The Effects of Excessive Drilling on Wood Decay in Trees

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Introduction

The effects of excessive drilling of the trunk with an increment borer and drilling resistance measurement device were determined for various types of trees. The trees investigated were rotten inside (soft rot, white rot, rot cavity). This was reflected by external defect symptoms, such as bulge formation or open cavities with wound wood building.
For comparison, a healthy, i.e. rot-free tree that had been subjected to excessive drilling in the past was studied.
All trees selected were “test trees” used in previous field studies or for repeated demonstration of drilling tools. 8 to 10 years ago, these trees had been subjected to repeated drilling using an increment borer and IML-RESI (drilling resistance measurement device) and since then, drillings were made several times per year.

The following questions were to be answered:

1) How does a tree with an inner rot react to the repeated use of invasive diagnosis techniques?
2) Does decay penetrate through the drill holes from the inside (rot cavity, inner rot) to outside – or does decay enter the trunk from outside – or both?
3) How does a healthy tree react to the repeated or excessive use of invasive diagnosis techniques?
4) Are drilling techniques “hazardous” to the tree?
5) Does the hazard potential of different drilling techniques differ?
6) Does the tree controller have to drill at all?

Borer sizes: The diameter of the RESI drilling needle was 3.0 mm. The outer diameter of the increment borer that produced a 5 mm increment core amounted to 11.3 mm.

Fundamentals

Drilling Techniques [1]

Depending on the individual circumstances, various drilling techniques can be applied to study fungus-infested trees in detail. Use of the increment borer is the method providing the highest information content. Visual inspection of the increment core supplies comprehensive information on tree growth rates and compartmentalization of decay in a tree. In addition, wood discolorations without a wood decay, as occurring after trenching damage, for instance, can be detected. Qualitative (shaking test) and quantitative fracture tests (fractometer measurements) of the increment core provide findings regarding the fracture behavior (brittle fracture, ductile fracture) and individual wood strengths. Moreover, the increment core may even be assessed by smelling (bacterial wet wood!) or subjected to a detailed microscopic and biochemical analysis in the wood laboratory.
Drilling resistance measurement probably represents the most rapid of all drilling techniques. During the relatively rapid measurement process, a reading plot is recorded. This drilling technique is particularly suited for detecting dangerous wood embrittlements caused by brown rot or advanced soft rot. It is also possible to identify finer quality differences in healthy wood, e.g. earlywood and latewood of coniferous trees. Even the wind training the tree is subjected to is found in the drilling resistance.

Use of simple drill bits is another drilling technique, by means of which even hardest tropical woods can be studied, into which neither increment borer nor drilling needles can enter. Using a drill bit, shavings are removed at various drilling depths. These shavings are long in case of fracture tough wood and short in case of hard and brittle wood. Also wood discolorations can be detected visually long before the wood is decomposed. Use a borer which is made to drill into steel but not into wood. So one can remove shavings easier.
A general drawback of drilling techniques is the generation of a more or less large drill hole (cf. Fig. 1). The tree is locally wounded and has to repair this wound again.

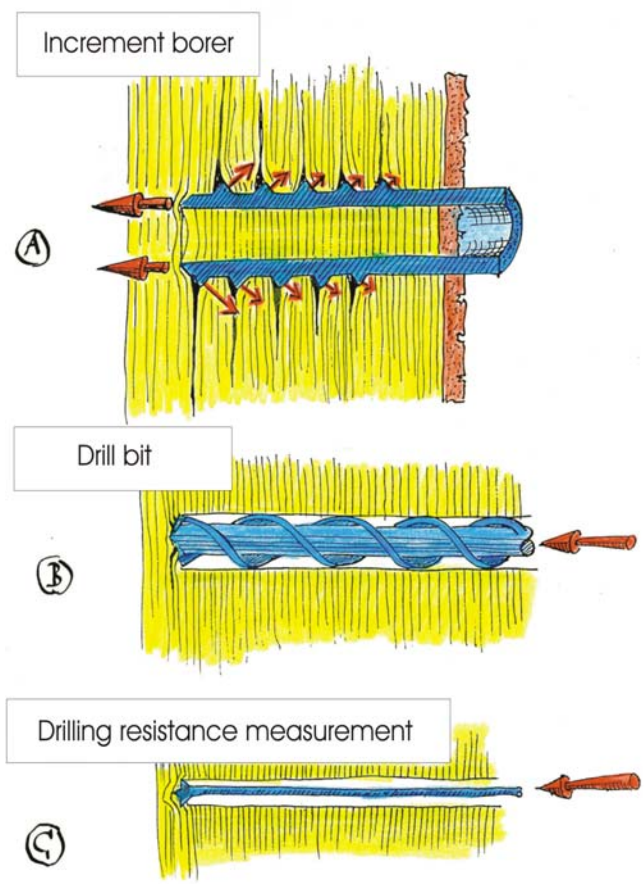

Fig. 1: Drilling techniques generate drill holes. **A:** When using a self-cutting increment borer, lateral cracks run into the wood from the thread. **B:** When using the drill bit, pressure is applied from outside. This also applies to drilling resistance measurement **C** which does not cause lateral crack formation. Drawing taken from [1].

Wood Decay and Its Compartmentalization [1]

In 1977 [2] and 1979 [3], *Alex Shigo et al.* described the mechanisms of decay compartmentalization in a living tree using a model, i.e. his compartmentalization theory which he called CODIT. CODIT stands for ***C****ompartmentalization* ***O****f* ***D****ecay* ***I****n* ***T****rees* and applies when a fungus enters the sapwood from outside after the cambium has been injured. The penetrating decay fungus is prevented from propagating in the sapwood by a total of four walls (walls I – IV).

Wall I
Decay is prevented from propagating in axial direction, i.e. “above” and “below” the location of decay by closing the vascular elements and incorporating fungicidal substances. Deciduous trees often form tyloses (cf. Fig. 2), some also include gummy substances as films or plugs in their vessels. Coniferous trees may seal off their tracheids by bordered pit closure. The existing upper and lower cell walls (transverse walls) also represent an axial barrier. The quicker a tree builds up wall I, the shorter is the column-like decay zone in the wood and, thus, the longitudinal extension of the rot.

Wall II
Decay is prevented from propagating in radial direction by the latewood of the previous years. At the annual ring boundaries, the thin-walled earlywood cells abruptly meet with the thick-walled latewood cells of the previous year. Penetration of fungal hyphae through the latter is usually more difficult (Fig. 2). Moreover, living parenchyma cells often exist in the form of tangential bands in latewood or at the annual ring boundaries. They may additionally inhibit the growth of hyphae by the production of fungicidal substances. Generally, however, the latter only happens in sapwood, as all wood cells die off during the process of heart wood formation.

Wall III
Decay is prevented from propagating in circumferential, e.g. in tangential direction, i.e. “right” and “left” of the decay by the wood rays. Living wood ray cells form repellents in the sapwood and their spindle-like shape also represents a mechanical barrier. As the wood rays have variable heights and are tangentially offset, wall III is no consistent tangential barrier, but consists of non-continuous separate obstacles, which the hyphae have to penetrate or grow around. As a result of this wall, decay propagation in the direction of the annual rings is delayed at least (cf. Fig. 2).

Wall IV
It is referred to as **“barrier zone”** and consists of a special parenchyma-rich tissue that is formed by the cambium after the injury. In its cells, fungicidal substances are enriched. This zone is much larger than the wound itself. It does not rarely cover the entire trunk circumference (see also [5]). This often very effective barrier zone separates the decay fungus and the previously formed wood, in which it may already live, from the newly formed wood. Frequently, the barrier zone represents a clear boundary between healthy and completely rotten wood.

The compartmentalization walls I – III generally exist in sapwood (except for tyloses) and are modified in a purely chemical way during defense. Therefore, they may also be summarized as **“reaction zone”**.
In contrast to this, the **barrier zone**, wall IV, represents a chemical and anatomical defense reaction. In it, many metabolically active cells (parenchyma cells) are formed that produce and also store fungicidal substances.

Fungi that enter a trunk not as a result of a cambium damage, e.g. via wounded roots or broken-off branches or pruning wounds, are not supposed to cause any formation of a barrier zone (wall IV) in the trunk. This is confirmed by the map-like contour (cf. Fig. 2) often found for root rots. A reaction zone is formed in the sapwood only. The heartwood cannot react actively to the fungal attack, as it consists of dead wood. Still, it is relatively resistant to many types of fungi due to the so-called “heartwood formation" (incorporation of polyphenols and resins, tylosis, lignin and suberin inclusions in cell walls, etc.).

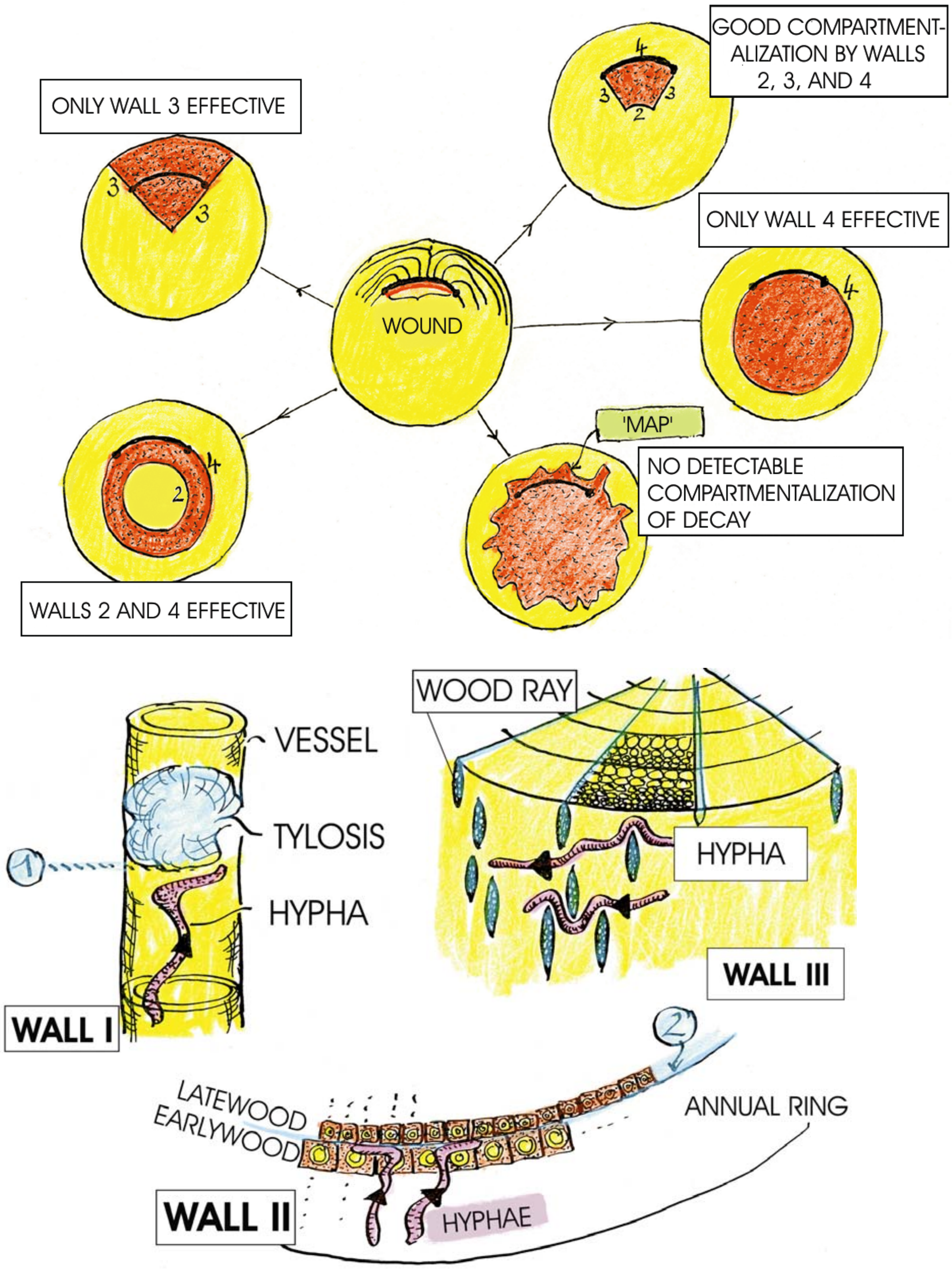

Fig. 2: Schematic representation of stem cross sections with variable compartmentalization of the inner decay and CODIT compartmentalization walls I, II, III. Drawings taken from [1].

Material and Method

The test trees:

1) Poplar (*Populus nigra* L.) with extended inner decay and decay cavity, defect symptom: Buttress swelling (with “elephant” foot, i.e. recesses in between root buttresses are no longer visible), many RESI drill holes, some increment borer holes. Agent of heart rot: Honey fungus (*Armillaria mellea*).
2) Sycamore maple (*Acer pseudoplatanus* L.) with *Ustulina deusta* (“Carbon cushion”) inside, extremely extended inner rot, partly overgrown wound with barrier zone at the stem base, many RESI and many increment borer holes.
3) Oak (*Quercus robur* L.) with smaller inner rot and crack. Defect symptom: Swelling of the trunk in front of the decay, rib formation in front of the crack, many RESI and increment borer holes.
4) Sycamore maple (*Acer pseudoplatanus* L.). Leaning sycamore maple with many increment and some RESI drill holes on the tension and compression sides of the bending (through-going drillings of the stem) at the stem base and the root buttress. No inner rot prior to drilling.

The test trees were felled for subsequent sampling and investigation of tree disks from the relevant trunk areas.

The decay compartmentalization zones found were verified by light microscopy. The material and method applied for the microscopic investigation were described in detail in [5].

Results and Discussion

First, the total effect of excessive drilling, i.e. several drillings annually for more than 10 years using the drilling resistance measurement device (less often, increment borer), shall be presented by studying a fresh saw-cut made after felling the black poplar. Figure 3 shows the black poplar with buttress swelling that indicates extended inner rot, which was confirmed by repeated drilling. The area of excessive drilling is marked in Fig. 3.

