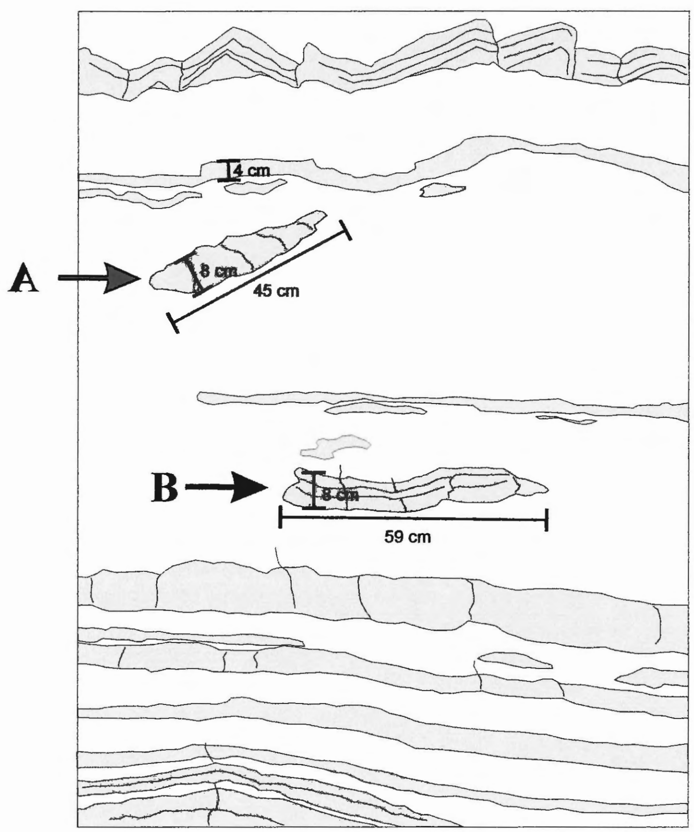


Figure 8: Largest tree stump cast found in the cliff face at BBN-A. The diameter measured is a minimum diameter for the cast. The cast is preserved as fine-grained sandstone/siltstone within shale strata. The characteristic curved base and inward flaring at an angle of 56 ° can be seen. The thin overlying sandstone/siltstone layer was likely deposited contemporaneously with the infilling of the cast. The scales of both the photograph and the interpretive diagram are equivalent.

Figure 9: Tree stump cast (**A**) and large tree root (**B**) observed in the cliff face at BBN-A. Both the root cast and the stump cast are formed of fine-grained sandstone/siltstone contained within dark shale strata. The tree root is likely a stigmarian root, possibly from a lycopsid tree. The shales beneath the cast are deformed more intensely than the adjacent shales. The scales of both the photograph and the interpretive diagram are equivalent.


4 cm
A
8 cm
45 cm
B
8 cm
59 cm

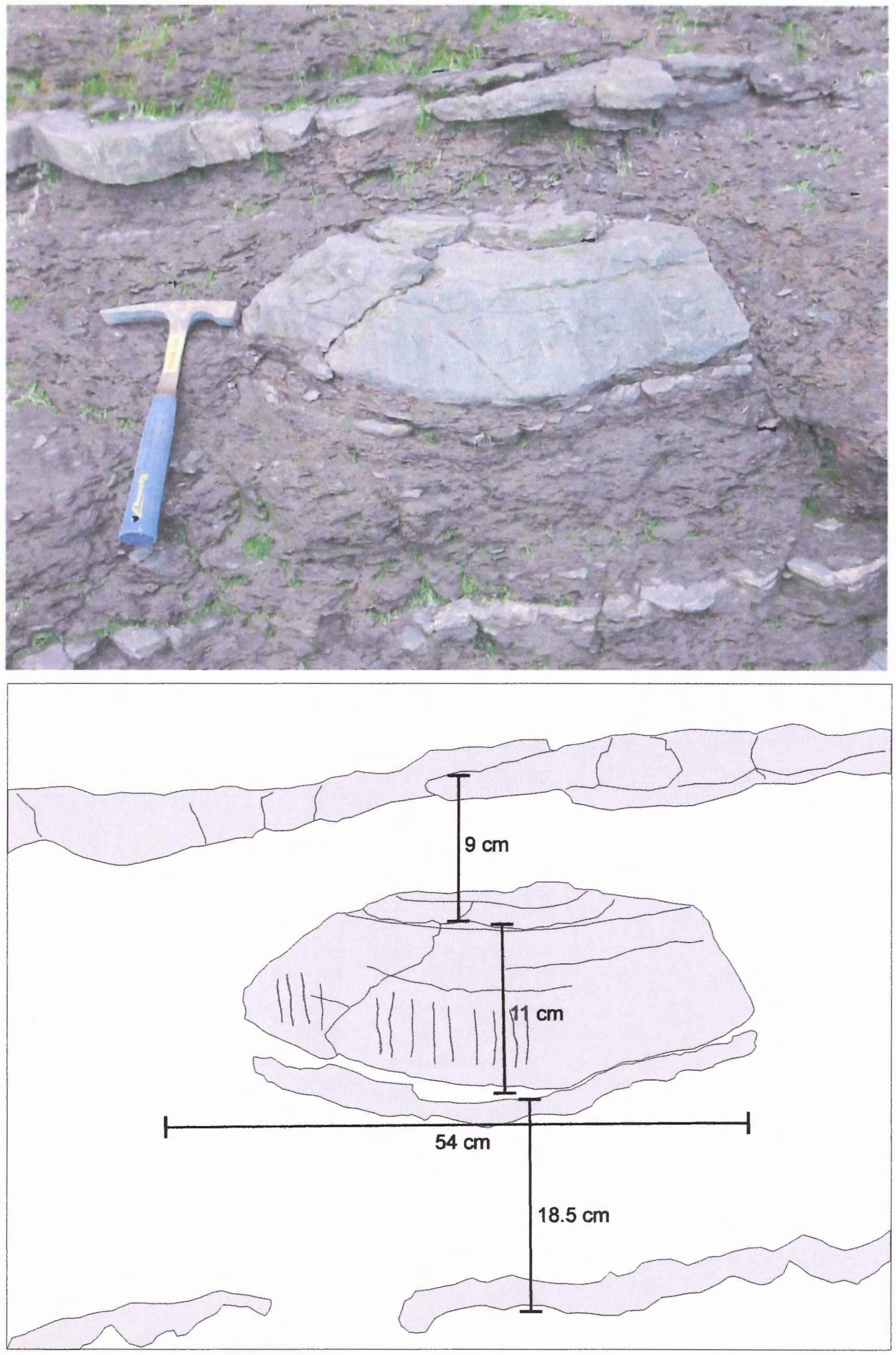


Figure 10: Tree stump cast of fine-grained sandstone/siltstone within dark shale. Bark imprints in the form of lineations are visible on the outer surface of the cast, and organic matter and roots are found within the surrounding sandstone/siltstone and shale. The cast demonstrates the characteristic curved bottom and rounded edges, and flares inwards at and angle of 58° from vertical. The scales of both the photograph and the interpretive diagram are equivalent.

