Collapse phenomena in eucalypts *

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Summary. Trees belonging to the genus Eucalyptus are specifically prone to developing damage due to collapse soon after felling. Observations on 150 trees of five Eucalyptus species from two growth sites, indicate that collapse occurs in the wake of the receding liquid water supposedly moving from the heartwood fibres into the rays, and from there to the vessels of sapwood and to the pith (heart shakes), respectively from where it evaporates. Collapse was observed over the entire cross section of stems. Anatomical evidences suggest a collapse modifying process across the stem from the pith to the cambium. Generally, the stresses generated cause tangential flattening of fibres and open radial/longitudinal splits in the tissue. Fibres seem to collapse in radial strings and also in small lumps scattered over the xylem. Based on their effect, the level of collapse stresses must be greater than the cross-grain tension strength but smaller than the longitudinal compression strength of the wet wood. The results suggest that the prediction of collapse susceptibility of standing trees is possible.

Introduction

Collapse seems to generally affect woody plants. In the relevant literature some 10 softwood and more than 30 hardwood genera are reported to show damage caused by collapse (Bariska et al. 1987a). Eucalyptus species are important for planting in the southern hemisphere but are particularly prone to collapse damage soon after felling. Collapse is generally considered to be one of the worst kinds of damage that can occur naturally in wood, and it often results in uneven, rough surfaces and/or warping of sawn timber. It is the excessive shrinkage of timber which can start well above the fibre saturation moisture content of wood and take place also in the hygroscopic range. Indications of its occurrence are radial/longitudinal splits normally in the heartwood. These cracks release the cross grain tension stresses which are created by the initial caving-in of the cells. Collapse substantially affects the strength properties of wood, especially the cross-grain tension strength and the shear strength, it increases the costs related to timber drying, and lowers the exploitable volume of wood. As to date, the only proper, cost effective remedy seems to be the selection by breeding.

Collapse is the result of the interplay between the liquid water content of wood on the one side and the anatomical structure, ultrastructure and the strength of the anatomical units on the other. Although this knowledge is fairly well established the actual process of collapse is still not well understood. The aim of this study is to relate the established knowledge on the collapse to observations made in the plantation and in the laboratory.

Materials and methods

Heavily collapsing and non-collapsing stems of five Eucalyptus species (*E. elata, E. fastigata, E. grandis, E. macarthurii* and *E. nitens*) from two growth sites in Natal, South Africa, were identified after felling. In the plantation the formation of splits was observed over six days at the bottom end of each log.

For the investigation with a scanning electron microscope in the laboratory, disk samples were cut from each selected tree. The radial/longitudinal specimen surfaces were prepared for observation without wetting by water. The final clamping and cutting direction was radial.

Causes of collapse in wood

A number of biological and physical factors are known to cause collapse. These include the following:

Collapse due to transpiration effects

The water uptake by plant roots is an active biological process making use of osmosis and ion exchange. The water transported upwards in the sapwood of the stem is, therefore, in a de-gassed state i.e. entirely free of dissolved air. For this reason the water columns can transmit quite substantial tension stresses without the development of air bubbles, cavitation, in the vessels. If the transpiration in the crown exceeds the water supply from the root due to insufficient water in the soil during drought or frost periods, a large hydrostatic tension gradient may be built up in the stem. Because the cross grain tensional strength of the wood substance in green state is very low, separations and collapse at microscopic and macroscopic level are highly probable (Reid, Mitchell 1991; Lutz 1952). Evidences indicate that collapse also occurs in living trees (Kaumann 1964 b).

Collapse due to surface tension of water

Tiemann (1942), while working with collapse susceptible species, recognized the existence of pulling forces created by water menisci in the cell capillaries of sawn wood, and stated that these forces may be accountable for the excessive shrinkage, the collapse, above the fibre saturation region.

Ellwood and Ecklund (1963), by replacing water in freshly cut green wood with organic liquids having lower surface tensions than that of water, found that the incidence of collapse was markedly reduced or completely eliminated. It was also found, however, that the extent of collapse could not fully be explained by the laws of Young-Laplace and Kelvin, and so it was assumed that other factors were involved in the collapse process, for example bulking, creep and stress relaxation.

Collapse due to hydrostatic tension

When hydrostatic stresses become active in the micro-voids of the cell wall capillaries, the diameter of the voids decrease which creates hydrostatic tension in the surrounding cell wall regions (Barkas 1949). In minute capillaries the surface tension of water menisci can increase beyond the strength of the capillary walls and the voids cave in. Thereby, the material around the void is loosened and a number of smaller voids are generated which undergo a similar process. The result of this is the distortion of the entire cell wall and consequently the collapse of the cell and the tissue.

Collapse due to moisture gradient

According to Clarke (1972), the drying generates tension within the outer, drier zones of sawn timber which puts the inner, wetter zones under compression. Since wood under compression is weaker than when under tension, and because wet wood is weaker than dry wood, collapse may be observed in the inner green zones of the timber. This, however, will only occur if a large moisture gradient exists and if the moisture content in the outer zones drops below fibre saturation. This drying damage is known as case hardening and is indicated by tensional checks in the dry surface zones and cell deformations and collapse in the inner zones.