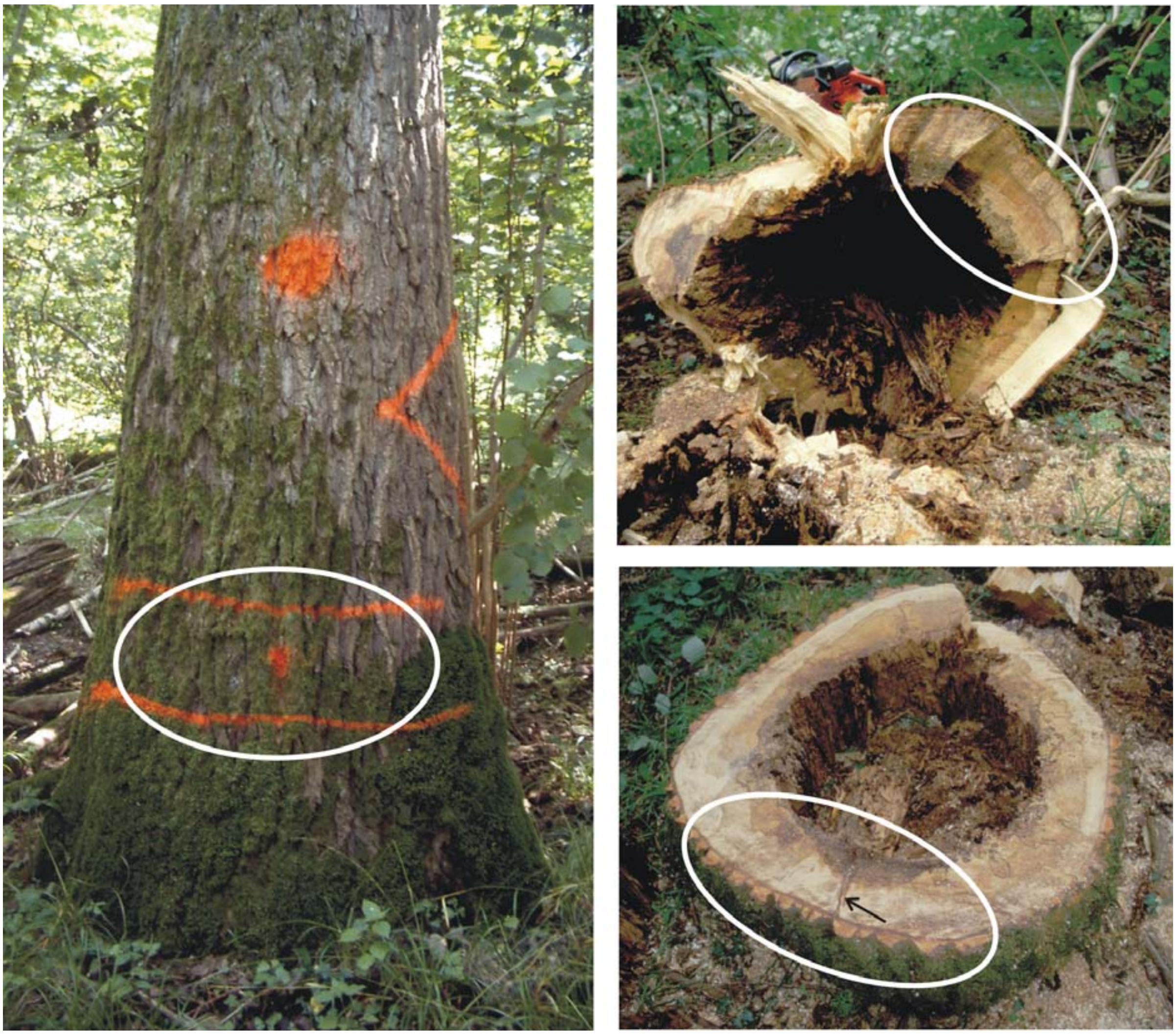

Fig. 3: Poplar (*Populus nigra* L.) with inner rot (wood-softening white rot by the honey fungus). Trunk diameter 1 m. For 10 years, repeated drilling each year. The area of excessive drilling in the trunk is marked by a circle. Arrow (bottom right): Sawed-in RESI measurement drill holes; detailed study see Fig. 5.

Residual wall thickness of the trunk area of excessive drilling (about 50 – 70 mm rot-free) did not differ significantly from that of the remaining trunk area that had not been subjected to drilling. This means that the numerous drill holes which penetrated the decay compartmentalization walls (e.g. reaction zones, possibly also barrier zones) from year to year did not significantly affect the structural integrity or breaking strength of the tree. In the area of excessive drilling, the inner rot was not found to "migrate" significantly through the drill holes and destroy the outer, still healthy residual wall (see Fig. 4).

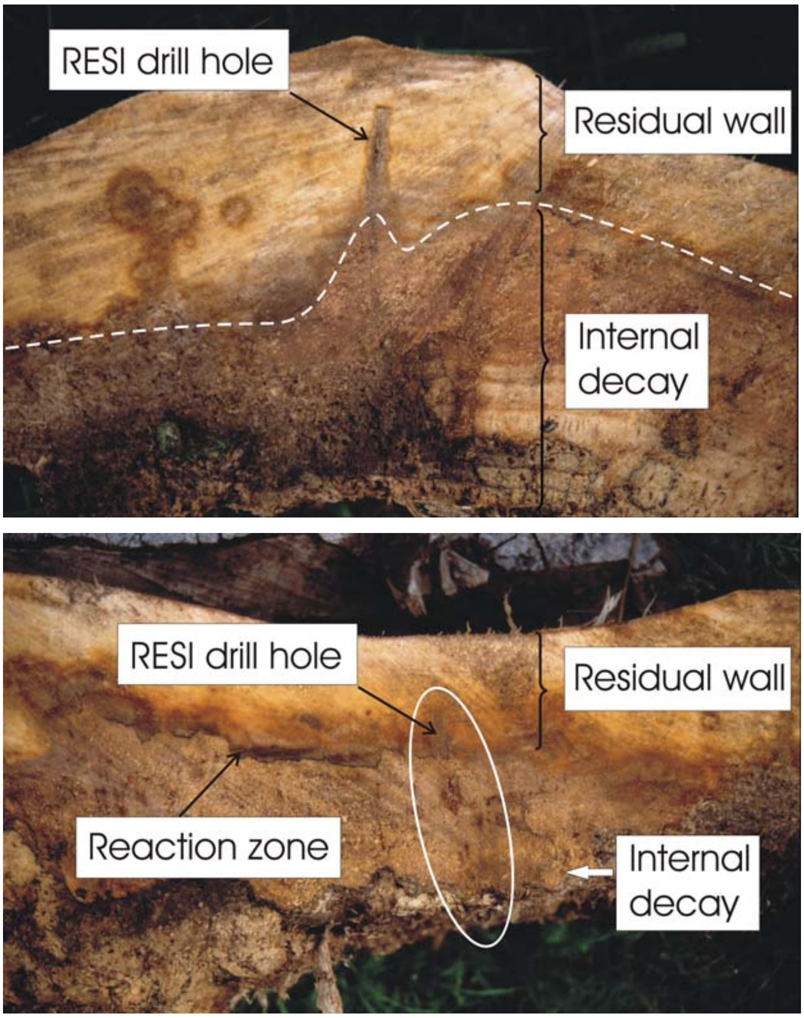

Fig. 4: RESI measurement drill holes in the fresh saw-cut. Top: Situation 7 years after a measurement drilling. Bottom: Situation 10 years after another measurement drilling. The resulting residual wall thicknesses were not affected significantly by the drillings.

Having evaluated the total effect of drilling for years on the tree trunk, modifications of the wood corpus by individual drilling shall be presented below. Figure 5 shows the residual wall in the area of a 3 mm RESI measurement drill hole six years after drilling. Around the drilling channel, a relatively well-defined reaction zone had formed in the poplar's sapwood. By subsequent annual ring formation, the drill hole was closed again within half a year. First, a thin, yellowish-brownish layer, a "barrier zone", was formed around the drill hole by the cambium. After the drill hole had been covered by six annual rings without decay entering from outside, inner decay started to decompose the wood at the inner end of the drilling channel. Via the drill hole, the inner decay can be assumed to have initially migrated more rapidly through the reaction zone than it would have done in the neighboring zone, where no drilling took place.

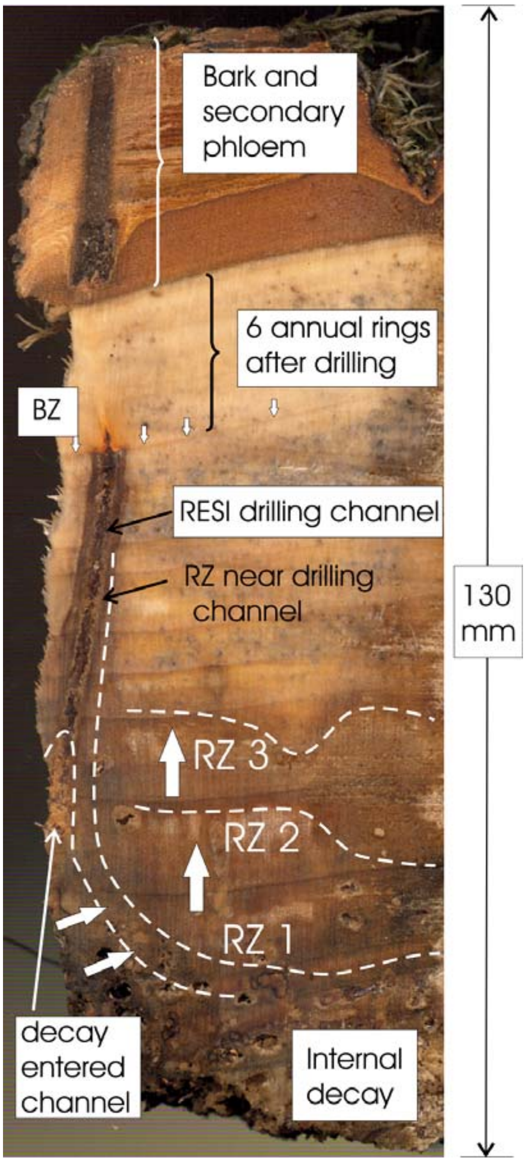

Fig. 5: Residual wall of the poplar six years after RESI measurement drilling. The reaction zone of the trunk (RZ 1, 2, 3) migrated outwards in front of the extending internal decay. The reaction zone (RZ) around the drilling channel extended tangentially at the inner end with or in front of the decay that had entered the channel. BZ = Barrier zone caused by the drilling.

Penetration and slow propagation of the rot into the drilling channel remained within relatively close limits and caused a pronounced reaction zone formation in the sapwood. At the same time (within six years), the inner rot propagated in the poplar trunk, thus “pushing” a concentric reaction zone that had formed in front of the rot. The initial reaction zone (RZ 1 in Fig. 5) was penetrated by the decay fungus in a stepwise manner. Consequently, a new reaction zone (RZ 2) formed in the sapwood area radially in front of the initial reaction zone, etc. The degree of decomposition of the “left behind” rotten wood increased towards the inside, as a result of which the already existing central decay cavity was widened.

After 6 – 7 years (Figs. 4 and 5), the general, all-around reaction zone reached about the radial extension of the decay that had entered the drilling channel. After 10 years (Fig. 4, bottom), the general, all-around reaction zone in front of the inner decay caught up with the decay in the drilling channel, such that the local negative effect of drilling was compensated nearly completely.

It must be noted that the extent of reaction zone formation around the drilling channel in the sapwood due to drilling, i.e. mechanical damage during drilling (cf. Fig. 5), obviously was smaller than the reaction zone formed at the inner end of the drilling channel due to the locally migrating decay. Here, the tree seems to save energy and to form a thick “energy-consuming” reaction zone only when an actually existing decay fungus has to be prevented from spreading (but also see discussion to reaction zone formation of Fig. 13A/B).

Based on this observation, it may be assumed that a fungus-induced reaction zone formation is more intensive and presumably also more effective than a purely mechanical, injury-induced reaction zone formation without fungal infestation. In other words: At places, where the reaction zone is really needed in a tree, it is better than at places, where it is only formed by way of precaution (or to prevent air embolism).

The thicker the reaction zone, the more difficult it is for the decay fungus to grow through it, i.e. the better is the inhibiting effect on decay propagation. In the poplar studied, a reaction zone was formed along the entire drilling channel (which may be several centimeters long) and another one near it in the rear area of the channel by the migrating rot. Therefore, this reaction zone was locally (at the point of drilling) very thick in radial direction and particularly inhibited radial decay propagation. As a result, the all-around concentrically extending internal decay also succeeded in catching up with the locally “migrating” decay.

As all drill holes found in the poplar exhibited the above phenomena (barrier zone, reaction zone, etc.), the “*effects of drilling*” could be represented in general and schematically (Figs. 6 – 9).

In no case had the rot entered the drilling channel from outside and survived in the outer area of the hole.

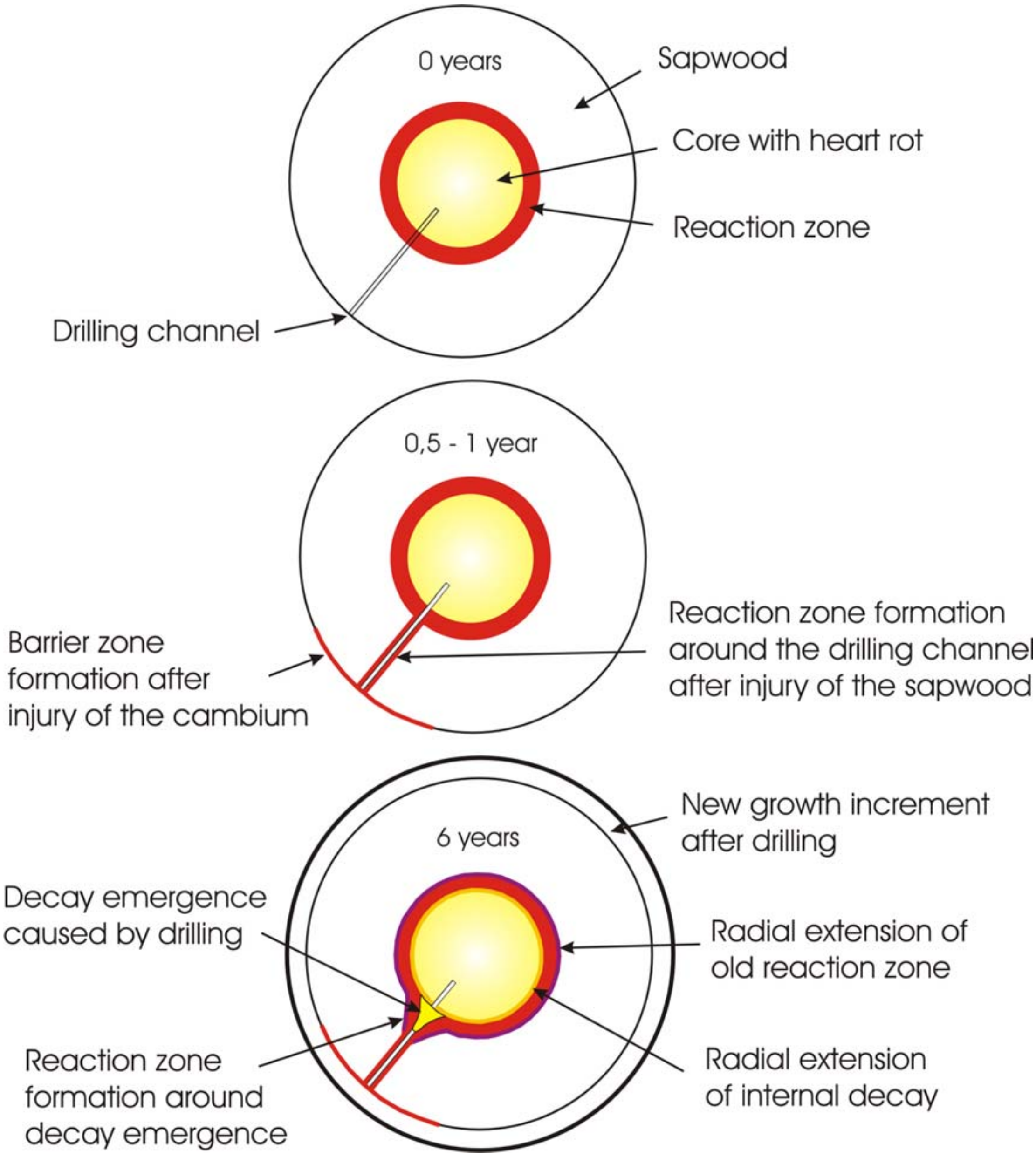

Fig. 6: Schematic representation of the effects of RESI drilling on the honey fungus-infested black poplar. Stem cross sections through the drilling plane. Top: Situation directly after drilling. Center: Situation after 6 – 12 months. Bottom: Situation six years after drilling.