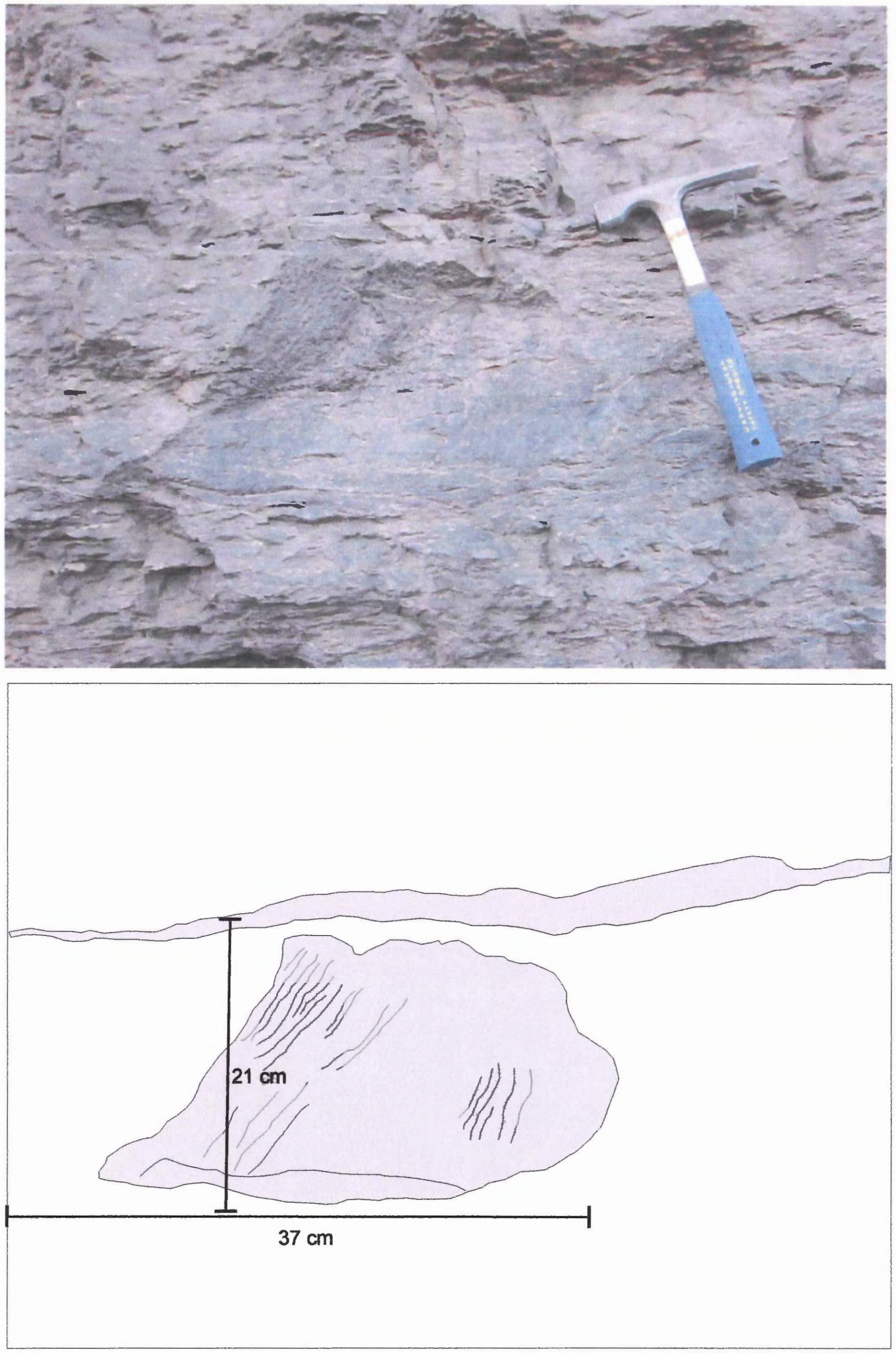


Figure 11: Bark imprint found within the cliff face at BBN-A. Black organic matter lines the surface of what would have been a tree stump cast, likely similar to those seen along the cliff face. The bark imprints are found in dark shale. The characteristic curved base and rounded, flaring-inwards sides are evident in both the photograph and interpretive diagram. The scale of both is equivalent. Organic matter can be found in the surrounding and underlying shales.

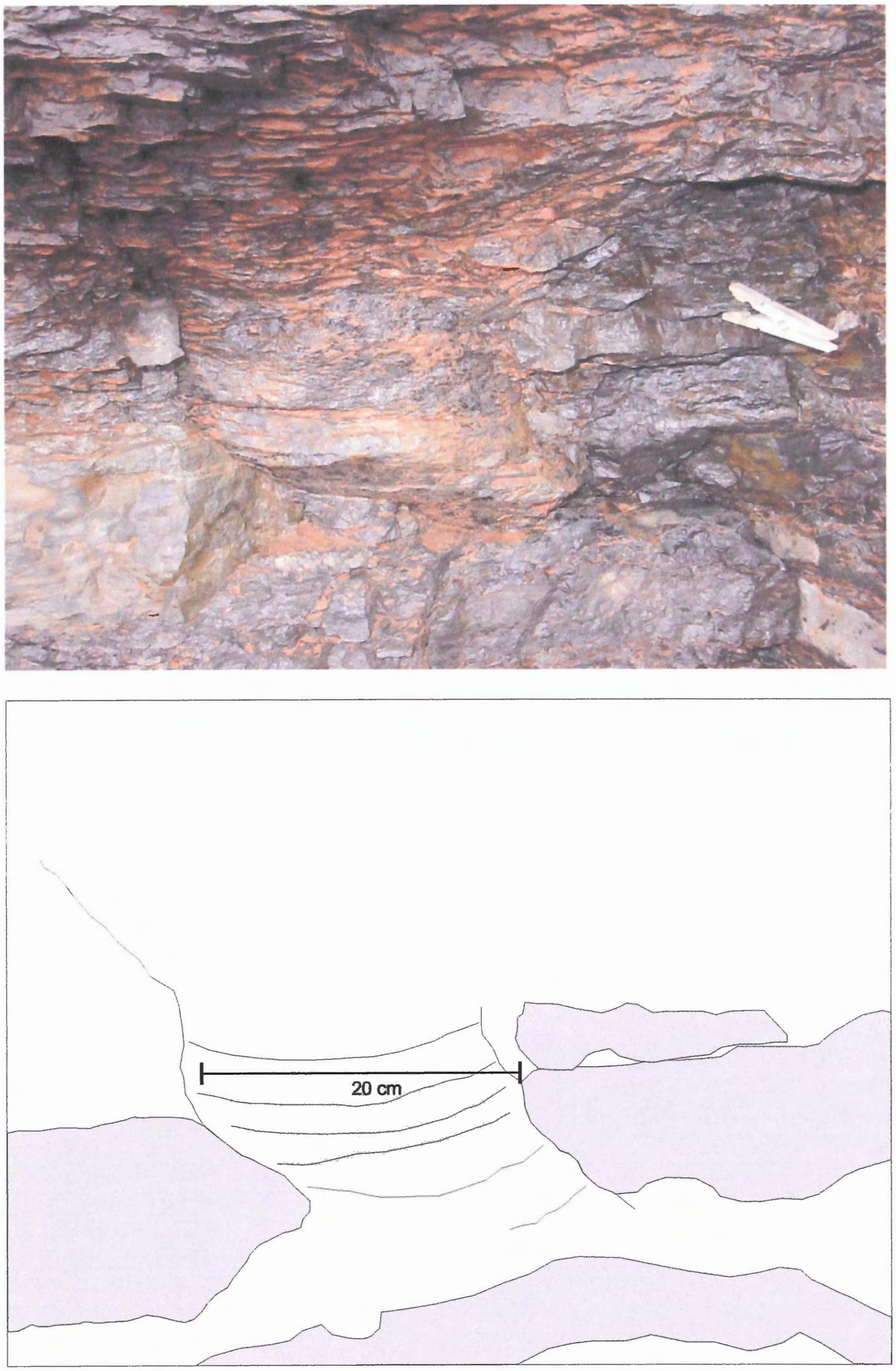


Figure 12: Tree trunk cast found in the cliff face at BBN-A. The tree trunk cast cuts across a fine-grained sandstone/siltstone bed, and is formed of dark shale. Black organic matter is seen on the outer surface of the cast, as well as horizontal shale laminae. The width of the tree cast is a minimum diameter, due to incomplete exposure of the cast in the cliff face. The scales of the both the photograph and the interpretive diagram are equivalent.

hollows. Carbonized organic remains, presumably from bark, can be seen on the outer surface of the trunk. The trunk is approximately 20 cm tall.