Collapse due to anatomy

Hardwoods containing reaction wood zones, the tension wood, may show collapse due to shrinkage at any moisture content. Wardrop and Dadswell (1955) showed that this collapse is caused by differences in the chemical composition of the wood substance: For example lack of lignin, or some anatomical features, such as the orientation of microfibrils in the gelatinous layer of the fibres, can cause dimensional changes upon moisture movement.

Collapse is thought to occur in material with low strength and many micro-pores, but the statistical variation of these independent features makes it extremely difficult to demonstrate a direct relationship between anatomy and collapse susceptibility of wood (Kaumann 1960).

Results and discussion

Generally, splits begin appearing two days after felling, usually midway between the pith and the cambium regions. In time, collapse splits tend to extend in both direc-
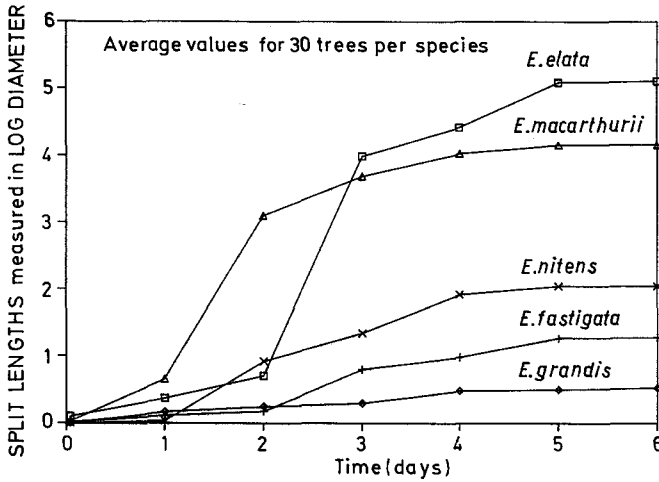
Fig. 1. Development of collapse splits at the bottom end of stems in five eucalypt species

tions, towards the pith and the cambium as seen on the bottom end of the log. Figure 1 depicts the collapse splits that have developed over a period of time. It indicates that the collapse is a rapid process; the majority of the splits have developed between the second and fourth days. The collapse damage seems to be complete five days after felling, at least in the end zone of logs. As regards the collapse susceptibility, the species show large variation: *E. elata* and *E. macarthurii* seem to be significantly more susceptible to collapse than *E. nitens, E. fastigata* or *E. grandis*. The least damage was observed in *E. grandis*. Interestingly, the severest damage was recorded in *E. elata* in which collapse had developed with an initial delay.

Figure 2 shows the frequency distribution of damage as observed in the five species. Remarkable is the large variation of the values especially in *E. elata* and *E. macarthurii*, the species with the most severe collapse. This fact can be advantageously exploited for breeding if there is intention to reduce collapse susceptibility. Additionally, Fig. 2 suggests that the growth site is not influencing the collapse formation. The extent of damage seems to be equally distributed on both growth sites.

A marked interaction was observed between heart shakes, growth stress splits and collapse splits. For instance, collapse splits were frequently transformed through growth into "heart shakes". Normally, heart shakes are the first damage resulting from stress adjustments occurring in the log due to felling; They originate from the pith and are confined to the heart region. Because these apparent "heart shakes" originated in the xylem region, they were classified as collapse splits. If, however, these collapse splits extended to the perimeter of the log and spread along its side, they were re-classified as growth stress splits. This interaction between collapse splits and growth stress splits occurred frequently. The damage due to collapse obviously weakens the log, and if growth stresses are active in these regions, the spread of the otherwise stabilized collapse splits is caused.