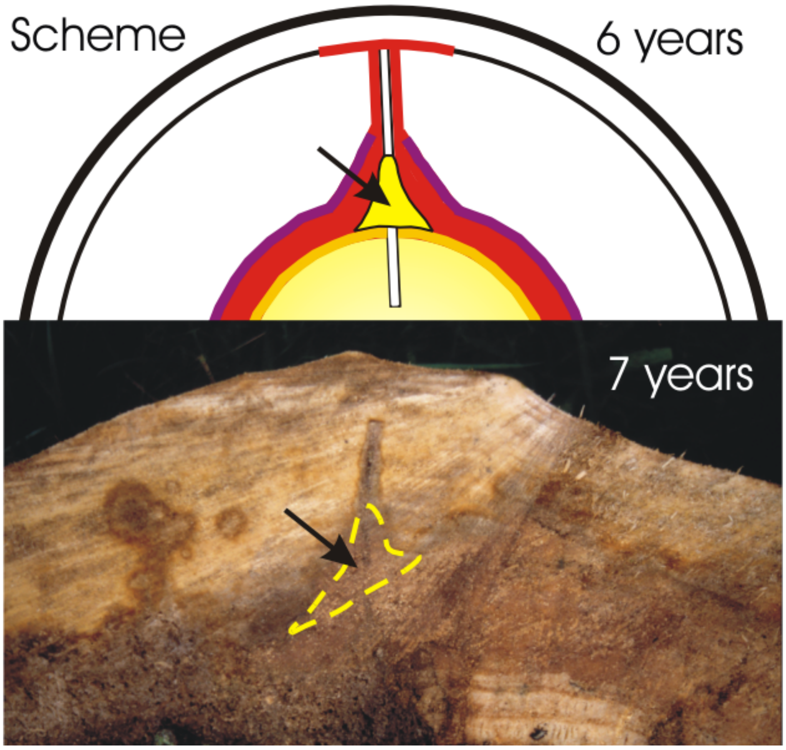

Fig. 7: Emergence of the internal decay (arrows) caused by drilling in the stem cross section 7 years after RESI drilling. Comparison of scheme and saw cut.

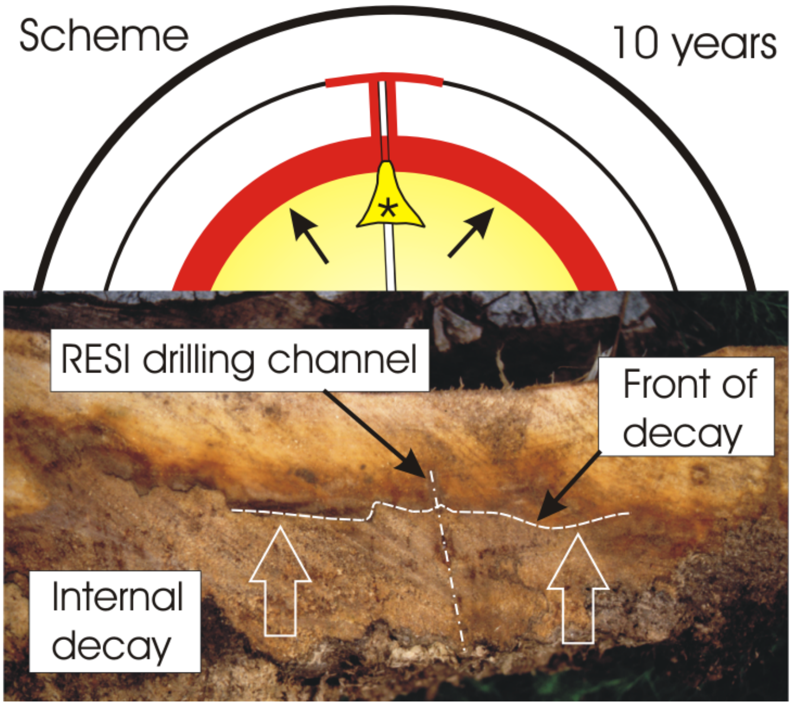

Fig. 8: The additional radial extension of the inner decay (* in the scheme) that was caused locally by drilling has been caught up with after 10 years by the generally propagating internal decay (large arrows) near another RESI drill hole.

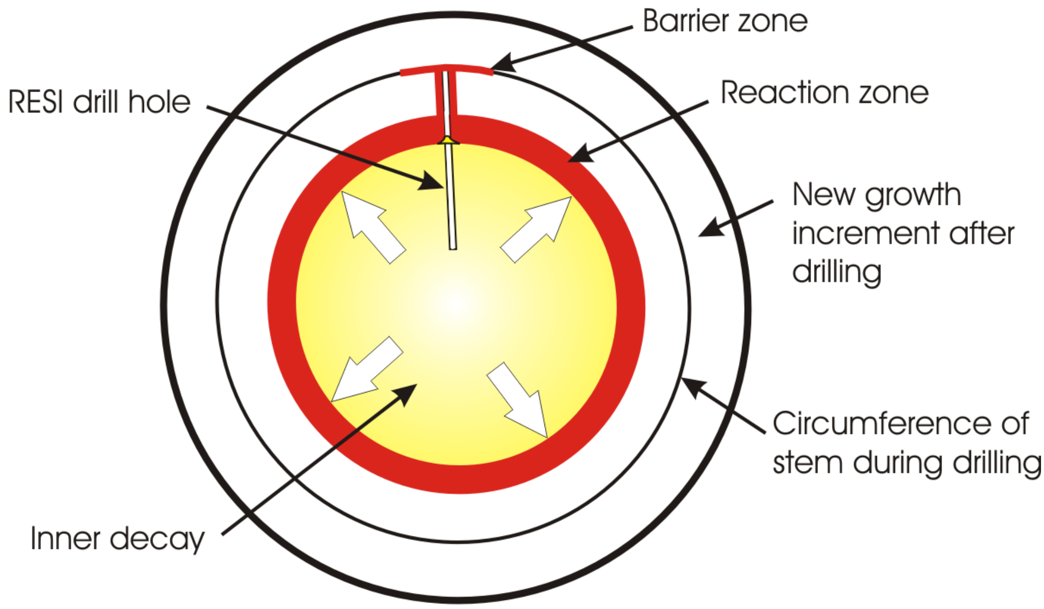

Fig. 9: Schematic representation of the long-term effects of RESI drilling on a honey fungus-infested black poplar. Stem cross section through the drilling plane. Situation 10 years after measurement drilling. The radially (or concentrically) extending inner decay (arrows) has caught up with the additional radial extension of the inner decay that was caused locally by drilling.

Now, the effects of drilling shall also be studied in axial direction, i.e. along the trunk axis. Figure 10 shows a wood shaving that was withdrawn directly near a RESI drilling channel. The induced barrier zone (BZ) and the reaction zone above and below the drill hole can be seen clearly.

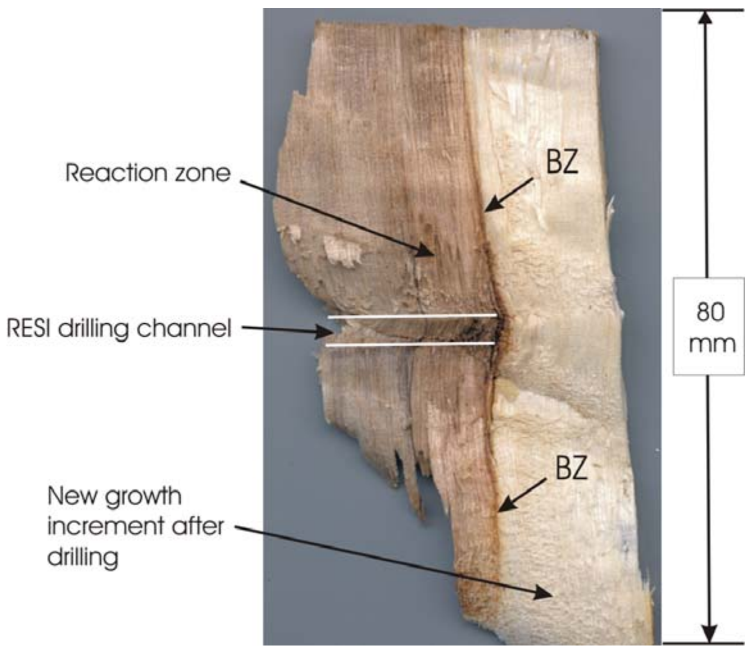

Fig. 10: Longitudinal section of the barrier zone (BZ) and reaction zone formed near a six year old RESI measurement drill hole of a black poplar.

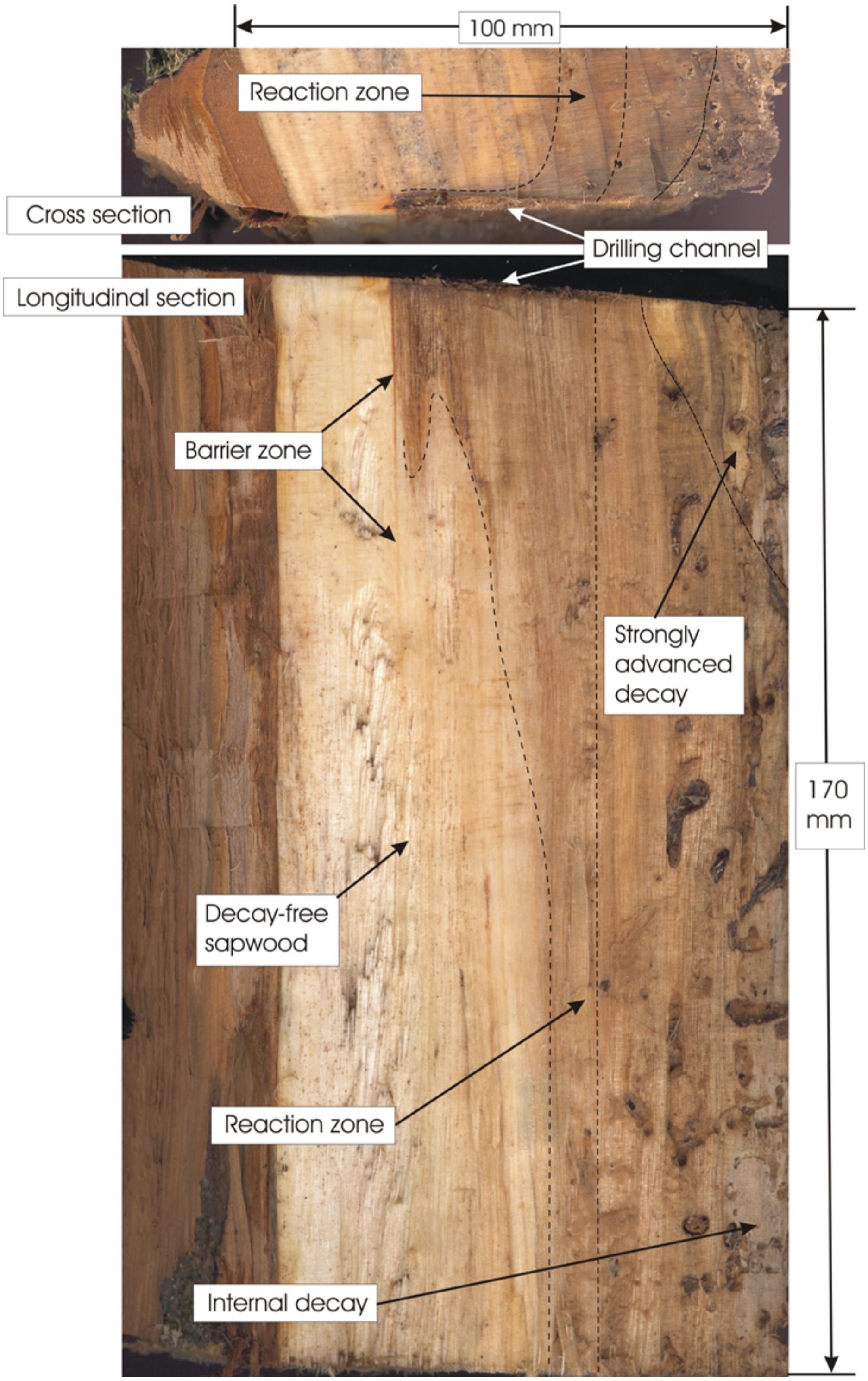

Fig. 11: Cross and longitudinal sections of the local residual wall thickness of the rot-infested poplar near a drilling channel 6 years after RESI measurement drilling.

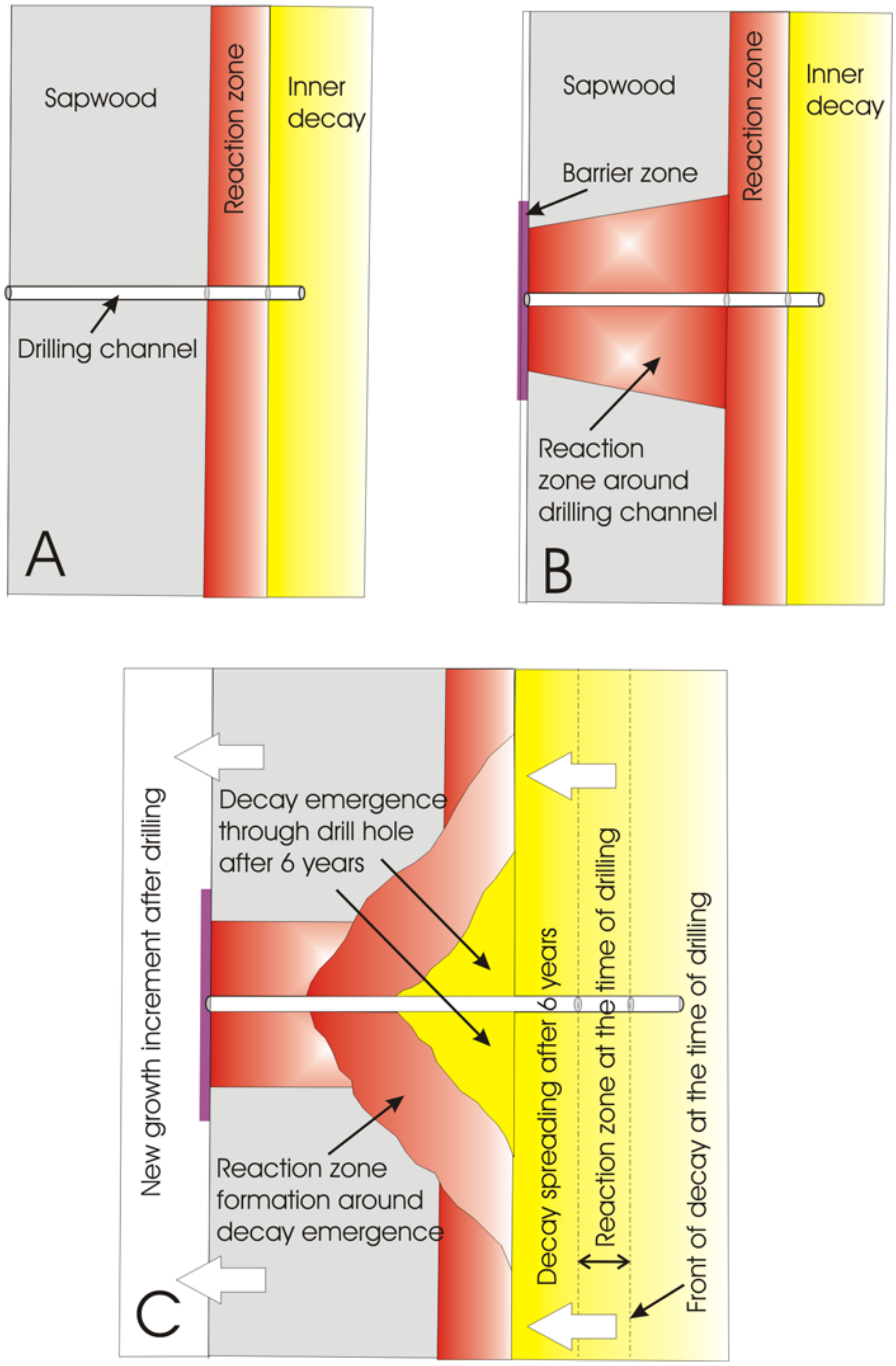

Fig. 12: Schematic representation of the effects of RESI drilling on a honey fungus-infested black poplar (heart rot). Longitudinal sections of a trunk through the drilling plane. **A:** Situation directly after drilling. **B:** Situation after 6 – 12 months. **C:** Situation 6 years after drilling.