Figures 13 and 14 show decay hollows found at BBN-A, at the top of Unit 2. These features truncate a sandstone/siltstone bed, the gap left in the bed being filled with dark shale. The strata overlying the hollow have sunk down, with highly deformed shale in the hollow and slumping of the overlying sandstone/siltstone. The sandstone/siltstone beds adjacent to the decay hollow dip down towards the hollow, particularly apparent in Figure 14.

4.2 BBN-B: Decay Hollows

4.2.1 Stratigraphic context

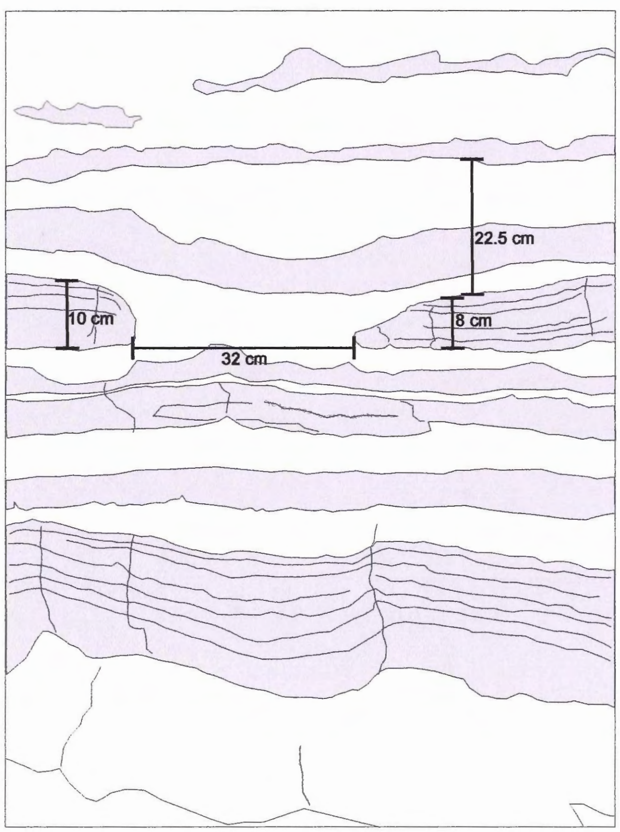
The cliff face in which the decay hollows at BBN-B are found is shown in the photo-mosaic of Figure 15. The tree structures occur in a poorly developed 1.2 m-thick green shale paleosol, Unit 3. This unit is shown as the shaded horizon in Figure 15, and is described more fully in Figure 16, where parts of two cycles are shown. The cliff face pictured in Figure 15 is approximately 60 meters horizontally. The units are shown on the cliff section in Figure 15-C.

The decay hollows in the paleosol unit occur as deformation in the semi-continuous sandstone layers and in the shale lamina. The paleosol layer contains abundant vegetative matter, such as root structures and plant remains, as well as horizons of reworked nodular material. Where the sandstone layers extend onto the wave-cut platform they contain abundant root traces.

4.2.2 Detailed tree occurrences

Detailed photographs of three of the hollows seen in the BBN-B cliff section can be seen in Figures 17 to 19. The decay hollows are characterised by deformation of the strata, most clearly seen in the sandstone horizons of the paleosol. The arrow in Figure 17 is pointing to the hollow, defined by down-dipping of the shale strata, a rubbly texture, and abundant plant fossils,

Figure 13: Decay hollow in BBN-A defined by a truncation of the fine-grained sandstone/siltstone beds, with shale filling in a 32cm gap. The strata within and above the gap are sunken down, as is evident in the photograph. The bedding in the truncated fine-grained sandstone/siltstone strata is down-turned. The scale of both the photograph and the interpretive diagram are equivalent.