During the observation period the weather suddenly changed from dry-warm conditions to wet-cold conditions. Within one day the growth of collapse splits
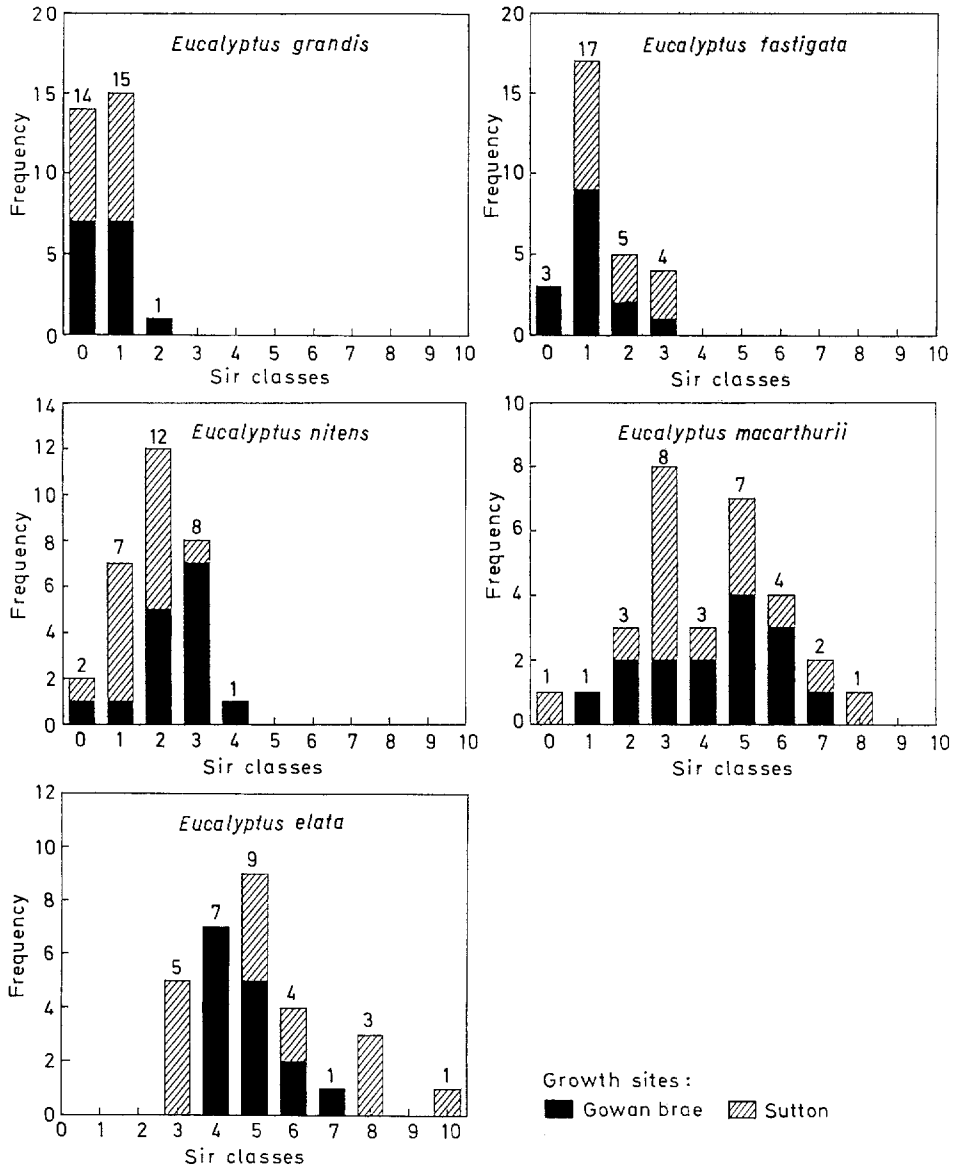
Fig. 2. Frequency distribution of collapse damage in five eucalypt species are measured on the sixth day after felling. The influence of growth site is negligible. The SIR value is defined as the sum of the collapse split lengths as measured on the fifth day, or later, after felling divided by the diameter of the log (Bariska M. et al. 1987b)

stopped in the smaller logs. With the continued cold and rainy weather the growth of all kinds of splits came to a halt and some splits even seemed to start closing up again.

The forces leading to collapse splits appear to have a long range character because the damage seems to be bigger in large stems or planks than in smaller ones (see also Kanagawa, Hattori 1978). However, the physical size of the splits indicate that the
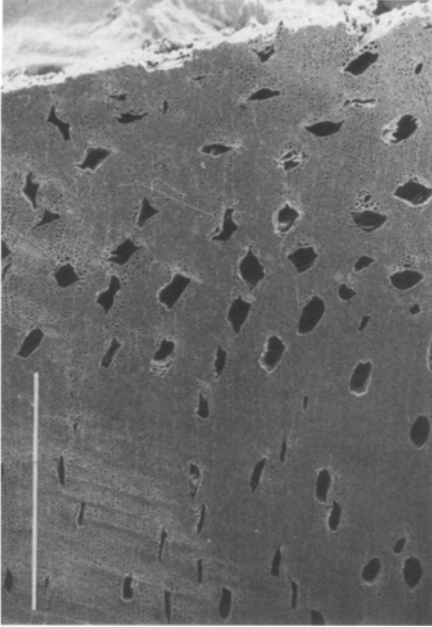
Fig. 3. Collapse takes place perpendicularly to the grain as shown here in a freshly sawn *Eucalyptus macarthurii* block. Close to the bock surfaces (top and left edges) fibers will be flattened parallel to the newly cut planes as indicated by the shape of the deformed vessels. Bar 1 mm

forces are active in shorter ranges, of centimetre and decimetre magnitude. Within this range the stresses remain below the ultimate strength of the wood. The relatively equally spaced splits depict the boundaries of such ranges. The level of stresses generated is smaller than the longitudinal compression strength of the bulk wet wood because the longitudinal damage is a bow or a twist at the most, however, it is larger than the cross-grain tensional strength of wet wood.

Collapse damage is essentially transverse. This fact is well illustrated in Fig. 3 which depicts a *E. macarthurii* specimen, cut to size in the green state and subsequently seasoned. The long axis of the flattened vessels lay parallel to the lateral surfaces indicating the prominent transverse direction of collapse stresses. In this specimen the collapse was caused by the drying process.