Figure 11 shows the cross and longitudinal sections of the modifications of the poplar corpus six years after RESI measurement drilling. Again, the compartmentalization “walls” can be seen in the tree. The barrier and reaction zones induced by drilling as well as the reaction zones formed by decay entry into the drilling channel, together with decay itself, were much stronger in axial direction, i.e. parallel to the wood fibers, than in radial direction (vertical to the wood fibers). As this applied to all drill holes, the effects of drilling in axial direction were represented schematically, cf. Fig. 12.

Finally, both schematic representations, i.e. Fig. 6: Effects of drilling in the stem cross section and Fig. 12: Effects of drilling in the longitudinal section, were combined in a three-dimensional schematic representation. Figures 13A and 13B show the effects of drilling on wood decay in a tree 6 and 10 years after RESI drilling, respectively (three-dimensional schematic representations).

The larger reaction zone formation by decay entry into the inner part of the drilling channel as compared to the outer sapwood area is probably due to the fact that the young, outer tissue regions have a higher metabolic activity than the inner tissue regions. The latter possess older cells of smaller activity and probably less living cells (parenchyma), as a result of which defense zones are established more slowly and zone extension inside is increased.

Now, a general conception shall be outlined as to how the reaction and barrier zone formation may be influenced.

The more vital a tree is, the more rapidly its living cell fraction in the wood corpus reacts to an injury, i.e. the more rapidly are the compartmentalization walls built (reaction zone, barrier zone) and the shorter and narrower are the column-shaped discolorations inside the trunk. Vitality, however, mainly depends on the growth conditions and the genetic prerequisites or factors of a certain type of tree. By selecting resistant young trees of a certain type and by an optimum site selection and optimum site conditions (including tree care), the best possible, tree-inherent reaction processes can be ensured.

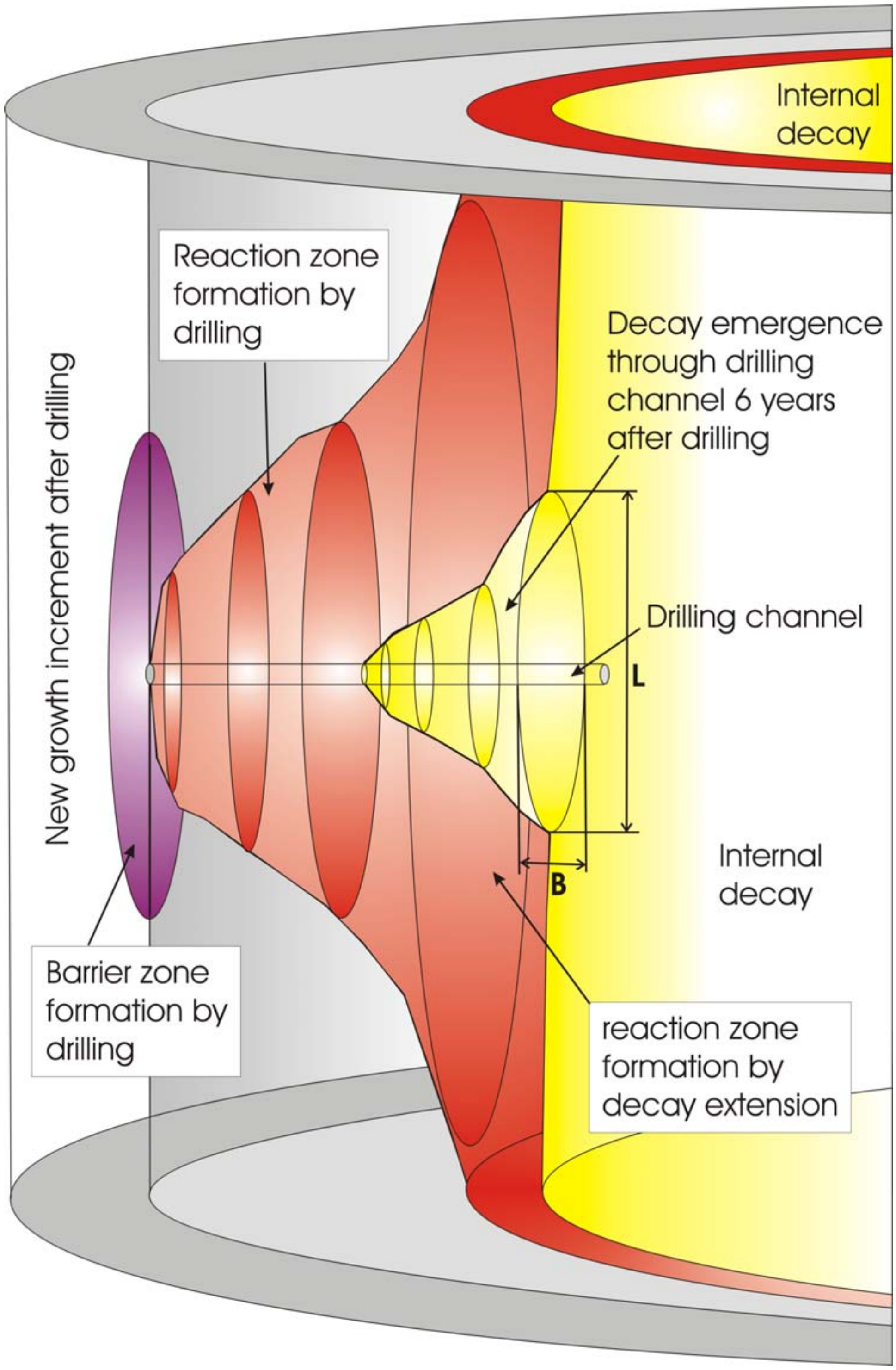

Fig. 13A: Effects of drilling on wood rot in a tree. 3D schematic representation of the modifications of a wood corpus of a honey fungus-infested black poplar (heart rot) six years after RESI drilling. The reaction zone around the drilling channel and the local emergence of the rot are column-like structures in the wood cylinder. They are tangentially slender (small width 'B') and axially relatively long ('L' = length) or high.

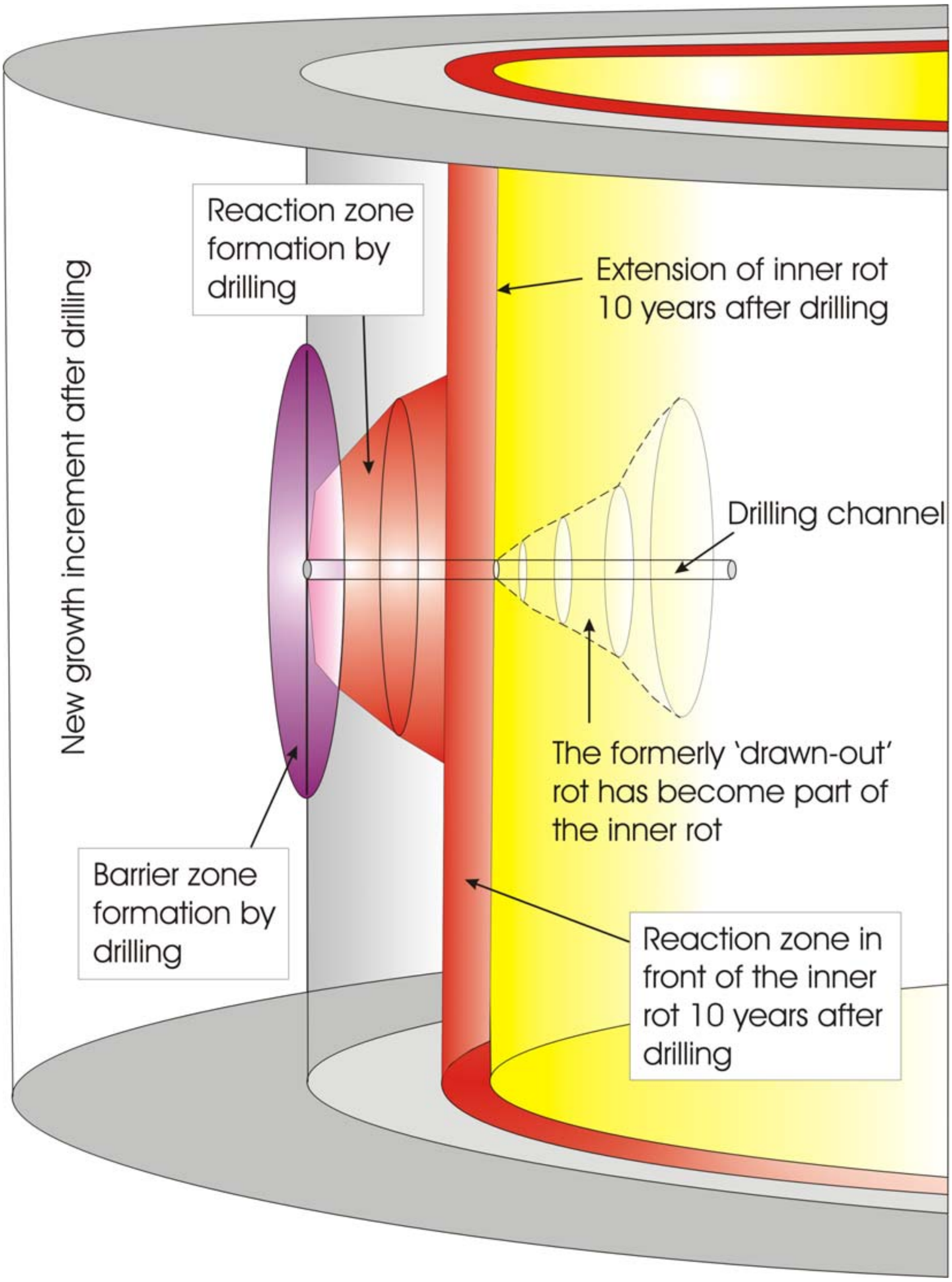

Fig. 13B: Effects of drilling on wood rot in the tree. Three-dimensional schematic representation of the long-term effects on the wood corpus of a honey fungus-infested black poplar (heart rot) 10 years after RESI drilling. The spreading central inner rot has caught up with the formerly "drawn-out" rot around the inner part of the drilling channel. Hence, the local negative effect of drilling has been compensated nearly completely, cf. 2D scheme and stem saw-cut in Fig. 8.

Figure 14 shows the sycamore maple studied. Inside the trunk, it was infested by an extensive soft rot caused by the *Ustulina deusta* fungus. The many increment borer and RESI drill holes caused barrier zone formation in the newly produced trunk wood and a strong reaction zone formation in the sapwood around the drilling channels.

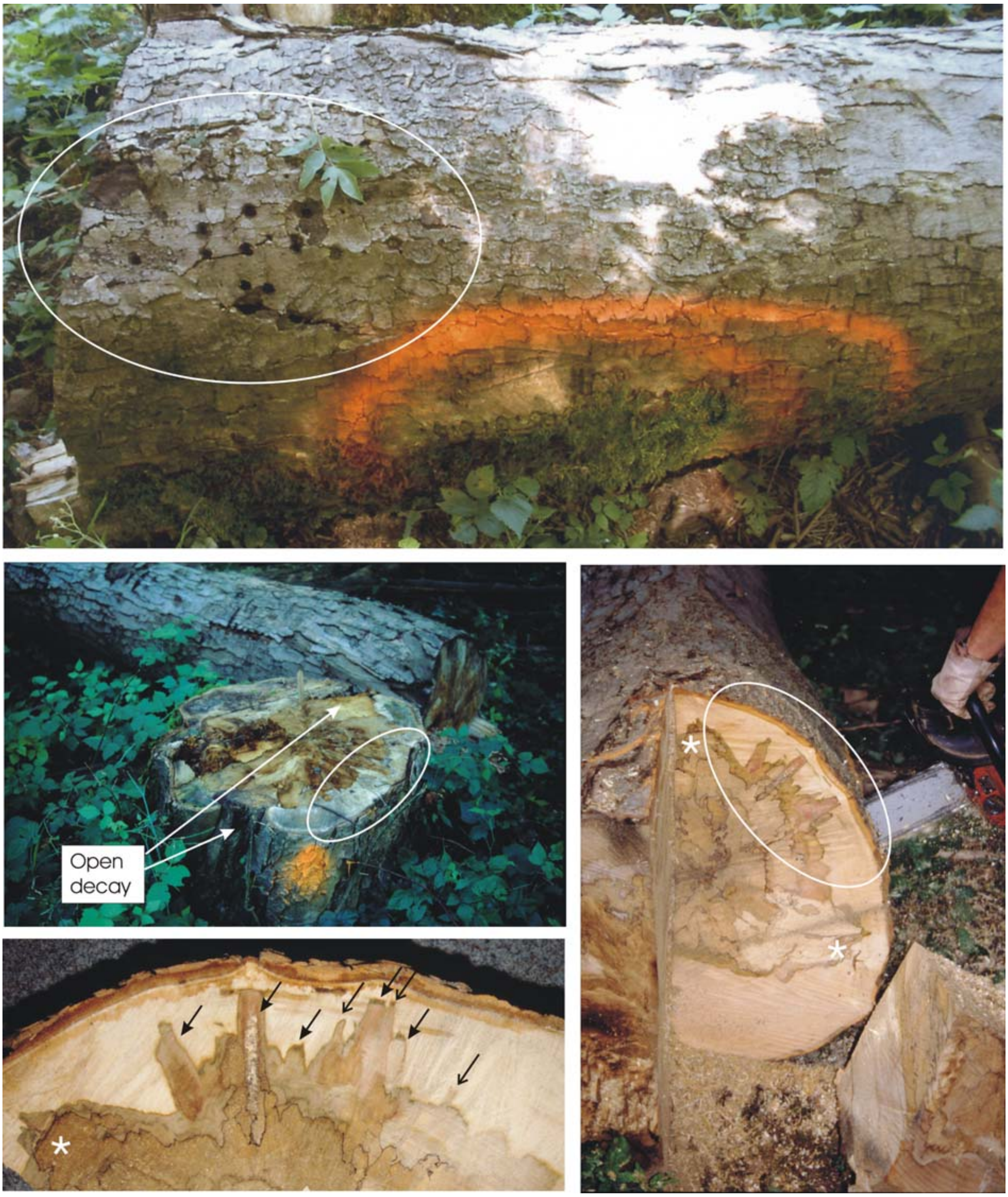

Fig. 14: Sycamore maple (*Acer pseudoplatanus* L.) with *Ustulina deusta* fungus inside. Trunk diameter about 0.8 m. The trunk area of excessive drilling is marked by a circle. Thick arrows (bottom, left) show the increment borer holes. Outer diameter of the drill 11.3 mm. Thin arrows show the RESI drill holes, (*) natural wounding.