22.5 cm
10 cm
8 cm
32 cm

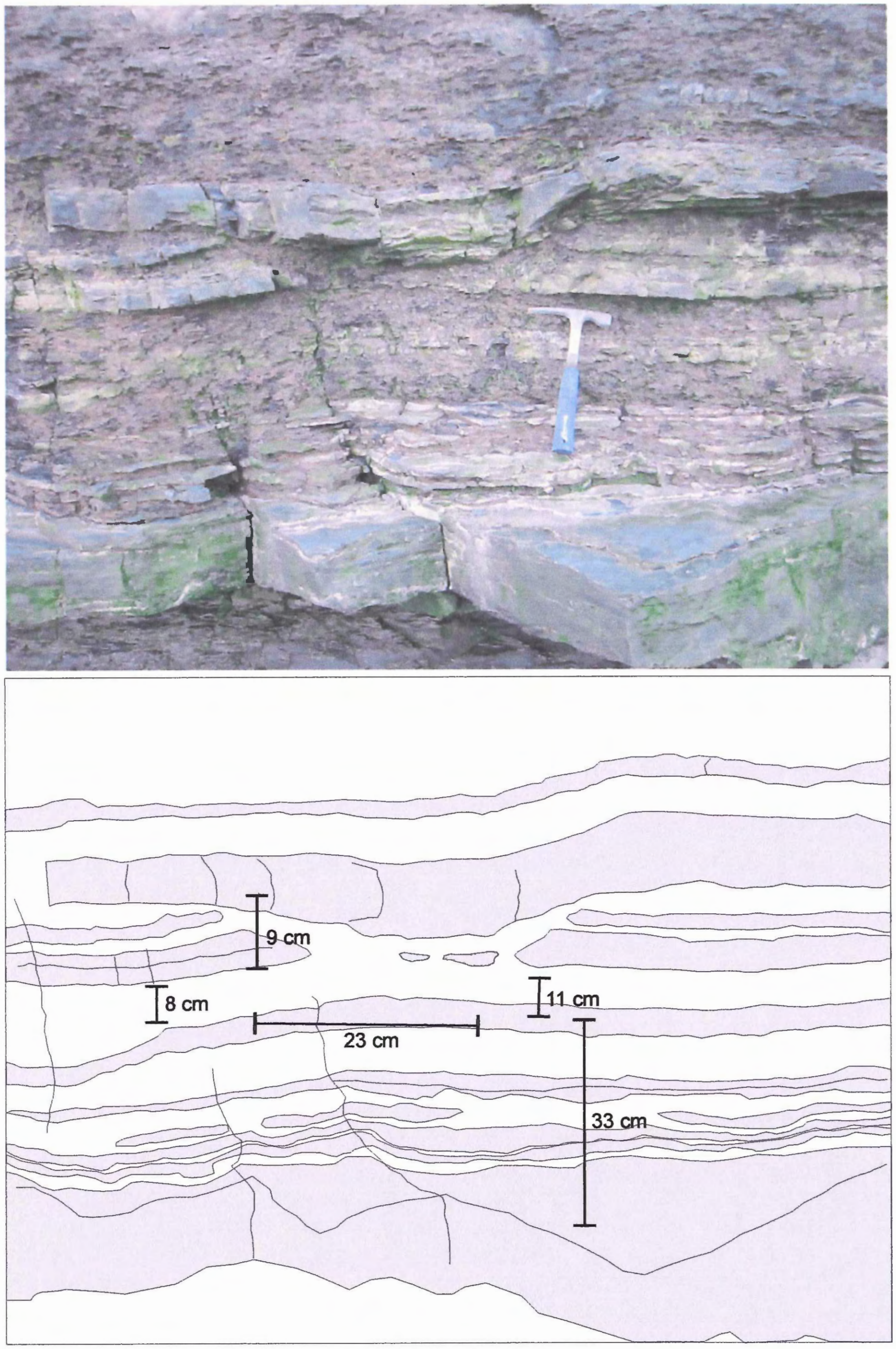
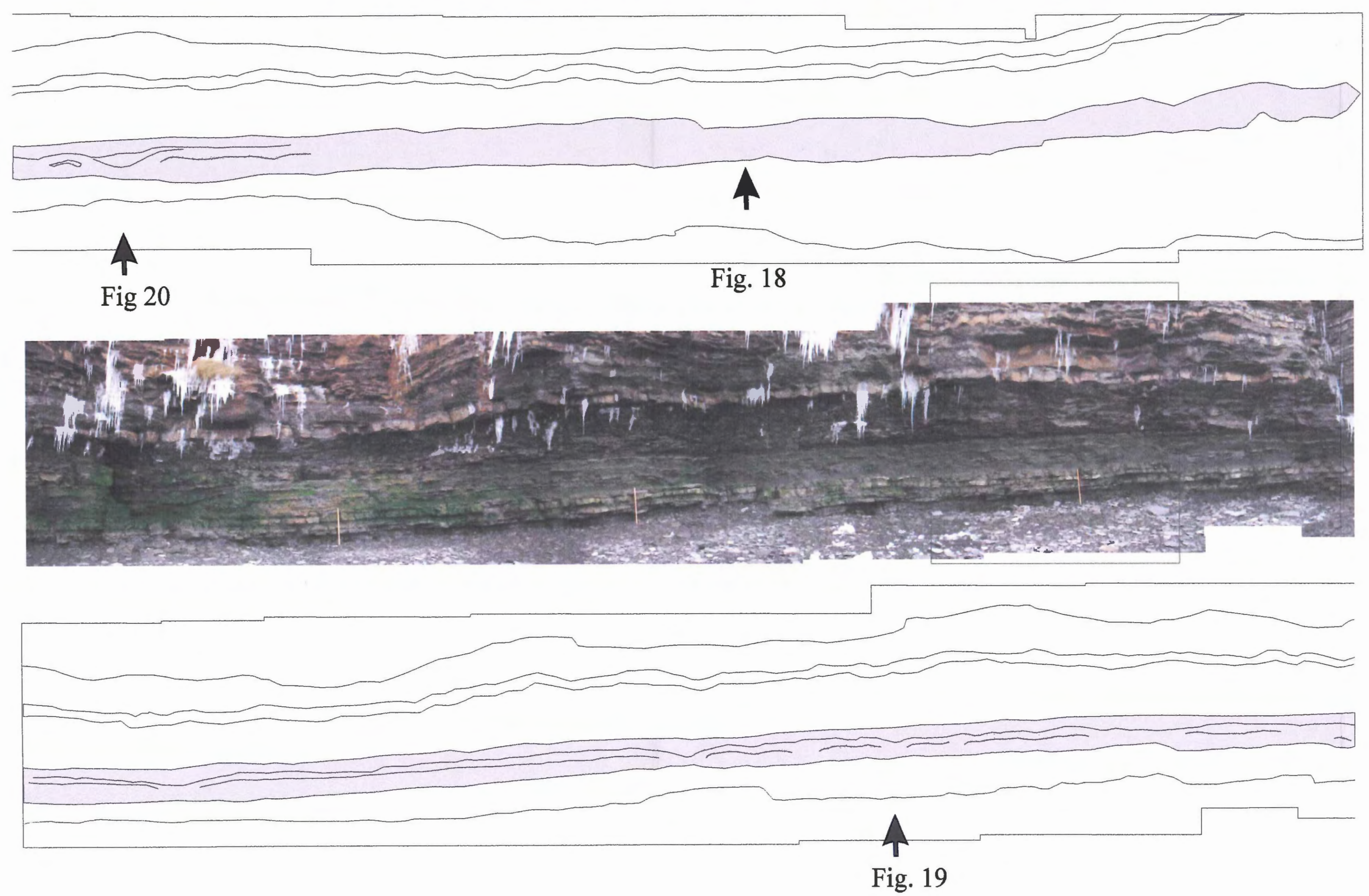


Figure 14: Decay hollow at BBN-A indicated by a break in the sandstone/siltstone bedding. The gap left by this break is filled in with shale and minor sandstone/siltstone. The overlying strata have sunken down into the scour produced by the decay of a tree, and the bedding in the sandstone/siltstone are down-turned. Multiple root traces are found on the upper surface of the sandstone/siltstone layer seen near the bottom of the frame. Large, curving roots, 2 cm in diameter are found in conjunction with numerous smaller fibrous roots below the hollow. Organic matter is present in the surrounding strata. The scale of both the photograph and interpretive diagram are equivalent.

Figure 15-A

Figure 15-B



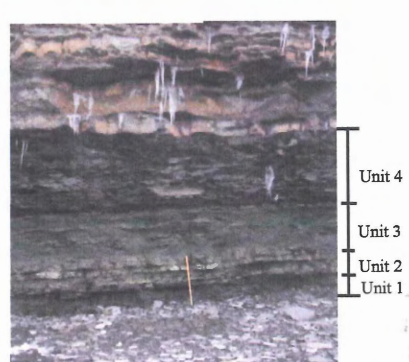
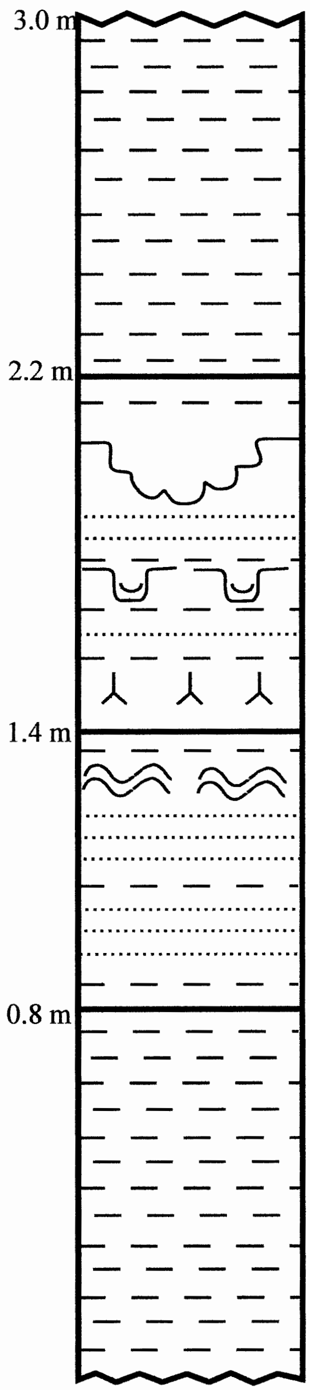


Figure 15-C

Figure 15: Cliff section of BBN-B. **A:** Photo mosaic of the cliff face in which the decay scours were found. The scale varies somewhat along the cliff section and can be determined from the meter-stick propped against the cliff at intervals. An approxiamted average scale is shown on the right. The green shale paleosol layer where the decay hollows are located is shown by the shaded horizon in **B**. This layer is characterized by intense deformation, nodular layers and semi-continuous sandstone layers within a matrix of green shale. All of the decay hollows are found along the same horizon in the paleosol, and are marked by arrows. A single cycle of the cyclical succession is show in **C,** with decay hollows in Unit 3.