Collapse splits usually appear midway between the cambium and pith regions. Sapwood, i.e. the outer zone of a stem, is usually free from splits. There are a number of factors possibly preventing the split formation despite the occurrence of collapse in sapwood. Firstly, there are growth stresses present in every individual tree which cause tension stresses in the tangential direction and compression stresses in the radial one. The nett effect of the combined collapse and growth stresses is a slight reduction of the stem diameter, especially effective in the outer zone of the stem. Secondly, any radial deformation of the size $-\Delta R$ calls for a tangential one of $-\Delta T$, and mathematically it can be shown that at small changes $-\Delta R \simeq -\Delta T$. Thereby, the tangential stresses will be reduced preventing the formation of splits. Thirdly, sapwood has a higher moisture content than heartwood rendering the latter more prone to collapse. Fourthly, heartwood has a more juvenile character and thus will have a higher collapse susceptibility than sapwood (Elliot 1930; Pankevicius 1962). Finally, stresses

in heartwood are generally reduced by split formation thus, the residual stresses will have only little effect on sapwood.

The pith also seems to be less affected by collapse splits. Presumably, the split causing stresses are dissipated by the heart shakes which compulsorily appear in the pith of every individual tree.

Microscopic observations revealed the presence of collapse from the cambium region through to the pith region, over the entire cross section of stems (Fig. 4a–c). After examination of the five eucalypt species, including low and high splitting individuals, it can be stated that collapse was found everywhere to a greater or lesser extent. Even in stems seemingly not affected by collapse, lumps of cells were found to show a progressed stage of cell closure (Figs. 5 and 7a–c).

Collapse seems to start in thick walled fibres. As observed elsewhere, vessels, parenchyma cells and thin walled fibres showed deformation only in response to the collapse of the nearby thick-walled fibres (Wilkins, Wilkes 1987). Vessels often indicate the prevailing direction of collapse stresses: In the cambium region they normally remain round, suggesting a rather homogeneous distribution of stresses in the main anatomical directions. In the region midway between the cambium and the pith, vessels are frequently distorted and become radially elongated slits, or occasionally polygons, indicating the presence of competing tangential and radial forces (Fig. 5). In the pith region the vessels generally become radially orientated slits.

Over the whole cross section of stems, the fibres caved-in in a tangential direction 5–10 times more often than in a radial direction, suggesting that the collapse stresses are essentially tangentially orientated (Fig. 6). Alternatively, it could also mean that the mechanical resistance of the fibre cells in tangential direction are lower than those in the radial direction in which the wall pits and ray cells exert a reinforcing effect. For instance, in one *E. macarthurii* sample some 53% of fibres were flattened in tangential direction, 42% in intermediate and 5% in radial direction, resulting in a ratio of tangential to radial stresses of 10:1. At odd places the fibre cells closed up completely, thus forming nests of densified tissue. This was again found to occur mostly in transverse directions. In the longitudinal direction no buckling or cell shortening was observed (Fig. 8).

Table 1 identifies the size range of ultra structural voids in which, according to the theory of Tiemann (1942), collapse may occur. It relates the idealized diameter of a cell wall capillary to stresses exerted by the water menisci. In minute capillaries water condenses substantially below its saturating humidity level due to capillary depression. The surface tension, which is active in the meniscus of the capillary water, must thus exceed the wall stiffness to cause collapse.