The inner rot started to propagate from the inside to the outside along the increment drilling channels in a locally relatively limited area, but was inhibited by the channel-enclosing reaction zone. Consequently, the “migrating” decay could attack the inner part of the residual wall close to the drilling channel only. These additional local decay propagations caused by numerous drillings only slightly reduced the residual wall thickness of the tree, see Fig. 14, bottom, right. The total effect of drilling on the stability of the trunk was of minor importance only in view of the existing “natural” injuries of the trunk.

When studying the modifications of the wood corpus around the individual increment borer holes in detail, these are in qualitative agreement with those of the above RESI drill holes in the heart-rotten poplar. The trunk section is shown in detail in Fig. 15.

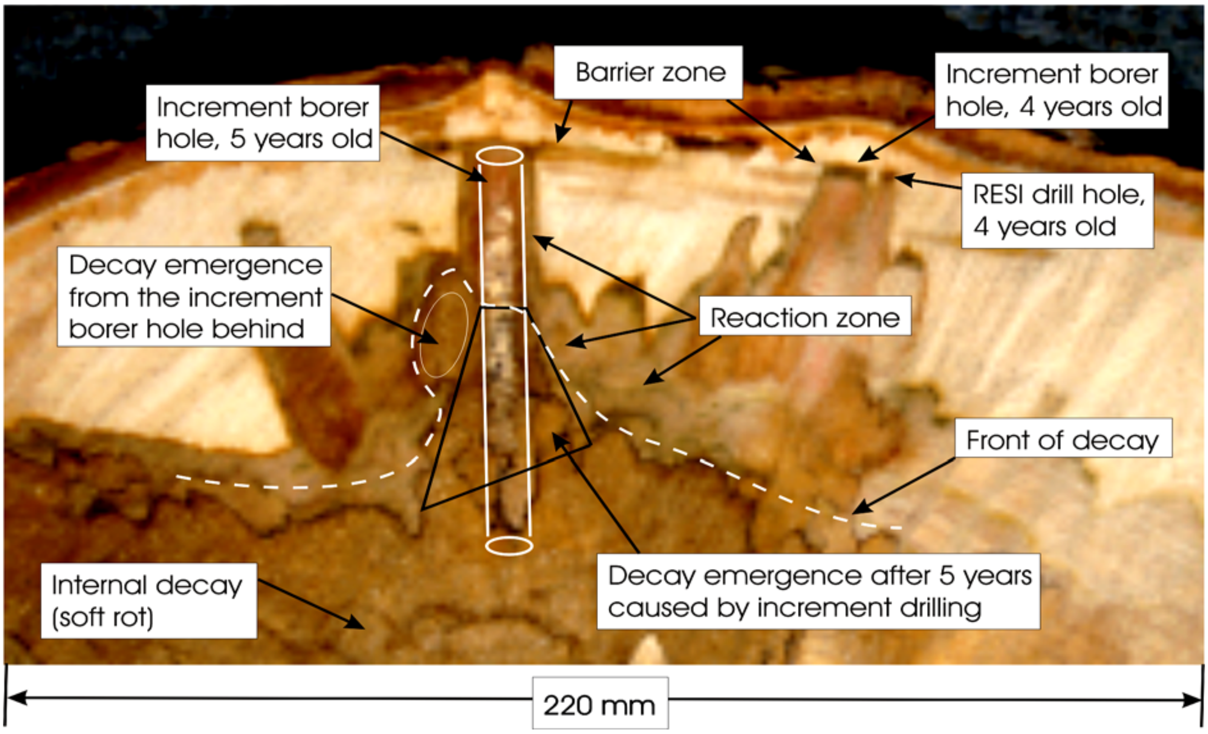

Fig. 15: Measurement drillings in a sycamore maple with inner rot. Fresh saw-cut (stem cross section) through a 5 year old increment borer hole. The figure shows the effects of 12 drill holes located close to each other.

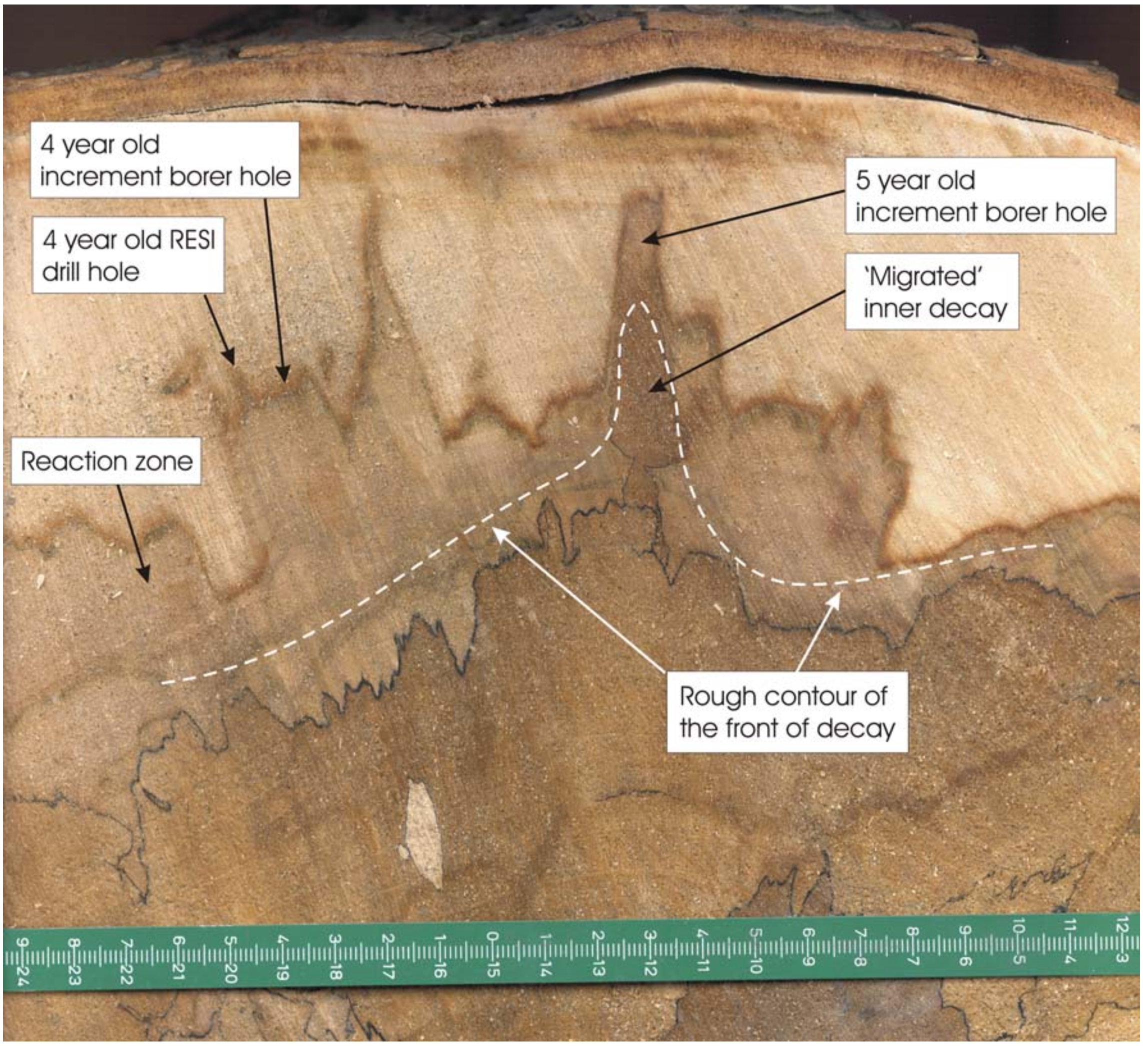

Fig. 16: Back of the 10 cm thick tree disk shown in Fig. 15: The reaction zones and the area of the “migrated” inner decay are more slender than in Fig. 15 (reduced widths in the 3D schematic representation, Fig. 13).

The reaction zones of the individual drillings fused or merged with each other and formed a wide, closed “rot defense wall”. When comparing Fig. 15 with the cross sectional area at 10 cm axial distance in Fig. 16, it can be noticed that the reaction zones become more slender, i.e. widths of the reaction zone columns around the drill holes are reduced (cf. 3D schematic representation in Fig. 13). Also the triangular surface area of the “migrated” rot has become smaller or more slender (cf. 3D schematic representation). Figure 15 also allows for a direct comparison of the reaction zones formed by increment and RESI drilling. Both drill holes were four years old and located near each other. The sycamore maple reacted in a qualitatively identical manner to both drillings. Quantitatively, however, the increment borer (larger borer diameter) caused larger modifications, a broader barrier and reaction zone. The height of both reaction zone columns (comparison of Fig. 15 and Fig. 16) was about the same. Figure 17 shows the radial longitudinal section of several merged reaction zones.

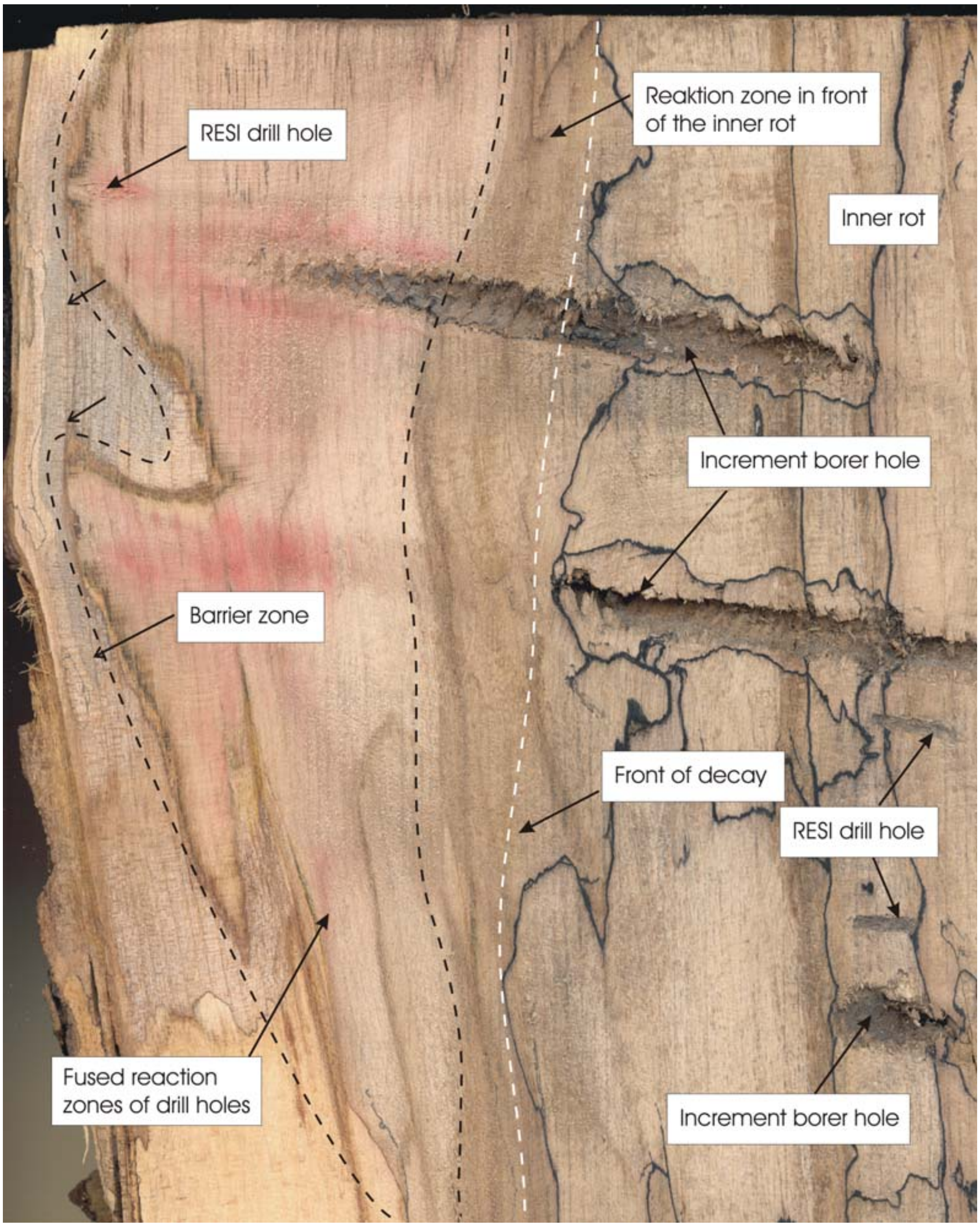

Fig. 17: Radial longitudinal section of the area of excessive drilling in a sycamore maple with inner rot. The reaction zones of the drill holes merged and add on the reaction zone of inner rot.

Figure 18 shows the studied oak tree (*Quercus robur* L.) with a crack. Defect symptom: Rib formation in front of the crack and smaller inner rot, defect symptom: Swelling of the trunk in front of the decay zone. The defective trunk areas were investigated and drilled repeatedly in the past years. A number of RESI drillings and several increment borer drillings were made.