Unit 4: Black shale unit, of well-laminated, organic-rich shales and minor sandstone..

Unit 3: Green shale unit, a paleosol, consisting of planar continuous beds and abundant hollows. The hollows can be up to 40 cm deep. The unit consists of approximately 60% shale and 40% sandstone. Abundant plant matter, such as root traces, bark imprints and other organic material are present within the paleosol.

Unit 2: Interbedded sandstone and shale, comprised of approximately 80% sandstone and 20% shale. Wave ripples are found at the bottom of the unit, while the upper section is structureless.

Unit 1: Black shale unit, well-laminated with high organic content.

Figure 16: Stratigraphic column of the lower portion of the cliff face at BBN-B. The column encompasses a single cycle within the stratigraphic succession of the formation. Unit 3, the paleosol unit, is the layer in which the decay scours are found. The strata represent a marine environment, with regressive and transgressive events. A photograph of the cliff exposure used to generate this column is seen in Figure 15.

Legend

...... Sandstone
— — Shale
Roots
Wave ripples
Tree casts
Decay hollows

including roots. The hollow in Figure 18 is characterised by slumping of sandstone beds, again with abundant plant material present. The hollow in Figure 19 occurs as slumping of both the shale and sandstone layers. All three of these hollows are of similar scale, and are generally larger than the tree casts and decay hollows of BBN-A. The hollow in Figure 17 is approximately 30 cm deep and 60 cm wide. The hollows of Figures 18 and 19 are shallower and wider, measuring 20 cm deep and 70 cm wide, and 25 cm deep and 150 cm wide, respectively. The Figure 17 hollow dips down at approximately 40^{O}, the Figure 18 hollow dips down at approximately 20^{O}, and the Figure 19 hollow dips down at approximately 30^{O}. The hollows are seen only in cross-section, their three-dimensional shape remains hidden in the cliff. It is inferred that these structures are basin-shaped, however is if feasible that they are linear. Some of the hollows are lined with thin, discontinuous calcite deposits.

4.3 BBS: Tree moulds

4.3.1 Stratigraphic context

The tree moulds in BBS are found in a single sandstone/siltstone bed. This portion of the outcrop is located adjacent to a large fault, the position of which can be seen in Figure 2. This sandstone bed is part facies 2, the shallow-water beach-face portion of the larger-scale cyclical strata at Blue Beach. The sandstone is over- and underlain by dark shale.

4.3.2 Detailed occurrences

The exposed portion of an 11-meter section of the sandstone bed was mapped to determine the density, spacing and diameters of the tree trunk moulds. A total of 163 tree moulds were identified and mapped. An example of the tree trunk moulds is shown in the photograph in Figure 20, which illustrates both the form and the density of two of the features. The spacing and the density are further demonstrated in Figure 21, an overhead view of the mapped section of the

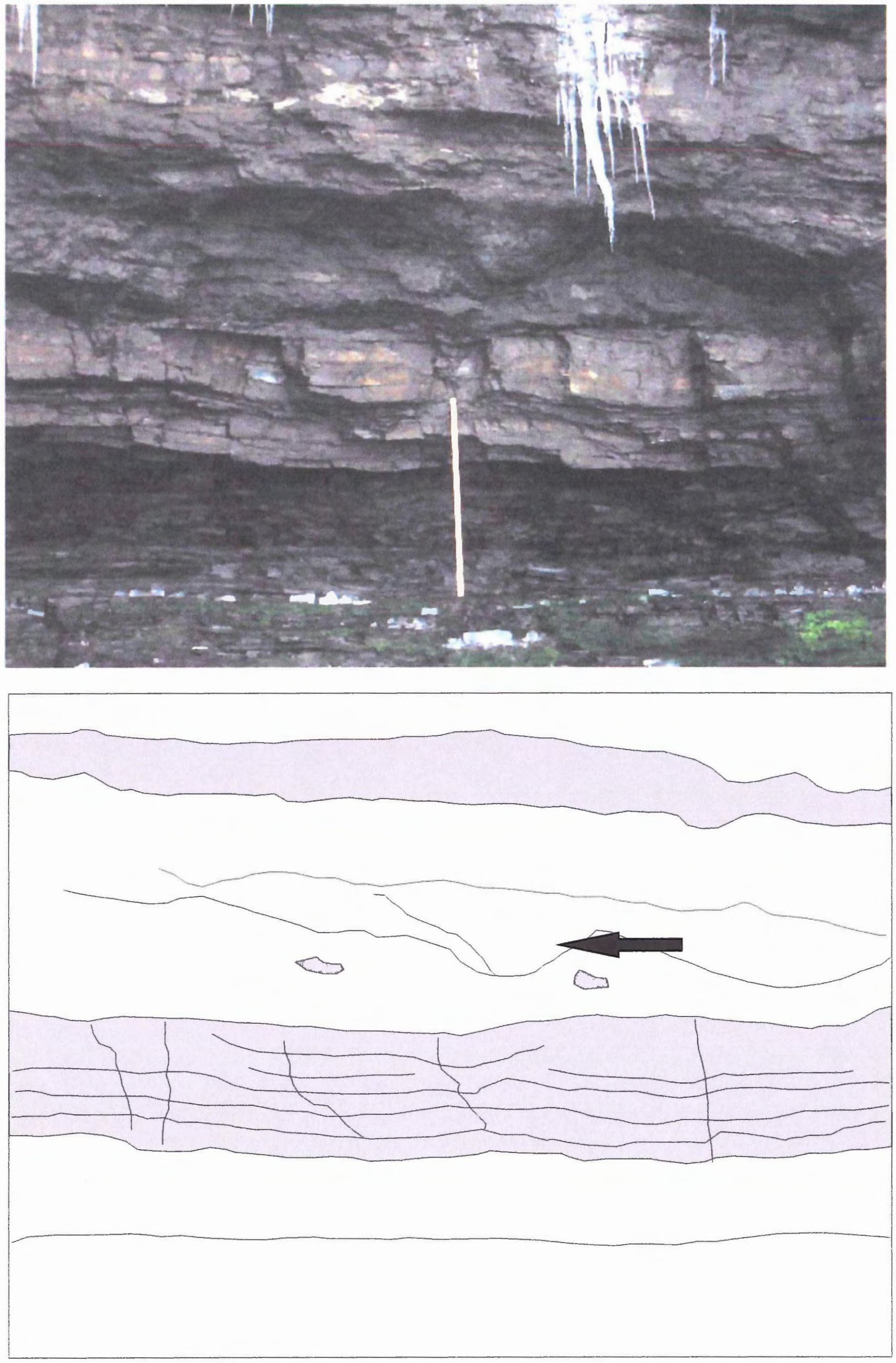
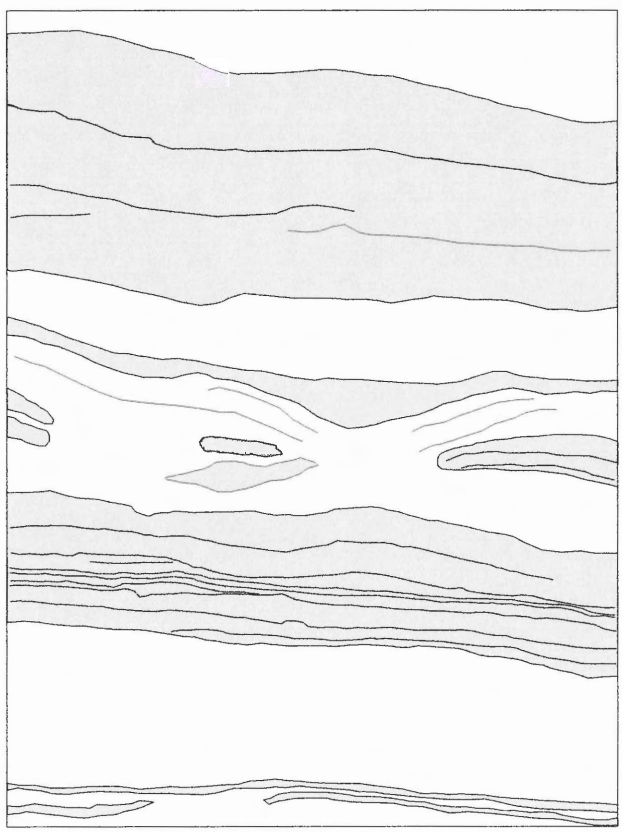