According to these calculations, collapse takes place within the cell walls and not in the cell lumina. If collapse occurs in voids with a diameter of 0.3 μm, then it should still be possible to discover clues to the collapse process with the aid of a scanning electron microscope. To this end, the surfaces of some splits opened by the collapse stresses in the different species were examined. In *E. macarthurii* and *E. elata,* which are the most susceptible species to collapse among the five species investigated, buckling of the ray parenchyma cells was observed along the long axis (Fig. 9). This has been expected due to the overall radial collapse shrinkage of the stems. Minuscule wrinkles running parallel to each other are visible. This suggests that separation of lamellae at a constant depth below the cell surface occurs. The width of a wrinkle is
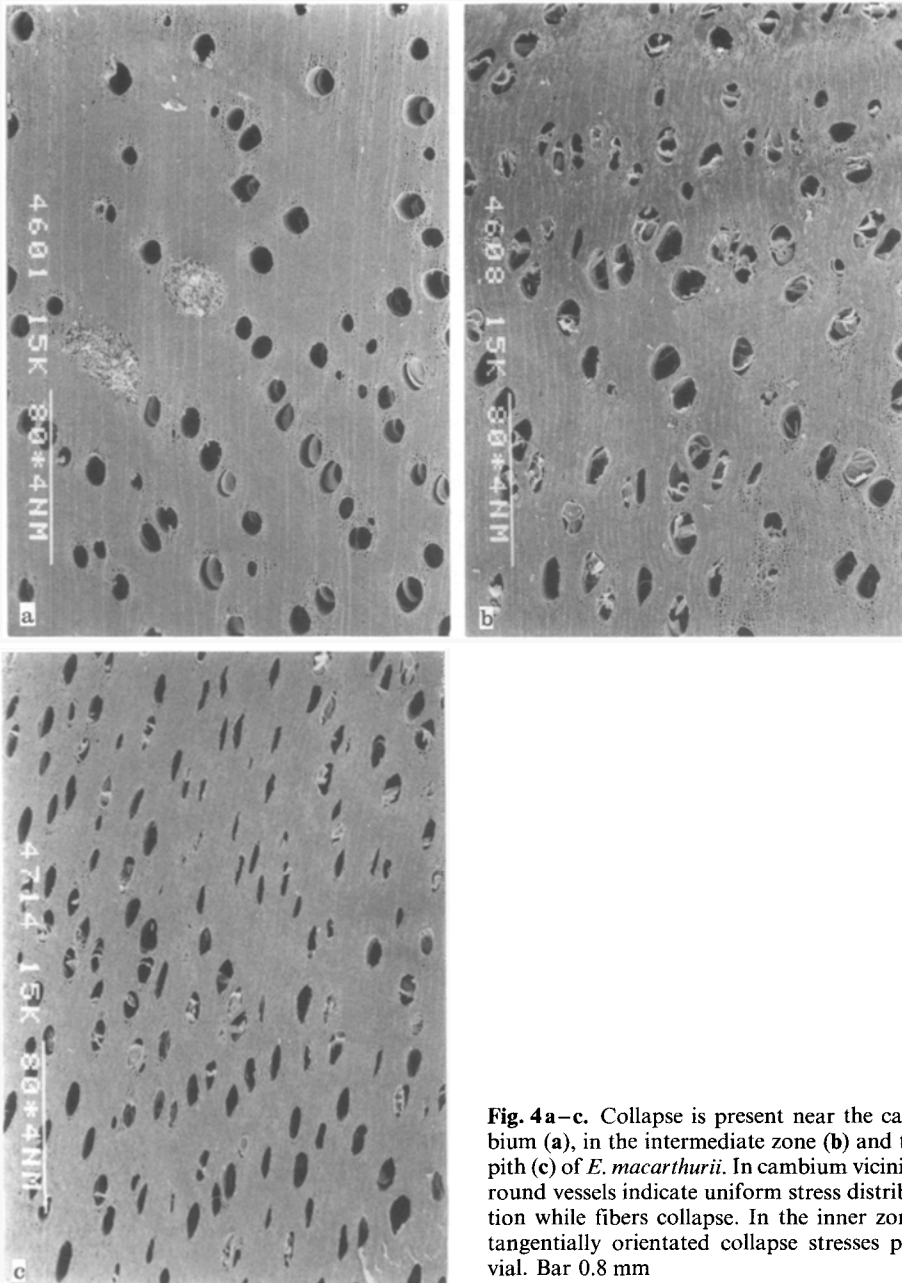
Fig. 4a–c. Collapse is present near the cambium (a), in the intermediate zone (b) and the pith (c) of *E. macarthurii*. In cambium vicinity, round vessels indicate uniform stress distribution while fibers collapse. In the inner zones tangentially orientated collapse stresses previal. Bar 0.8 mm

0.3 μm and equals the double thickness of a tightly folded sheath. Because this lamella thickness corresponds well to that of the S1, it will be assumed that the interface between the S1 and S2 opens in response to the overall collapse stresses. This is in accordance with Kučera and Bariska (1985) who found that the S1 and S2 interface is one of the weakest points of the cell wall. In the cavities generated between the S1
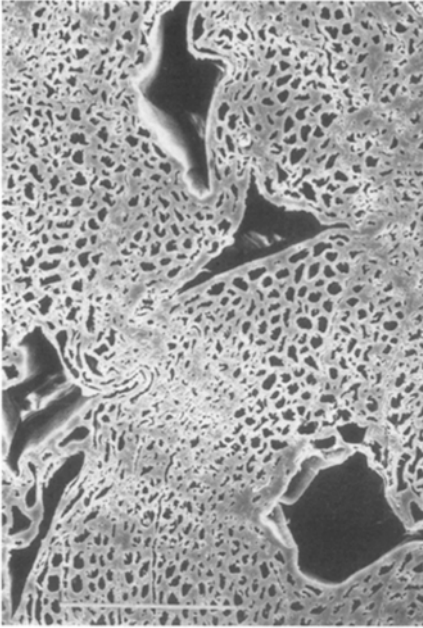
Fig. 5. Competing tangential and radial collapse stresses in the fiber tissue as indicated by the distortion of vessels in *E. macarthurii.* Bar 0.15 mm
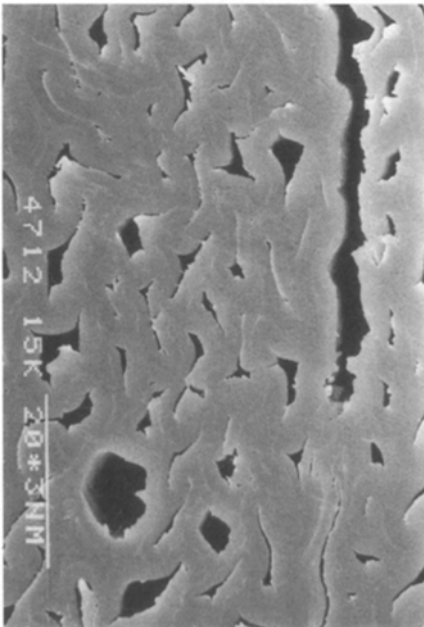