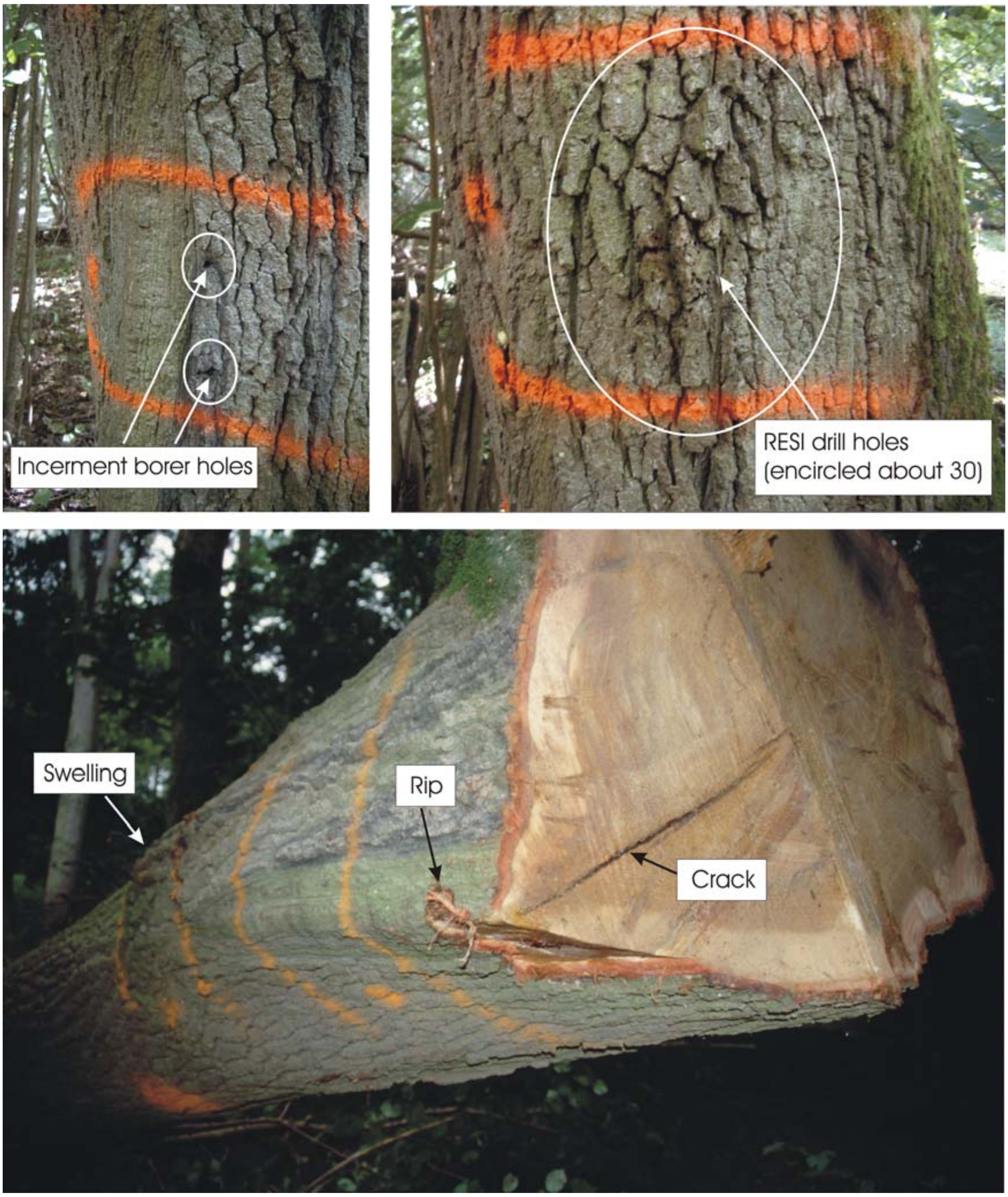

Fig. 18: Oak tree (*Quercus robur* L.) with rib formation in front of a crack and swelling of the trunk in front of a smaller decay zone (right, top). At the defects, a number of drill holes from previous years were located.

Trunk cross sections through the rib revealed the inner crack, the edges of which were colored dark-brown by reaction zone formation (cf. Fig. 19). This means that the crack successively continued in the sapwood. As a result, the injured, living sapwood tissue produced polyphenolic substances and stored them in the cells close to the crack, which finally caused brown discoloration. No wood decay was found in the crack. RESI measurement drill holes through the rib and the crack did not cause any entry of decay and, hence, practically had no effects on the safety of the oak trunk, see Fig. 19.

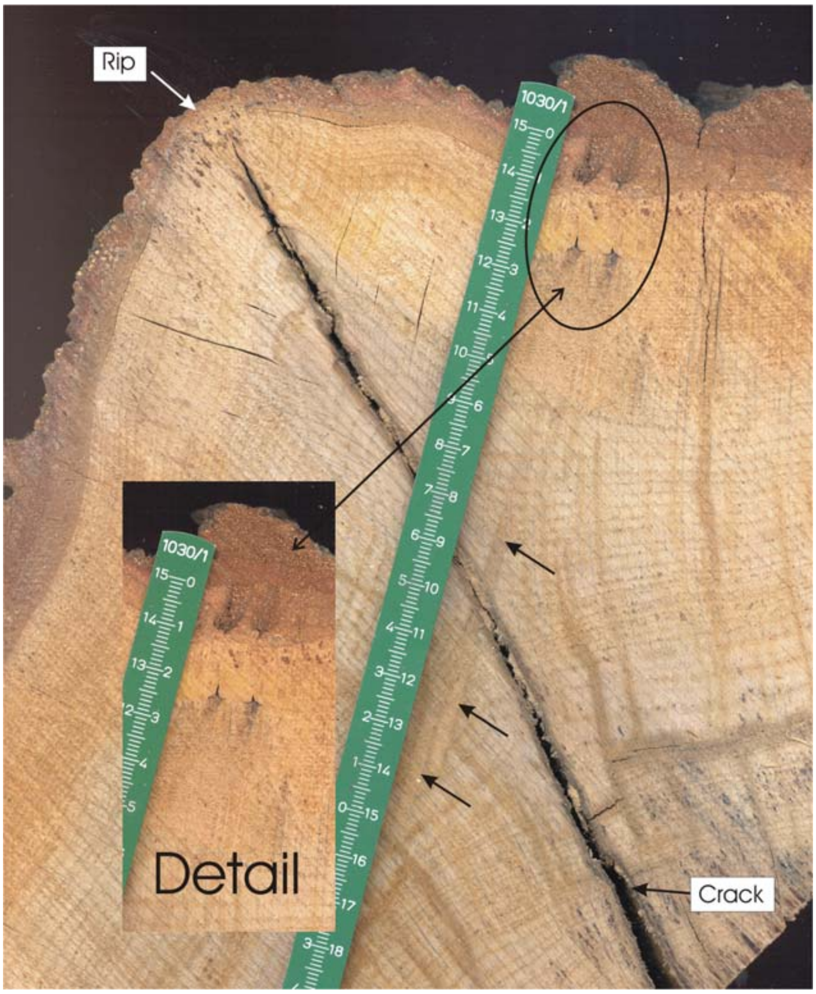

Fig. 19: Effects of two RESI measurement drill holes through the trunk rib of the oak tree. The drill holes were covered by eight annual rings, arrows = drilling channels. The dark-brown colored wood areas of the crack and drilling channel borders represent reaction zones. Saw-cut or stem cross section.

The drill holes were covered by the following annual ring and the sapwood responded in a locally very limited area by forming a reaction zone, i.e. brown discoloration due to the enhanced inclusion of polyphenolic substances. When wetting the saw-cut through the RESI drill hole at another point (s. Fig. 20), an intensive brown discoloration could also be noticed in the young heartwood around the drilling channel. By means of a microscopic investigation, this area was clearly identified to be a reaction zone (locally enhanced incorporation of polyphenolic substances) even though it was not as pronounced as in the sapwood. It was therefore concluded that the young heartwood still contained a sufficient number of living and physiologically active parenchyma cells that were able to execute this metabolic activity (see also [9]). It might be concluded that young oak heartwood at least is still "alive" and may respond to injuries by a reaction zone formation, i.e. potential decay compartmentalization. The fact that heartwood, although it is (or seems to be) "dead", may still respond to injuries by various discolorations was also mentioned in literature: Discoloration of heartwood after an injury was described by *Butin* [6], for instance, as an "oxidation discoloration". The penetrating oxygen reacts with the polyphenolic cell constituents generated by the heartwood formation and causes a grey-brownish “inlet-damage” in oak trees. *Holdenrieder* [7] mentioned that also in dead heartwood chemical reactions take place, which inhibit the propagation of fungi. *Shigo* [4] wrote that heartwood may react to injuries by forming a boundary zone that is capable of encapsulating pathogens. *Pearce* [9] even pointed out that phenol-oxidizing enzymes may remain active in the cell walls of dead heartwood cells!

Reaction of the oak tree to increment borer drillings was in qualitative agreement with its reaction to RESI drillings. Figures 20, 23, and 24 show the longitudinal and cross sections through increment borer drilling channels. As the diameter of the increment borer was larger than that of the RESI drilling needle, the drill hole and, hence, the extent of the injury or discolored zones was larger. An intensive reaction zone formation around the drill hole in the sapwood was observed, while reaction zone formation in the young heartwood was rather weak. In this study through no increment borer hole had decay entered from outside the wood.
Figures 21, 22, and 24 show the longitudinal sections with a barrier zone formation.

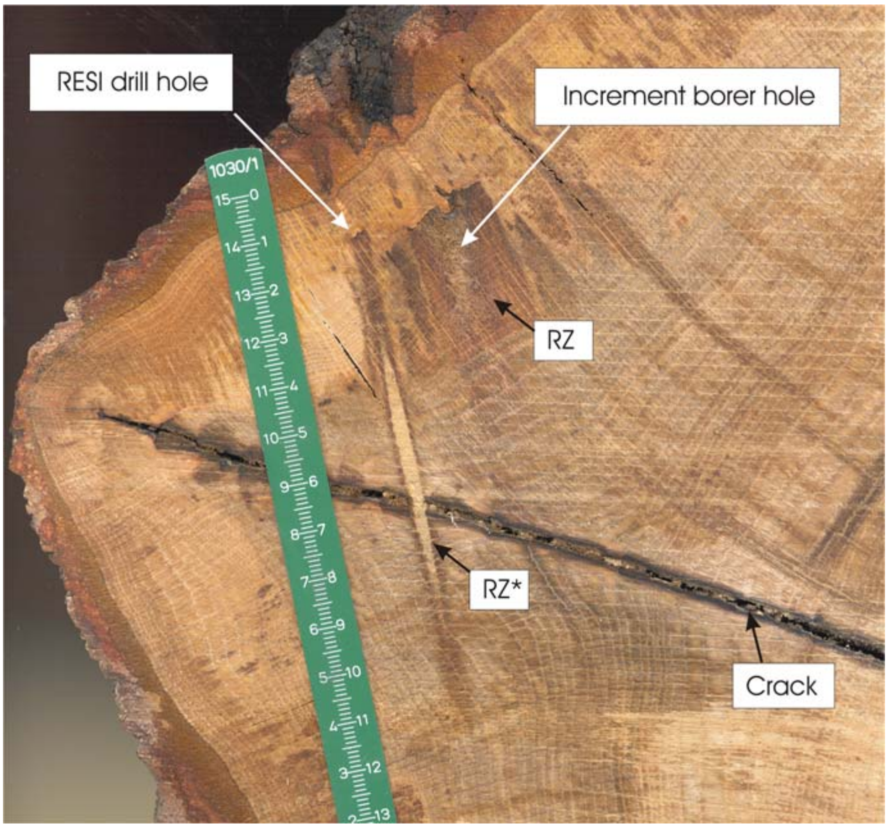

Fig. 20: Effects of RESI and increment borer drilling through the trunk rib of the oak tree. The drillings were made seven years (RESI) and nine years (increment drilling) ago, respectively. The RESI drilling channel still contains drilling splinters (light). Dark-brown discolored wood areas around the crack and the drilling channel borders represent the reaction zones (RZ). Also the young heartwood formed a reaction zone (RZ*) around the RESI drilling channel. Stem cross section.

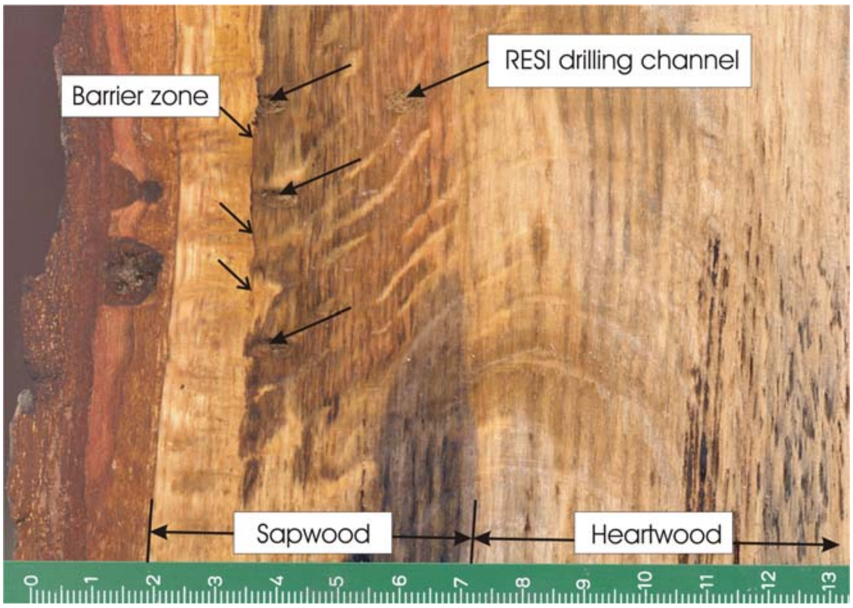

Fig. 21: Longitudinal section through seven year old RESI measurement drill holes in oak wood. The dark-brown colored sapwood area around the drilling channels represents a merged reaction zone.

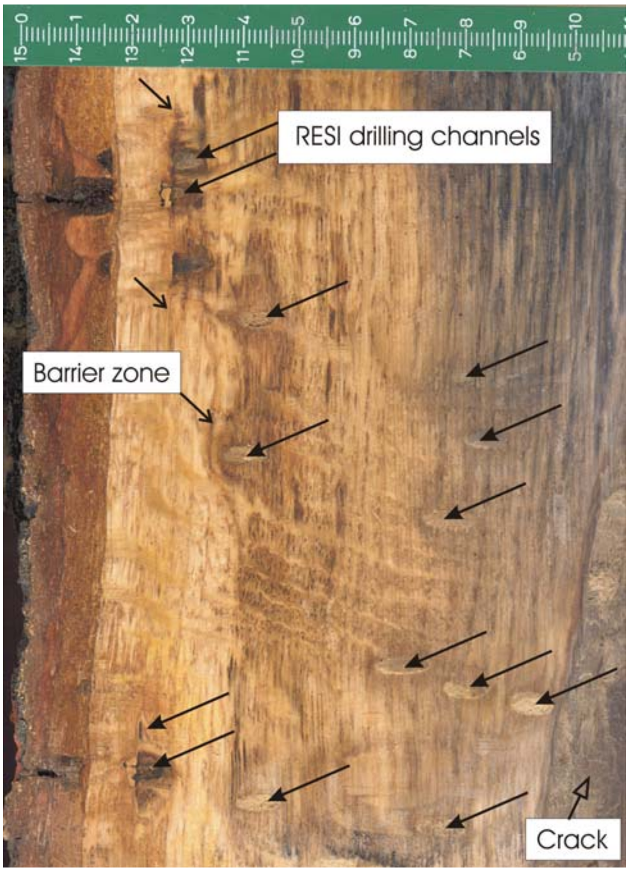

Fig. 22: Longitudinal section of 7 – 9 year old RESI measurement drill holes in oak wood. The dark-brown discolored sapwood area around the drilling channels (arrows) represents the reaction zones. The open arrows indicate the barrier zone.

Fig. 23: Effects of the increment borer hole and RESI drill hole through the trunk rib of the oak tree. The drillings were made 6 to 9 years ago. The dark-brown discolored wood areas around the crack and drilling channel borders represent the reaction zones (especially the sapwood reacts). Trunk cross section.