Figure 17: Decay hollow in the cliff face at BBN-B, shown by the arrow in the interpretive diagram. The scour is found within a green shale paleosol. This paleosol is highly deformed, and contains layers of reworked nodular material. The scales of both the photograph and the interpretive diagram are equivalent, with a meter-stick for scale. The white patches on the upper cliff are icicles

Figure 18: Decay hollow seen in the paleosol unit at BBN-B. This paleosol layer is highly deformed, and contains reworked nodular material, shales and sandstones. A meter stick is used for scale, and the scales of both the photograph and the interpretive diagram are equivalent. The white patches on the upper cliff are icicles.



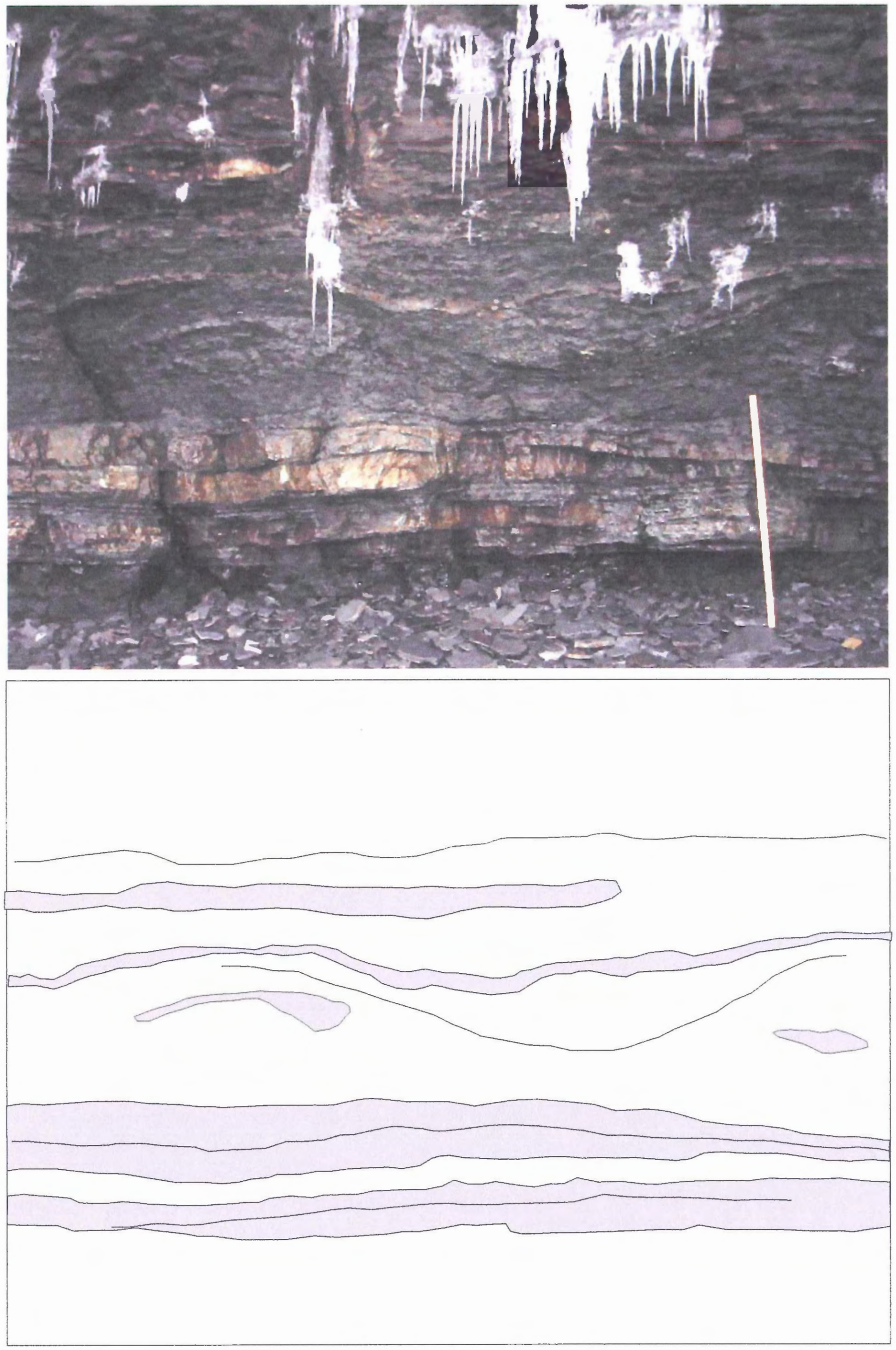


Figure 19: Large decay hollow found in the cliff face at BBN-B. The scour is present in a green paleosol layer with sandstone layers, reworked nodular layers, and abundant organic material. The bedding within the paleosol is highly deformed. The scales of both the photograph and interpretive diagram are equivalent, with a meter stick against the cliff face for scale. The white patches on the cliff are icicles.

bedding plane. This map shows the location and approximate relative diameters of the tree moulds.

The diameters of the 163 tree stump moulds were compiled and are shown graphically in Figure 22. The most frequent diameter range was between 5 and 10 cm. The majority of the moulds had a rounded to subrounded shape; however some of the structures had a more deformed elliptical or polygonal shape. The diameter measurements are accurate within approximately 2 cm, due to the gradual slopes of the sides of the moulds. The hollows on the surface of the bedding place were approximately 2-5 cm deep. Some of the hollows contained plant fossils in the bottom of the pit, and some were lined with bark traces. It is possible that some of the hollows were not formed by vegetation, but it was not possible to distinguish these hollows from the tree hollows.

Figure 20: Photograph of tree trunk moulds in the sandstone bed at BBS. These two specimens are fairly large relative to many of the other moulds. The shale debris that covers large portions of this bedding plane can be seen in the upper left-hand corner of the photograph.