Fig. 6. Fibers of *E. macarthurii* are some 5 ... 10 times more often flattened in the tangential direction than in the radial one. Bar 20 μm

and S2 layers true collapse of the ray parenchyma cell walls may occur. This phenomenon was, however, not observed within fibres of *E. macarthurii* and *E. elata* or within any other cell type of the other species. From the above it is concluded that collapse is limited to voids of fibre walls on the one hand, and to wall lamella gaps in parenchyma cells on the other with a size beyond observable limit at a magnifica-
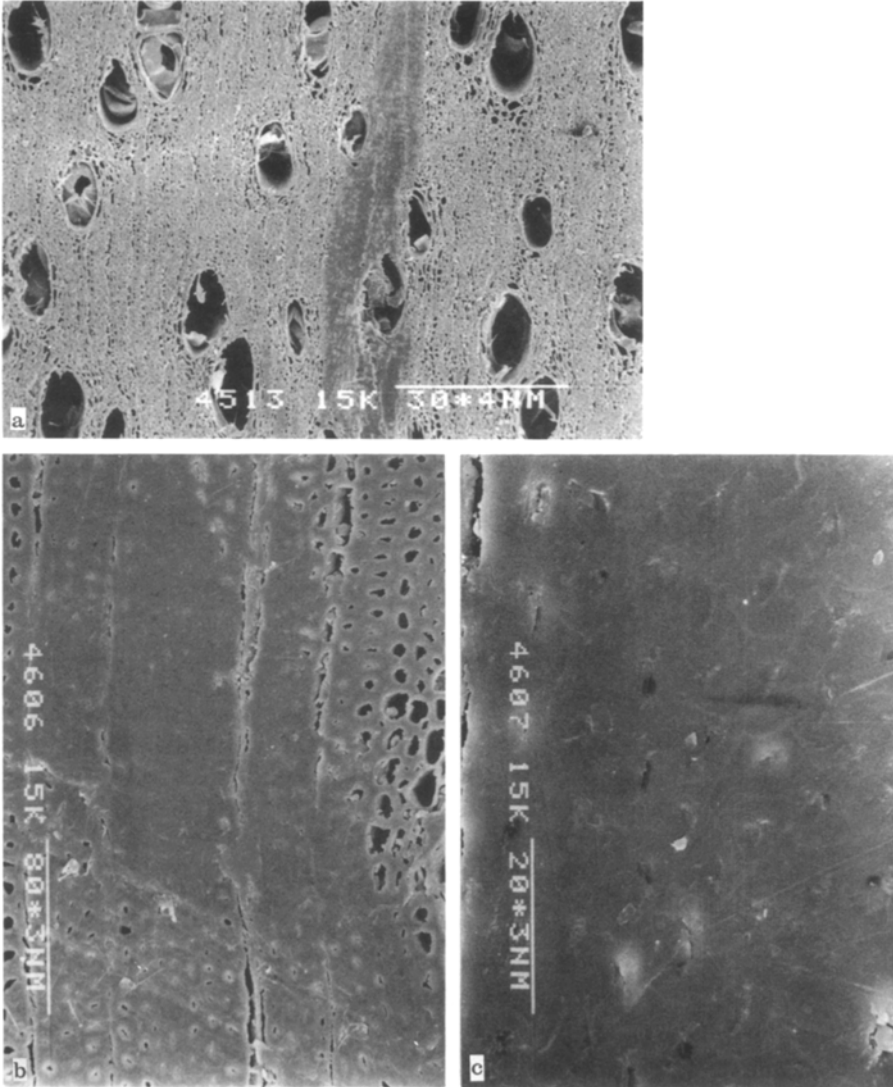
Fig. 7 a–c. Patches of completely collapsed fiber cells were found scattered in the xylem of *E. macarthurii*. Bar **a** 300 μm, **b** 80 μm, **c** 20 μm

tion of 10,000 ×, i.e. 0.2 μm. Accordingly, the size of collapsible voids would have a diameter of 0.2 μm or less, and the stress correlated with it of 2.4 MPa or more.

The question can be raised at this place again as to how the cells become empty of water so that the water trapped in the capillaries can begin to exert a pulling force to cause collapse? The answer may be as follows:
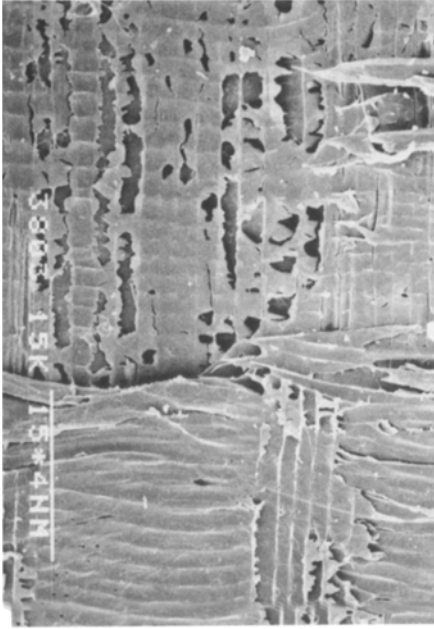
Fig. 8. Fiber cells do not seem to be affected longitudinally by collapse. *E. macarthurii*. Bar 150 μm

Table 1. Surface tension of capillary condensed water as calculated by the Kelvin equation (Stamm 1966) related to void size and collapse of the wood substance