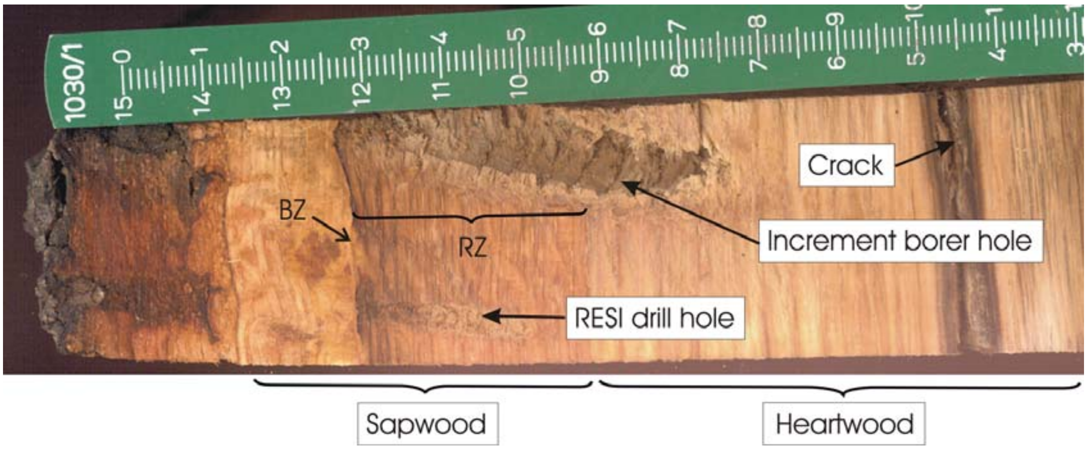

Fig. 24: Effects of the increment borer and RESI measurement drill holes through the trunk rib of the oak tree. The drillings were made about 9 years ago. The dark-brown discolored wood areas around the crack and drilling channel represent the reaction zones (RZ). Pronounced reaction zones are visible in the sapwood only. Barrier zone (BZ). Longitudinal section of the trunk.

The effects of excessive drilling on the inner decay in an oak tree are shown in Figs. 25 and 26. The inner decay was compartmentalized very well by the tree (cf. Fig. 26: walls II, III, IV) and did not propagate outside into the healthy wood in spite of intensive drilling (IML-RESI) during the past nine years. The age of the decay-causing injury was 57 years. As also no decay from outside entered the swollen trunk via the RESI measurement drill holes and the increment borer holes, the drillings did not have any visible negative effects on the safety of the oak trunk.

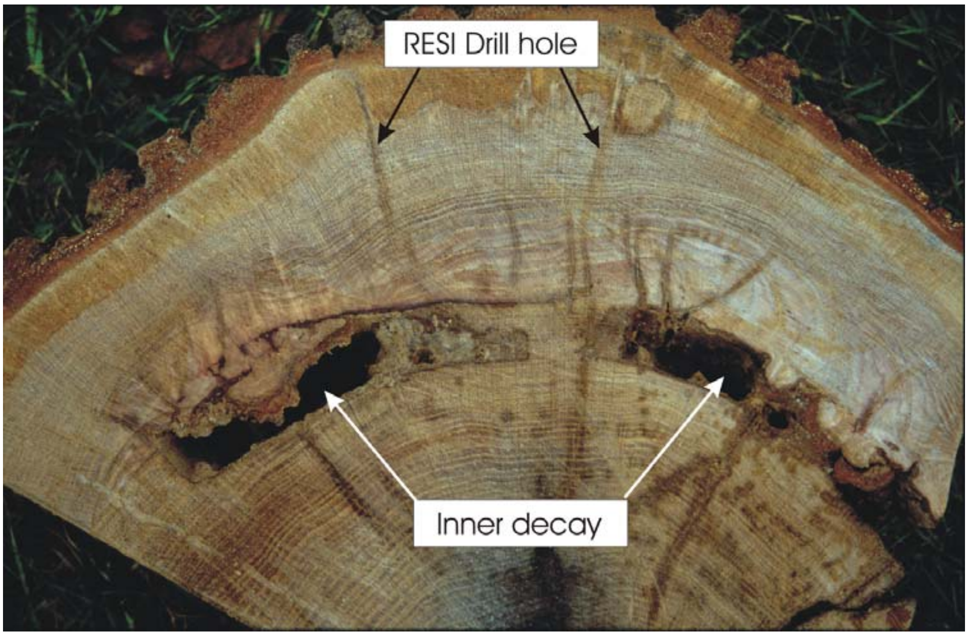

Fig. 25: Effects of excessive drilling on the inner decay in an oak tree. The age of the decay-causing injury was 57 years. For about 9 years, the inner rot has been subjected to IML-RESI drilling several times per year. Cross section of the swollen trunk (cf. Fig. 18).

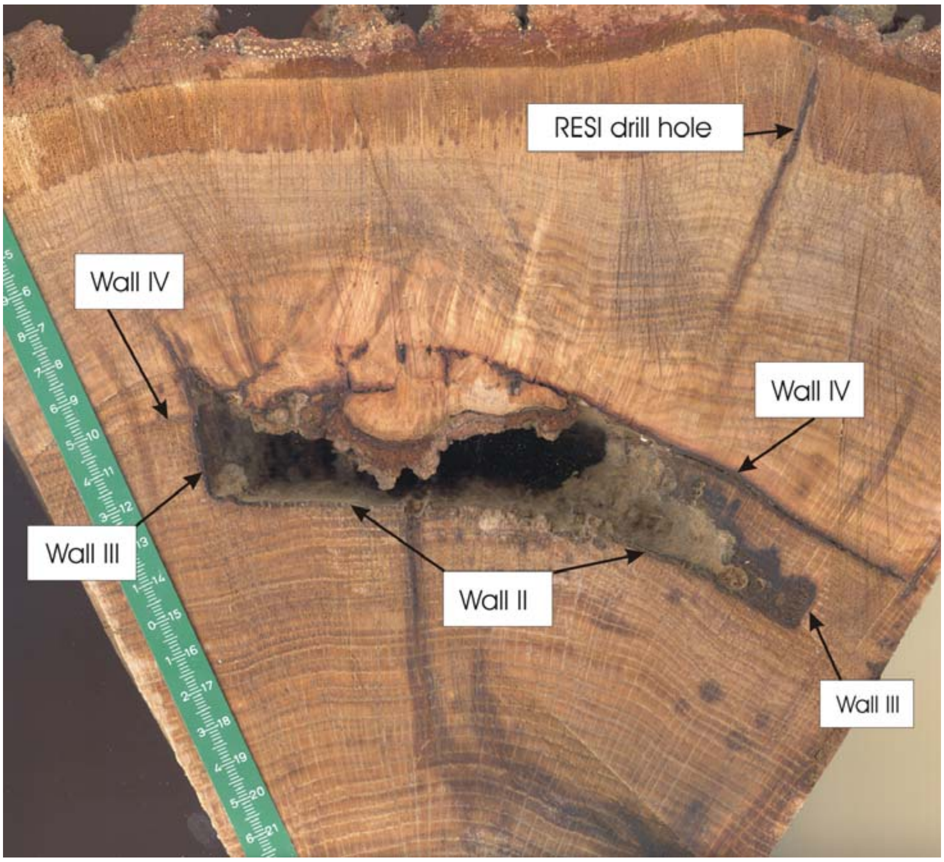

Fig. 26: Detailed view. Effects of excessive drilling on an inner rot in the oak tree. The age of the inner rot was 57 years. For about 9 years, the rot has been subjected to IML-RESI drilling several times per year. The inner decay was compartmentalized rather well by the tree (walls II, III, IV) and did not propagate outside into the healthy wood in spite of intensive drilling.

Figure 27 shows a lopsided sycamore maple tree (*Acer pseudoplatanus* L.) with many increment borer holes on the tension and compression sides of the bending near the trunk base. Prior to drilling, this tree did not possess any inner rot. The increment drillings were made nine years before felling and produced complete through holes through the trunk. Moreover, the trunk was subjected to a number of RESI measurement drillings.

Fig. 27: Sycamore maple tree (*Acer pseudoplatanus* L.) with many increment borer holes on the tension and compression sides of the bending. The drillings extended through the complete trunk and were made nine years before felling.

If a decay fungus would have entered the healthy trunk by excessive drilling and established there within the 9 years, a wood rot or a decay cavity would be found inside. Wood discolorations caused by drilling do not represent any decomposition or rot. Now (after nine years), the discolorations can be distinguished clearly from a real wood decay which, if existent, would meanwhile have reached an advanced stage.

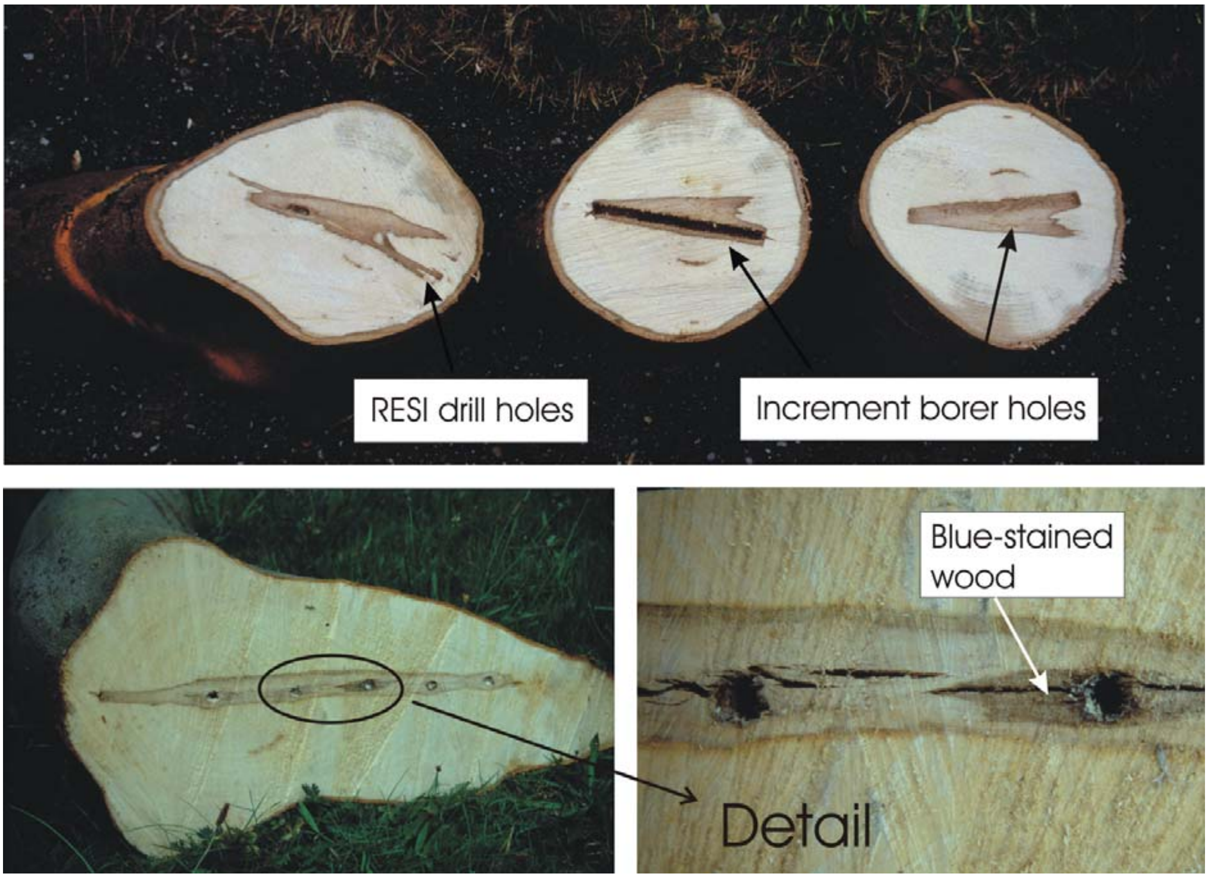

Fig. 28: Saw-cuts through the buttress of the sycamore maple tree (*Acer pseudoplatanus* L.) with many increment borer holes and some RESI drill holes (complete through holes through the trunk, increment drilling was carried out nine years before felling). The drillings caused locally limited discolorations of the wood corpus. Detail: Near an increment drill hole that had been drilled vertically into the lying buttress, an additional grey-black discoloration (blue-stained) was observed. It was caused by blue stain fungi.

Figures 28 – 32 show several cross and longitudinal sections from several perspectives of the sycamore maple trunk that was subjected to excessive drilling. The trunk that had been rot-free prior to drilling still was free of rot nine years after drilling. No wood rot had entered the corpus of the trunk. As obvious from Fig. 28, fungi causing blue stain had entered the lying, basal section of the trunk through a vertically drilled increment borer hole. These fungi could establish in the dead wood around the hole. The so-called blue stain fungi cause a bluish-black discoloration. They colonize in (dead) wood, but usually do not destroy it. As pointed out by *Schmidt* [8], blue stain fungi practically do not attack the cell wall and hardly influence wood strength, as they only live on cell constituents. The wood is subject to discoloration, because the thick hyphae of the fungi are colored brown by melanin and shimmer through the wood tissue.

Presence of blue stain causing fungi in a drill hole shows that the ubiquitous fungal spores may well enter the drill holes and germinate, but that the fungi only rarely succeed in establishing there. It may be assumed that fungal spores (probably also spores of wood-decaying fungi) entered the other drill holes as well. However, they did not succeed in establishing there.
All these observations allow the conclusion to be drawn that increment and RESI drillings generally do not cause any risks for vital trees of being infected by rot.

Figure 29A shows the response of a tree to drillings in the trunk cross section. The wounded, superficial tissue layer around the drilling channel died off and directly behind, a reaction zone was formed close to the drilling channel in the cross section. The longitudinal section, Fig. 29B, clearly shows the axial extension of the reaction zones that by far exceeds the tangential one as well as the merging of the zones of the drill holes that are arranged close to each other. Figures 29C and 29D reveal the closure of the drilling channel by wound wood formation. The effects of both drilling methods are compared in Fig. 30. The RESI drillings caused far less discolorations (reaction zone formation) than the increment borer holes. In both cases, a barrier zone was formed, Figs. 31 and 32 (cf. Fig. 29B).