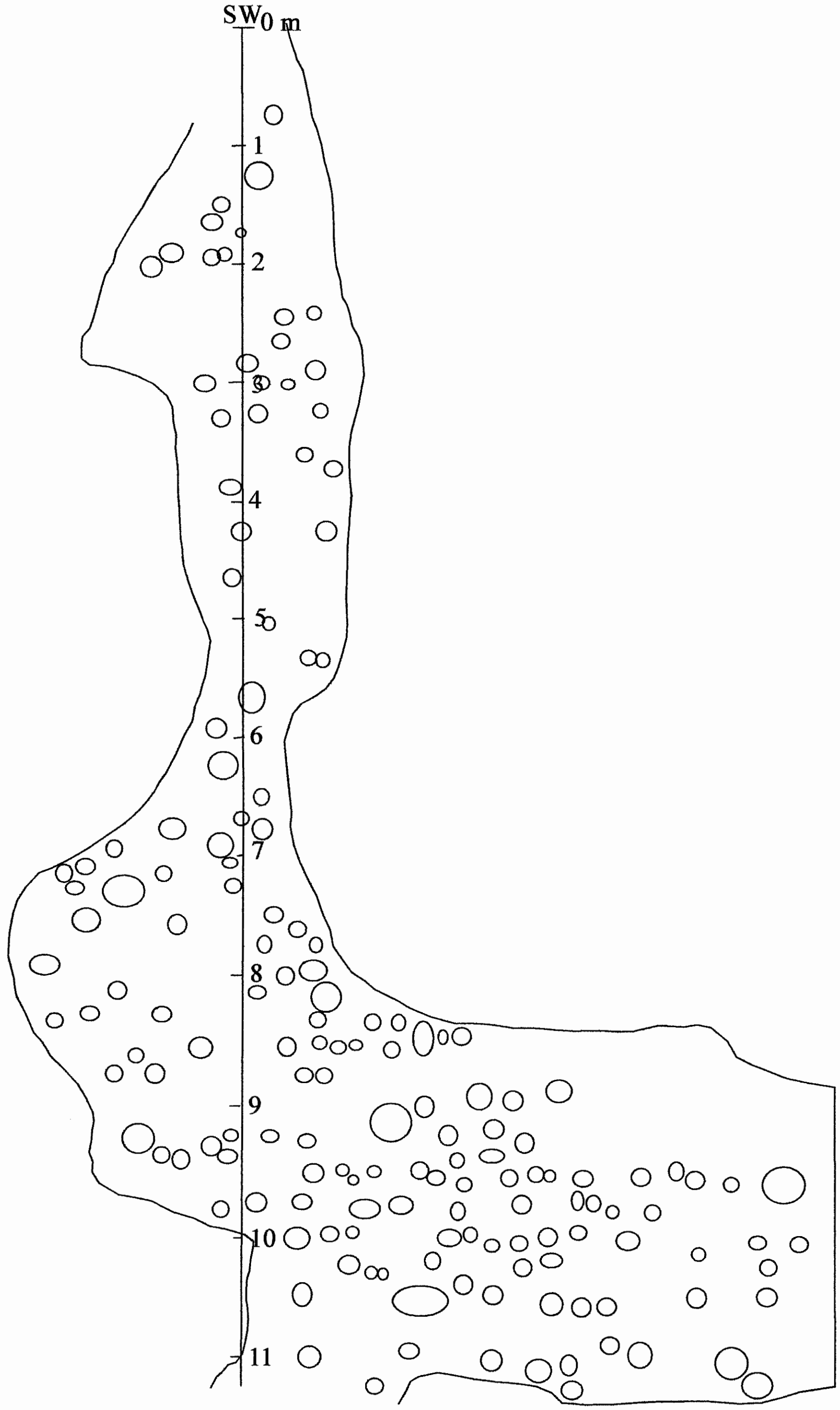


Figure 21: Aerial view of a sandstone bedding plane at BBS, in which are found many (n=162) tree molds. The map encompasses only 11 meters of the exposed portion of the bedding plane, the rest of the layer being covered by loose sediment or running under the cliff. The central line of the map trends SW-NE. The ellipses show the approximate form and size of the moulds.

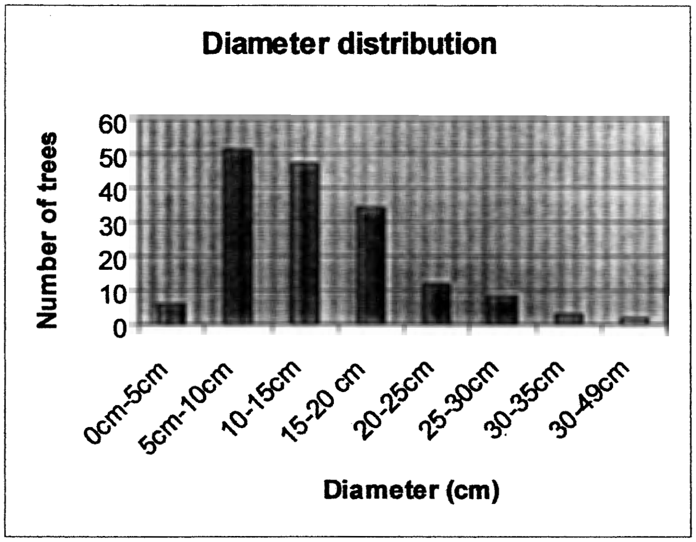


Figure 22: Summary of the 163 tree mould diameters, as measured from the sandstone/siltstone bedding plane at BBS. The diameters are classified into 5-centimeter intervals, with the height of the bars representing the number of measured tree moulds with a diameter falling within the range.

Chapter 5 Discussion

5.0 Introduction

It has long been known that the Horton Bluff Formation contains abundant fossilized plant material (Bell, 1960). This vegetation has not been studied quantitatively, however. The data put forth in this study help to quantify the density of vegetative cover, the frequency of forested levels and the size of the preserved vegetative structures of the Horton Bluff Formation.

Four forested levels have been identified in this thesis; two at BBN-A, and one each at BBN-B and BBS. These horizons are not the only locations where fossilized trees are found at Horton Bluff, but are the most spectacular examples. There are occurrences of isolated stump casts, as well as plant fossils, at numerous stratigraphic levels throughout the strata of the Horton Bluff Formation (Martel and Gibling, 1995). The occurrences described here demonstrate particularly good preservation and a higher density of vegetative features than at other levels.

The designation of a horizon as "forested" is somewhat ambiguous. In this study, a forested horizon is one that demonstrates a high enough density of trees to allow the possibility of interaction between the trees. This implies the need for more than simply isolated tree occurrences.

5.1 Justification of Stump Cast, Decay Hollow and Tree Mould Identification

Many similarities are found among the vegetative features in the rocks exposed at Horton Bluff. Each of these characteristics may not individually indicate that the structures were formed by trees, however the combination of these features and the repetition of these features along the cliff allow the inference of a vegetative origin. For example, all of the tree casts identified at BBN-A occur along a single horizon, as do the decay hollows at BBN-A and BBN-B. These structures are also found in the presence of evident plant remains, including bark traces and roots. All the features have a similar form, involving some combination of the following features: a curved base, flared sides and bark imprints on the outer edges.

The most likely explanation for these features is that they are the casts of tree stumps that were growing in a poorly-developed soil. The flared sides correspond to the flaring inwards form of the base of trees, a morphology that allows maximum stability. The roots of trees generally branch out, anchoring the plant in the substrate. The roots observed attached and near the tree casts branch out horizontally to slightly inclined from underneath the structures. The bark imprints further support this hypothesis, being likely formed from the decay and carbonization of the bark around the buried tree. The curved bases are another common feature of the tree casts. It is unclear whether the trees grew preferentially in pre-existing hollows, or if the compaction of the underlying sediment occurred due to the weight of the tree, either during or after the tree's life. The compaction could also have occurred during or after the deposition of the infilling sediments.

The decay hollows at BBN-A also show remarkable similarities across the cliff section. All decay hollow occurrences are found in a single sandstone layer at the top of Unit 2, slightly below the stump cast level. The gaps in this sandstone bed, presumably left by the decay of standing trees rooted below the sandstone, are all of a similar scale. The strata dip down towards the hollow, and the overlying strata have slumped down into the decay hollow. Although no trees are preserved in these hollows, the presence of a preserved tree trunk in this horizon (Fig. 13) provides further evidence for the relationship between standing trees and the truncations of the sandstone bed.