Ambient relative humidity at 20 °C %	Diameter of capillary filled with condensed water μm	Corresponding anatomical void	Surface tension of water meniscus at 20 °C MPa	Remarks
80	0.008	Meniscus along 10 H_2O molecules	40.0	↑ Collapse to occur
90	0.022		14.2	
93.5	0.03	Cell wall pores	9.7	
97.5	0.08	Small size inter-	3.6	↓
98.2	0.12	cellular voids	2.4	↑ Wet cell wall
98.8	0.2		1.4	substance can
99.3	0.3	Pores in pit	0.97	withstand
99.93	3.0	membranes	0.097	↓ collapse
99.993	30.0	Cell lumina	0.0097	

To generate a situation leading to collapse the liquid water must be drained away from the wood through the existing channel systems. Water escapes the easiest from the sapwood. This leads to a hydrostatic gradient between the sapwood and heartwood. Since the vessels in the heartwood are usually blocked by tyloses, the water will be drained away through the rays from the heartwood. Thus, the fibre cells in pith and
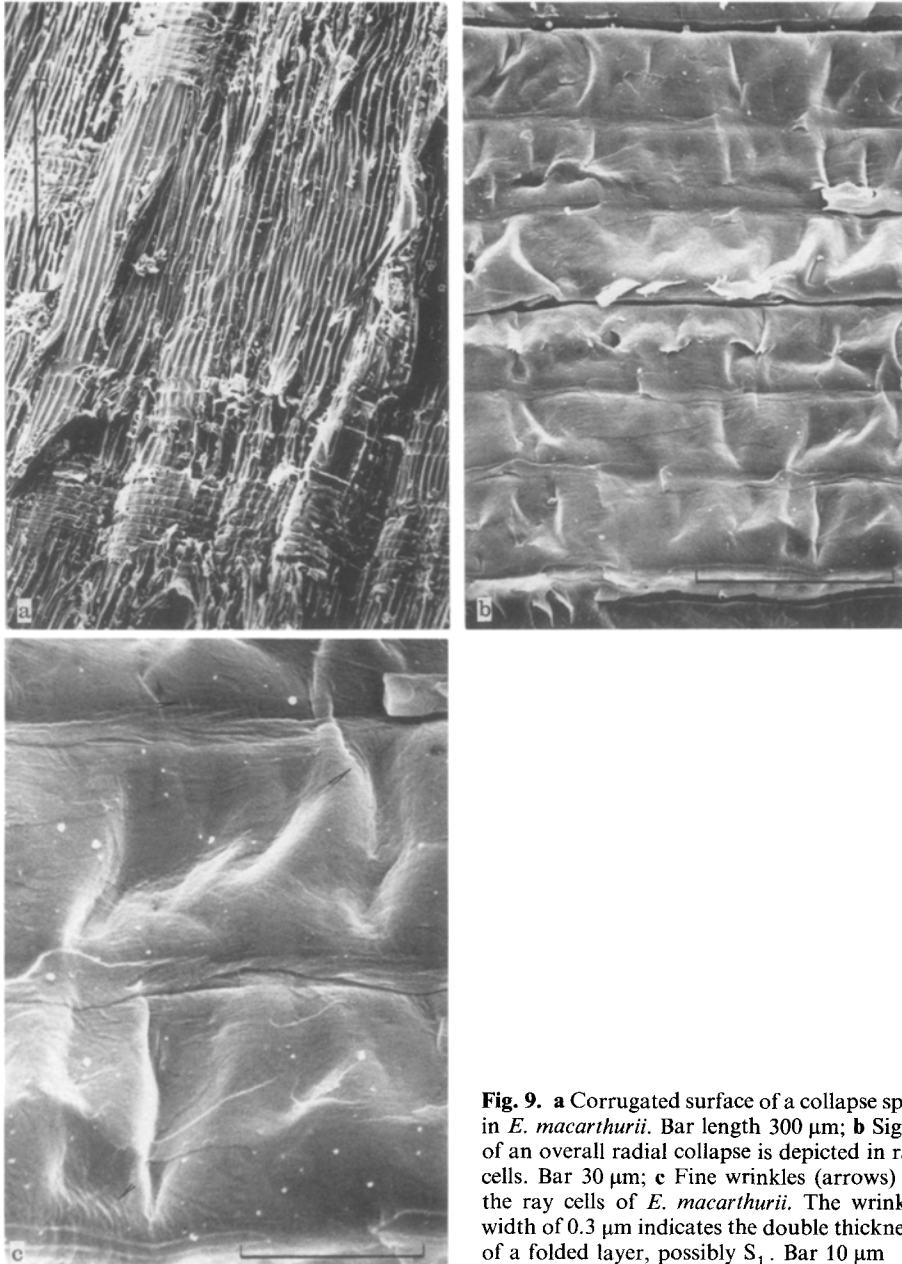
Fig. 9. **a** Corrugated surface of a collapse split in *E. macarthurii*. Bar length 300 μm; **b** Signs of an overall radial collapse is depicted in ray cells. Bar 30 μm; **c** Fine wrinkles (arrows) in the ray cells of *E. macarthurii*. The wrinkle width of 0.3 μm indicates the double thickness of a folded layer, possibly S_1. Bar 10 μm