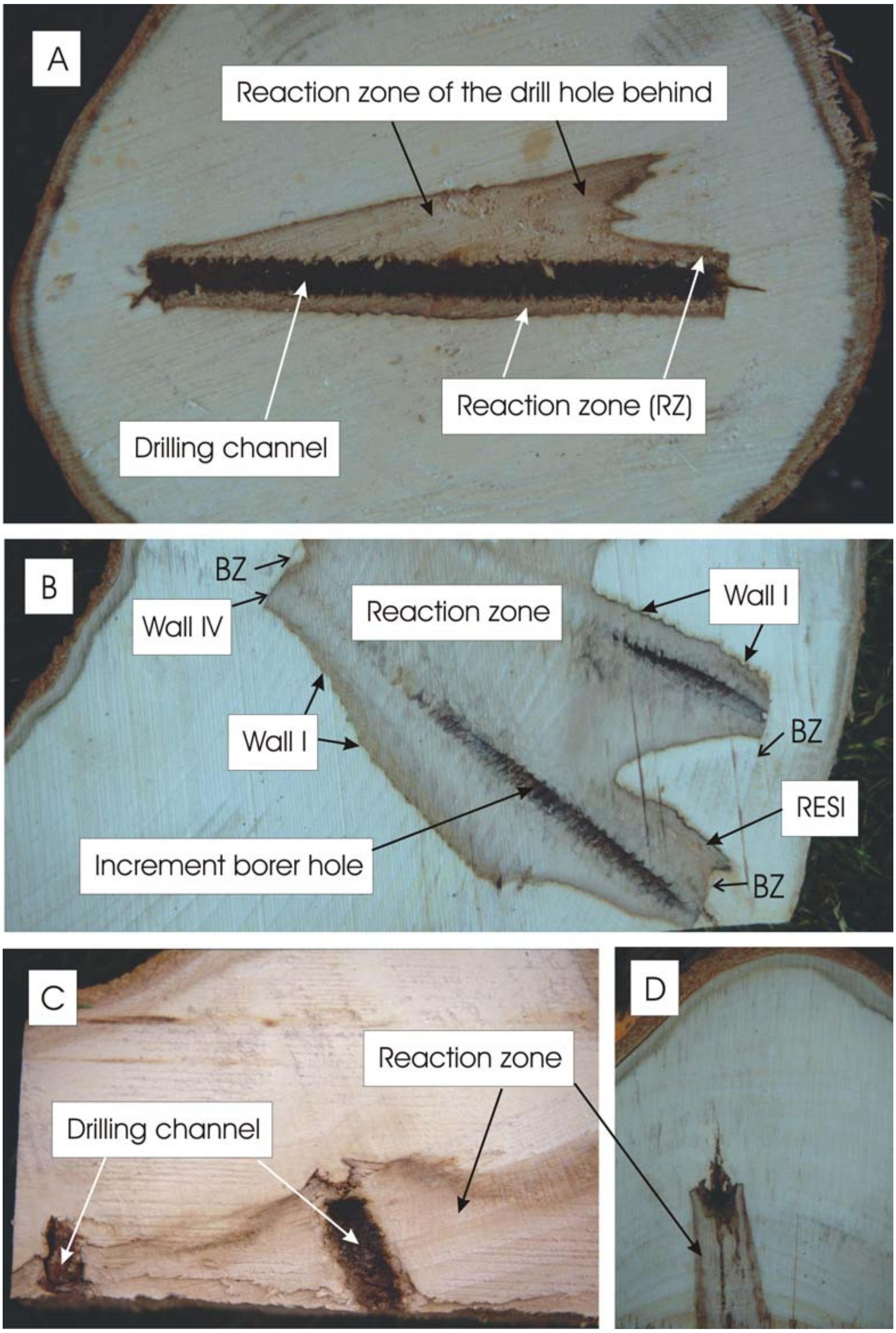

Fig. 29: Nine year old increment borer holes in a sycamore maple (*Acer pseudoplatanus* L.) **A:** Cross section of the drill hole. **B:** Longitudinal section of two increment borer holes and a RESI drill hole, BZ = barrier zone. **C:** Extended longitudinal section and cross section (**D**) of the closure of the drill holes by the first, newly formed annual ring after drilling.

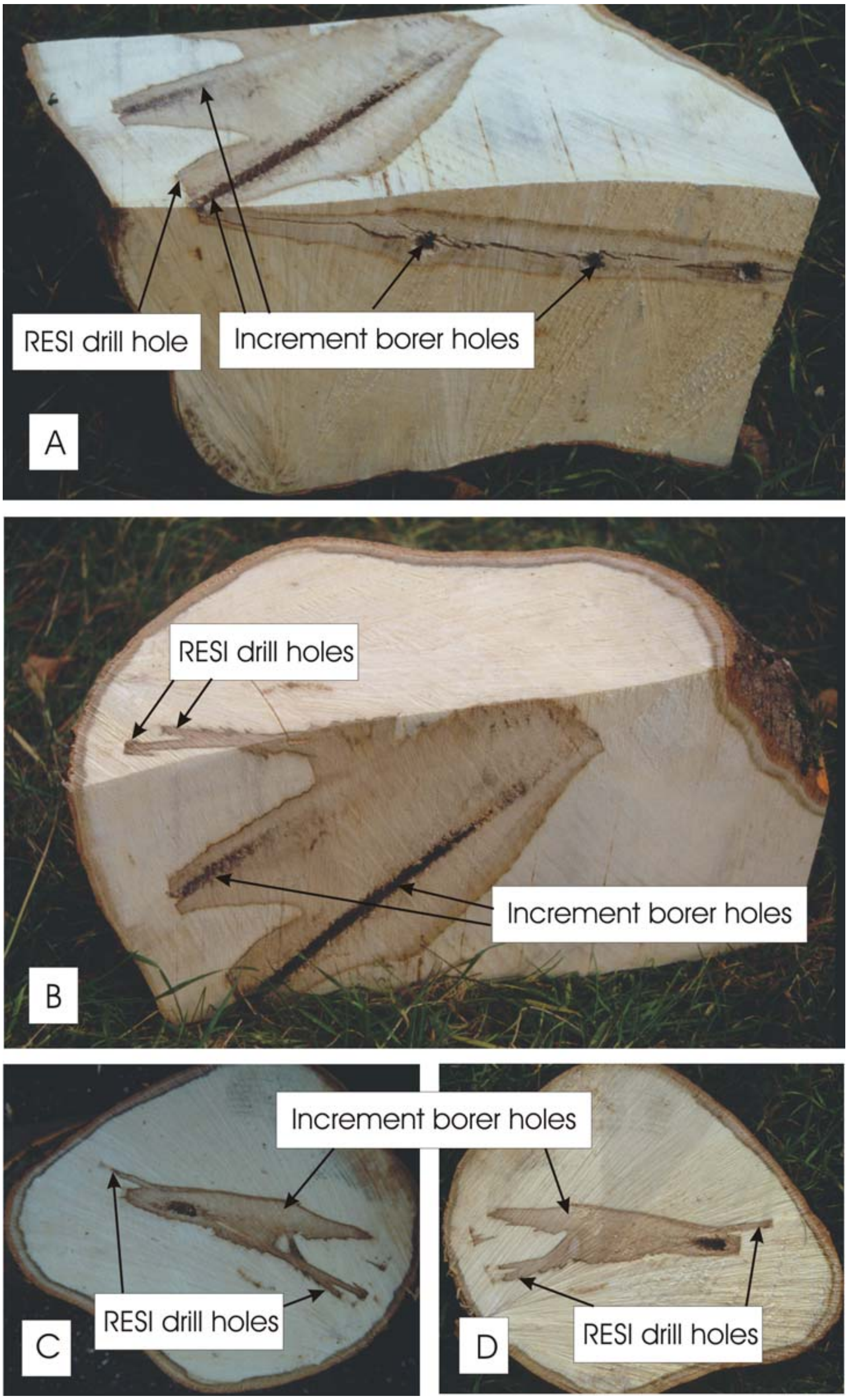

Fig. 30: Increment borer and RESI drill holes in sycamore maple (*Acer pseudoplatanus* L.). **A:** Angular view from below. **B:** Angular view from above. **C, D:** Direct comparison of the effects of both drilling methods, cross sections.

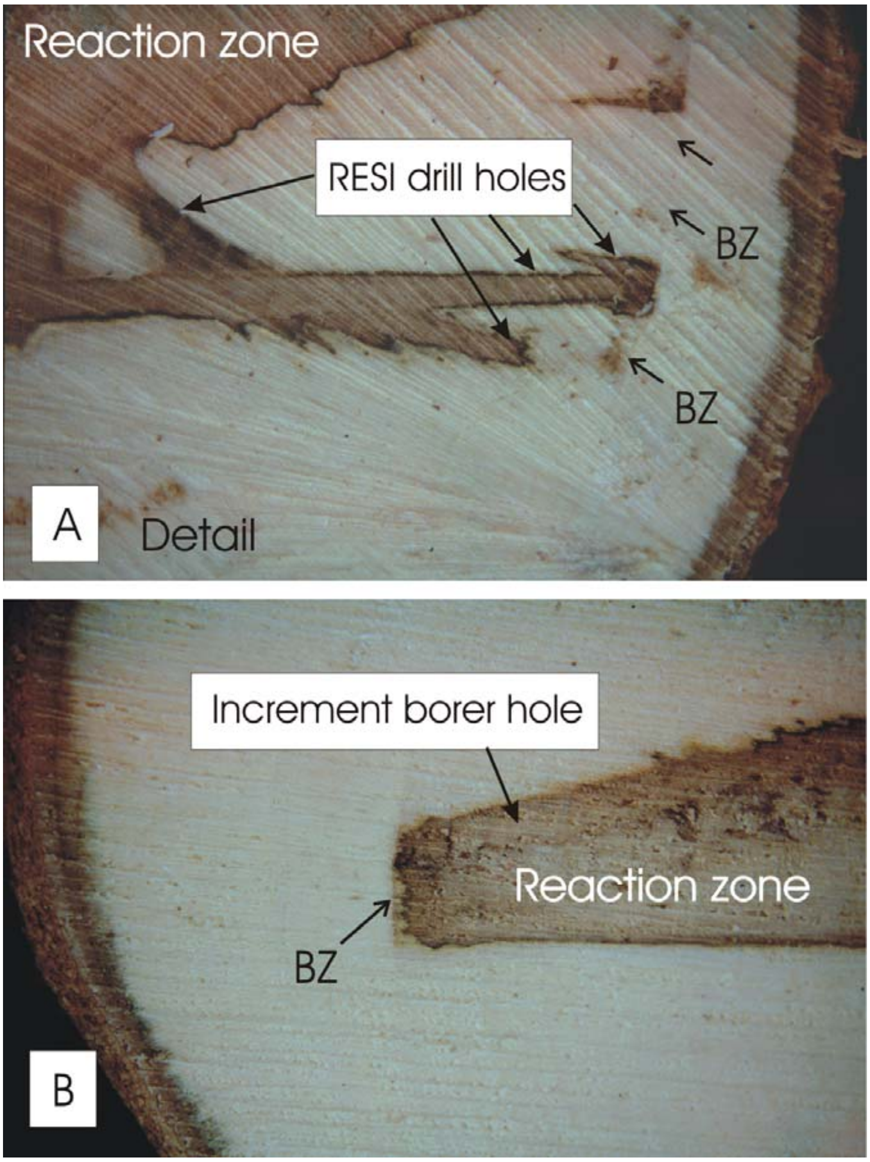

Fig. 31: Effects of increment and RESI drill holes in the wood corpus of a healthy sycamore maple (*Acer pseudoplatanus* L.) **A:** Cross section of the barrier zone formed after RESI drillings, enlarged detail of Fig. 30C. **B:** Barrier zone formation following increment drilling.

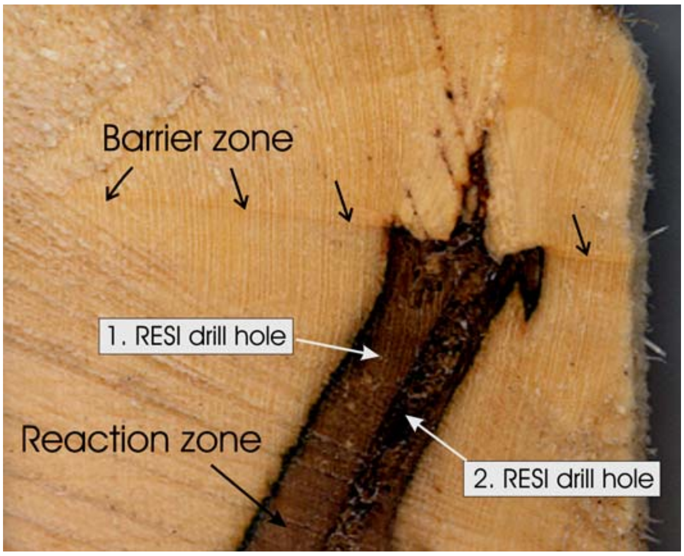

Fig. 32: Cross section of a sycamore maple (*Acer pseudoplatanus* L.), detail: Two RESI drill holes very close to each other caused the formation of barrier and reaction zones. The drill holes were closed by the first annual ring formed after drilling.

The wooden areas that are generally described as reaction zone in the maple trunk consisted of two differently colored zones. A dark-brown zone with polyphenolic inclusions and plugs for vessel closure confined the colored zone to the outside, the light-colored wood tissue. Between the drilling channel and the dark-brown zone, a light-brown zone was located that hardly possessed any phenolic inclusions and plugs. In this light-brown zone, phenolic inclusions were preferably encountered in the wood ray parenchyma cells. It was assumed to be wood tissue that had died off relatively rapidly after the injury by drilling (at the beginning of the test period of 9 years) due to the entry of air. When dying off, polyphenolic, antimicrobial substances were produced and deposited preferably in the longer living wood ray cells. The presence of polyphenolic substances made this zone a reaction zone per definition, as these substances were not found in the adjacent light-colored and heat wood area. Neither did this zone result from any typical heartwood formation process, as *Acer pseudoplatanus* does not form any colored heartwood. This zone may be considered an old, inner, embolism-damaged reaction zone in contrast to the fresh, dark-brown colored outer reaction zone.

With these statements, the three questions asked in the beginning have been answered, namely, how a tree with inner rot and a tree without inner rot react to excessive drilling. A major finding obtained from the studies is that discolorations should never be equalled with decay. A discoloration does not necessarily have to be a decay. Furthermore, wood decaying fungi and decay, i.e. cause and effect, should never be equalled, as a wood decay fungus possibly existing in the drilling channel (fungal spore or hypha) does not necessarily settle there and cause wood rot. The tree may successfully compartmentalize or repel the decay fungus.

Now, the effects of drilling presented shall be evaluated with regard to their hazard potential. The test trees were vital both prior to as well as 8 – 10 years after the first drillings. Drilling did not cause any noticeable loss of vitality of the trees. The reduced integrity and breaking strength of the test trees with an inner rot resulted only from this inner rot. The rot cones that had been extended locally and temporarily by drilling hardly contributed to the general decrease in integrity and breaking strength. It may therefore be concluded that the drilling techniques that are used in a limited and non-excessive manner in practice are not hazardous to the tree. As the increment borer had a larger diameter than the RESI drilling needle, the former caused accordingly larger discolorations in the test trees. However, this did not make it more or less hazardous.

Does the tree controller have to drill? If he finds a warning signal on the tree, e.g. fruiting bodies of wood-decomposing fungi, trunk swelling, etc., he has to make a deeper investigation. If he does not do it, he acts in a grossly negligent manner according to German legal decisions. If, for instance, the tree controller strongly suspects the tree of having an inner rot (e.g. in case of bulge formation at the trunk), he is obliged to determine the residual wall thickness and assess the potential hazard on the basis of failure criteria. At the moment, residual wall thickness and wood quality can only be determined with highest reliability using drilling techniques. This means that a tree controller has to drill in case of a strong suspicion so as to verify the hazard caused by the tree or he has to avert possible danger for man and fell the suspected tree. If the only alternative to drilling is felling, any “tree-friendly” controller will decide in favor of using drilling techniques.
In human medicine similar decisions have to be made for cancer diagnosis with punch biopsy for example. So invasive methods are common also for diagnosis of diseases in human bodies.

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