The preservation of tree structures at BBN-B is more enigmatic than at BBN-A. The green paleosol (Unit 3) is better developed at BBN-B, and so the strata are more disrupted. The abundant plant remains, root structures and decay scours allow the inference of forestation in this level.

The tree stump moulds at BBS are identified on the basis of bark imprints lining the insides of some of the hollows, by plant remains in the base of the mould, and by roots in the strata underlying the sandstone bed.

5.2 Sedimentary Details

The sediment source for the infilling of the tree stump casts was most likely a flood deposit of fine-grained sandstone/siltstone. A thin semi-continuous layer of this lithology can be seen above the tree casts in most cases. In some cases the sandstone layer is connected to the infilling sandstone. It is probable that the casts are pits left by the decay of trees that were filled during the deposition of this layer.

Scours associated with standing vegetation, while common in other sedimentary strata such as the Joggins Formation, are rare in the Horton Bluff Formation. Rygel and Gibling (2003) described centroclinal cross sets formed in scours around the bases of standing trees in the Joggins Formation. Possible explanations for the contrast in scour activity between the Horton Bluff Formation and the Joggins Formation are centered on energetic differences. Scouring occurs during rapid, high-energy flooding

(Underwood and Lambert, 1974). The lack of scours in the Horton Bluff Formation implies that flood energy was insufficient to allow the entrainment and scouring of the sediment adjacent to trees. The in-filling deposits are a very fine-grained sandstone/siltstone at Horton Bluff, and are sandstone at Joggins, implying lower-energy conditions at Horton Bluff. The sands of Joggins enter the forested levels via small distributary channels, none of which are found at Horton Bluff. The Horton Bluff flood deposits were likely quite distant from high-energy sources. The Horton Bluff strata might also have been more consolidated at the time of flooding, preventing scouring. These strata may have been stabilized by the roots of the standing vegetation. Densely spaced vegetation can slow down water flow, and trap sediment. This may have occurred at Horton Bluff, with the vegetation slowing the flow of flood waters enough to prevent scouring.

The stump casts and decay hollows at BBN-A are limited to Units 2 and 3, and to Unit 3 at BBN-B. These strata correspond to facies 2 and 3 in Martel and Gibling's classification (1995). Facies 2 is designated as nearshore or shoreline sandstones and siltstones, and facies 3 corresponds to hydromorphic paleosols. These strata constitute the regressive parts the transgressive-regressive cycles, or a regression of the shoreline with a steady base-level. This implies that the vegetation grew on sediment exposed during regression, where the exposure and environmental conditions would allow soils to develop. The vegetation would have been drowned out by local flood events, with the influx of sediment filling pits left by the decay of the standing trees. The coarser grain-size of the infilling sediment in comparison with the underlying strata supports this hypothesis of local flooding.

5.3 Vegetative Details

A study of details more specific to the standing trees and the vegetation can be undertaken using these data for the Horton Bluff Formation.

It is possible that different plant types were involved in the formation of the features, although no firm identifications could be made for the standing trees. For example, the cast shown in Figure 7 has a rougher surface texture than the cast in Figure 8. The rougher cast could be the preservation of a *Protostigmaria* rhizomorph, whereas the smoother cast could result from preservation of the tree trunk itself (J. Calder, pers. comm., 2002) Additionally, different plant types could be responsible for the moulds preserved at BBS and the casts and hollows of BBN: the tree moulds are on average smaller than the tree casts. A smaller plant type at BBS than BBN could be responsible for this, or the plants could have been less mature at the time of burial at BBS.

The width of the decay hollows and stump casts at BBN-A compare well. The stump casts average approximately 55 cm in diameter, and the decay hollows are more variable, averaging approximately 40 cm in diameter. These diameters are measured from incompletely exposed specimens, and so are minimum values only. These values allow us to infer that similar plants were responsible for all the studied features at BBN-A. The decay hollows at BBN-B show larger widths than those of BBN-A, on the order of 2-3 times wider, ranging from 60 to 150 cm wide. No tree stump casts are present in this level, and thus explanations for this large size are speculative. Individual trees might have been unusually large, or groups of plants growing in close proximity could have created larger scours. The disturbance associated with the soil formation could have also disrupted the features, resulting in wide scours. Vascular plants of this age had not yet evolved massive root structures required for the stability of large, thick-trunked trees (Willis and McElwain, 2002), as it is unlikely that very large trees are responsible for the large scours.

The paleo-botantical fossil assemblages of the Horton Bluff Formation indicate that these forests were formed in a "tropical everwet" environment (Willis and McElwain, 2002), and we can compare the tree density of modern tropical forests with these ancient forests. Perez *et al.* (2001) studied tree densities in tropical rainforests, and found an average density of 564 trees per hectare. This roughly corresponds to 1 tree every 20 meters along a linear traverse through the forest. The minimum densities of the paleo-forests at Horton Bluff are comparable or even slightly higher than these modern values, with a tree every meter to tens of meters at BBN. The preservation of tree moulds at BBS allows for a more accurate estimate of the degree of forestation. The mapped area was approximately 29m^2, and 163 tree trunks were observed in this area. These values give us an approximate high density of 5.6 trees/m^2. These density values are approximations only, as the actual values could be obscured by incomplete preservation of the individual trees or plants, or misidentification of some of the tree casts and moulds.

Fossilized forests are much better known for the Pennsylvanian than these older forests (Calder *et al.*, 1996; Rygel and Gibling, 2003). In regions where older forests have been identified, the preservation is poor (Elick *et al.*, 1998). The forests identified at Horton Bluff thus represent some of the better known paleo-forests dating from before the mid-Pennsylvanian.

5.4 Environmental Details

Tibert and Scott (1999) examined the microfossil assemblages of the Horton Bluff Formation from samples taken at various locations within the formation, and determined a marine paleo-environment for the strata. They found marine ostracode assemblages in nearshore facies of sandstone and siltstone, and non-marine assemblages for muddy strata containing root traces and common organic detritus. It is later suggested that these non-marine assemblages were, in fact, moderately tolerant to salt water (Tibert and Scott, 1999). These facies presumably correspond to facies 2 and 3 of the Martel and Gibling (1995) classification. This information leads to the hypothesis that the forested horizons could correspond to marshy, saline conditions. Should this turn out to be the case, these deposits could be one of the earliest well-preserved marsh vegetation zones.

Marine influence could help to explain the decay of the standing trees, and the preservation of only the base of the plants. Marine waters are alkaline and as such are prime environments for bacterial growth. An abundance of bacteria could have speeded the decay of the vegetation, allowing preservation only of the bottom-most portions of the plant. Rapid decay could also explain the poor preservation of bark and other identifying material in the tree fossils.

Chapter 6 Conclusions

6.0 Conclusions

Abundant fossilised plant material is found in the Horton Bluff Formation, with the preservation of fossilized horizons at various locations within the formation. The trees are well preserved, in the form of tree stump and tree trunk casts, stump mould, and decay hollows. These fossilized forests most likely grew during regressive periods, with exposure of the sediments to the environment, and were preserved as during minor flood events which would have brought in an influx of coarser sediment. The connection of these forests to saline marsh conditions is an interesting one, and one that deserves further investigation.

The forests in the Horton Bluff Formation represent one of the oldest well-preserved forests in Nova Scotia, and possibly Atlantic Canada.

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