heartwood region would be emptied first. If this is the case, then the prevailing direction of water movement from the heartwood fibres would be tangential into the neighbouring rays. This would possibly result in rows of radially aligned, tangentially collapsed fibre cells. This feature was effortlessly spotted, when searched for, using the microscope (Fig. 10).
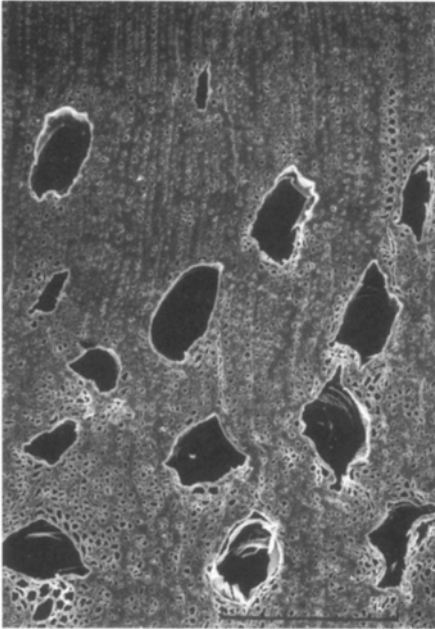
Fig. 10. Radial rows of collapsed fibers are a common sight especially in the late wood. *E. macarthurii.* Bar 300 μm

If the above sequence of event is accepted as true, many of the otherwise incongruent observations fit into the overall picture:
– The first indications of stem collapse appeared two days after felling and seemed to last for a number of days. The drainage of liquid water from the heartwood would be a time-delayed process which might take up only a few days.
– Over a period of time, the collapse splits expanded towards the cambium and the pith, thus marking the tail of receding water into the open.
– Sapwood does not show much collapse damage because its liquid water content is being continuously replenished from the heartwood. This sequence of events is similar to that of the timber reconditioning in the drying practice.
– Collapse is a transverse phenomenon. Hard evidence was obtained showing tangential collapse, less evidence to prove radial collapse and so far no evidence pointing to longitudinal collapse.
– Generally, collapsed fibres were found in contact with rays and not with vessels.
– Traces of collapse were also detected in the ray cells.

Conclusions

The observations obtained on the development of collapse damage in eucalypt species, both in the field following felling and in the laboratory, were evaluated in light of the findings obtained in the relevant literature. The formation of collapse can therefore be summarized in the following way:

On felling, the sapwood looses its liquid water content readily; from some eucalypt trees water runs out. This water flows through countless continuous threads, which wind their way through the wall openings of the heartwood fibres into the rays, from the rays into the sapwood vessels, from where it drips out or evaporates. Even if the heartwood fibres become empty with time, a continuous sheath of water will remain lining the cell and capillary surfaces. In capillaries with diameters less than 0.2 μm, the tension forces of the menisci become acitve, and the saturated fibre cell wall are placed under excessive hydrostatic tension. Thus, collapse starts after the cell luminae become empty. In *Ochroma lagopus* (balsa) this occurs at a moisture content of 600% (Chafe 1985) and in *Eucalyptus regnans* at 120% (Kaumann 1964a).

Because the water moves from the heartwood fibres to the rays in a tangential direction the collapse stresses will accordingly also act in a tangential direction. A radial split between cells is formed when these fibres cave-in or separate. Because the movement of water from the heartwood to the sapwood is in a radial direction there will be an accompanying radial stress component which is, however, smaller in value than the tangential one. This radial tension stress pulls the heartwood towards the cambium, which explains why the splits expand towards the sapwood during the collapse process. It also explains why the heart shakes in collapsing stems grow much longer and wider than those in non-collapsing ones; they often join into the collapse splits.

In sapwood the direction of water movement is mixed. It first moves in a tangential direction from the fibres to the rays, followed by radial movement to the next vessel and finally in a longitudinal direction out of the timber. Collapse stresses also develop in the sapwood fibres, but because water is steadily replenished from the heartwood zones, they develop much later, are smaller and more uniformly distributed. A cycle develops in which the fibres collapse only to be reconditioned by water coming from the inner parts. This supply of water becomes irregular towards end of the water loss process. The counterbalancing action of growth stresses, which are present in eucalypts, might also prevent the formation of more severe collapse damages in sapwood. Large collapse splits are missing in the sapwood. One of the reasons might be the fact that the majority of stresses have already been released by splits in the heartwood.

Since the evaporation of water from timber is dependent on environmental conditions, climatic fluctuations will slow down or accelerate the collapse formation. The observation that wet-cold weather caused collapse split development to stop confirms the above comments.

No direct effect of site on the collapse formation was observed in this investigation, although the growth site was found to have a strong influence with eucalypts elsewhere (Guernsey 1951). However, the controlling role of the species was confirmed. In terms of collapse damage the species investigated can be ranked as follows, starting with the species showing the least damage and ending with the worst one: *E. grandis* < *E. fastigata* < *E. nitens* < *E. elata* < *E. macarthurii.*

These findings substantiate the hope and that a technique to forecast the collapse susceptibility of standing trees can be developed on the basis of anatomical features, especially taking the extent of tyloses formation in heartwood vessels, the overall ray structure and the wall thickness of fibres into account. Ongoing investigations are dealing with this possibility even though little success was obtained in the past (Ilic, Hillis 1985).

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