RADIATA PINE BARK — ASPECTS OF MORPHOLOGY, ANATOMY AND CHEMISTRY

R. SANDS
CSIRO Division of Soils, South Australia

(Received for publication 22 April 1974)

ABSTRACT

The gross morphology of **P. radiata** bark is quantitatively described and the periodicity of periderm development is discussed. Variability in anatomical components, and in extractives obtained with petroleum ether, ether, ethanol and hot water extraction of the bark is assessed.

Preferential use of the bark from the butt log as a source of phenols for adhesives, and of cork is advocated.

INTRODUCTION

Although considerable research effort is being given to the efficient utilisation of *Pinus radiata* D. Don bark, such work often proceeds with insufficient knowledge of the basic material and its variability. Certain aspects of the morphology, anatomy and chemistry of *P. radiata* bark are examined here and their relevance to more efficient bark utilisation discussed.

In this paper phloem is defined as all tissue between the vascular cambium and the last-formed periderm; rhytidome refers to all tissue between and including the last-formed periderm and the outside of the stem; and bark is a non-technical term equivalent to phloem plus rhytidome. Only mature tissues were examined and therefore any trace of primary tissues (primary phloem, cortex and epidermis) would be in the rhytidome.

MORPHOLOGY

Bark is generally measured to give information on the encased wood. When bark itself is the product of interest existing data are inadequate to describe it.

Materials and Methods

In April 1973, five *P. radiata* trees of each of three ages (25, 31 and 45 yr) from nominal site quality IV plantations (Lewis, 1954) in the Mt. Gambier district of South Australia were felled as close to the ground as possible. (These trees were used for all three parts of this study.) Total height (h) was recorded and discs were cut at 1.22 m (4ft, to suit the utilisation practice of the area) intervals from ground level to the highest point where the stem was clearly defined. The lowest disc was cut at the 0.15 m level. The north point was marked on the lower face of each disc.

For each disc was recorded: the number of annual wood rings; the maximum number of periderms; the bark thickness (T_b) and phloem thickness (T_p) at the north, east, south and west point of each disc (measured with vernier calipers); and the diameter over bark (D) and under bark (d) (measured with a diameter tape).

The lowest few discs in each stem had bark in broad ridges separated by narrow fissures whereas those above had relatively smooth bark. The transition point (h_t) was quite abrupt and easily recognised. For discs below this point thickness was measured to ridges (as would be the case if using a Swedish bark gauge on the standing tree). Bark cross-sectional surface areas (S_b) below the transition point were measured with a dot grid while those above, as well as all phloem cross-sectional surface areas (S_p), were calculated geometrically assuming the vascular cambium, the last formed periderm and the outside of the stem formed concentric circles separated by mean thickness. The per cent bark in each cross-section (B%) was also calculated.

Results

Means of the variables for each age group at different heights are given in Table 1. The relation between T_b and h fitted an empirical curve of the form:

$$T_b = b_o + \frac{b_1}{b_2 + h} \qquad (1)$$

where b_o, b_1 and b_2 are constants.

The relation between S_b and h fitted a curve of similar form:

$$S_b = b_o + \frac{b_1}{b_2 + h} \qquad (2)$$

The curves for T_b and S_b for each age group are given in Figs. 1 and 2 respectively. Although these curves fitted the relationship very well indeed, the constants could not be meaningfully related to any measured variable. The decrease in both T_b and S_b with increasing h was initially rapid after which the rate of decrease declined.

Generally the effect of orientation (cardinal direction) on T_b was not significant and there were no consistent trends. Variability in T_p both around and up the stem was slight and no trends were apparent (Table 1). Variability in T_p between stems of the same age and of different ages (Table 2) was also small relative to that observed in T_b Therefore T_p could be regarded as constant for volume distribution studies without undue loss of precision.

Bark volume can be obtained by integration of equation (2), as follows:

$$V_B = \int_{h_1}^{h_2} \left(b_o + \frac{b_1}{b_2 + h}\right) dh \qquad (3)$$

where V_B = volume of bark between heights h_1 and h_2.

Bark volume was concentrated in the lower part of the stem, above which S_b declined most rapidly (Fig. 2). B% was also greatest in this part (Table 1). Since T_p was effectively constant the proportion of phloem to bark increased with height in stem (range 4% to 95%). B% of whole stems did not differ significantly between age groups and averaged 10.2% (Table 2).

The transition point (h_t) increased with age and h (Table 2). Over the range

TABLE 1. The number of annual wood rings, maximum number of bark periderms, diameter over bark (D), diameter under bark (d), bark thickness (T_b), phloem thickness (T_p), bark cross sectional surface area (S_b), phloem cross-sectional surface area (S_p), and per cent bark in cross section (B%) at various heights (h) in *P. radiata* stems aged 25, 31 and 45 yr. (Each figure the mean of 5 individual tree means. Average standard errors (Av. S.E.) shown.

	h (m)	Annual Rings	Max. Periderms	D (mm)	d (mm)	T_b (mm)	T_p (mm)	S_b ($mm^2 x10^{-3}$)	S_p ($mm^2 x10^{-3}$)	B%
Age 25 yr.										
	0.15	25.0	20.8	350	304	23.4	2.06	16.0	2.00	17.7
	1.22	23.6	15.8	311	279	16.2	1.84	10.1	1.65	13.9
	2.44	21.4	10.4	272	251	8.4	1.88	5.8	1.48	10.3
	3.66	20.2	6.4	258	242	5.9	1.86	4.2	1.45	8.1
	4.88	18.6	4.6	247	234	5.0	1.82	3.8	1.35	8.0
	6.10	17.6	3.2	233	221	4.5	1.97	3.2	1.37	7.6
	7.31	16.0	3.0	221	211	3.9	2.20	2.6	1.47	7.0
	8.53	15.4	3.0	211	202	3.6	1.95	2.3	1.24	6.7
	9.75	14.6	2.6	201	192	3.2	2.19	2.0	1.34	6.2
	10.97	12.8	2.6	189	180	3.3	2.04	1.9	1.17	6.9
	12.19	11.4	1.8	168	163	2.6	2.03	1.4	1.07	6.2
	13.41	9.8	2.0	156	148	2.6	2.10	1.3	0.99	6.9
	14.63	8.6	1.6	137	131	2.3	1.92	1.0	0.81	6.6
	15.85	7.0	1.0	115	110	2.1	1.90	0.8	0.67	7.4
	17.07	5.4	1.0	98	93	2.0	1.81	0.6	0.55	8.3
Av.S.E.		-	-	9.2	7.9	12%	0.15	14%	0.11	8.2%
Age 31 yr.										
	0.15	31.0	25.8	445	382	35.2	1.90	28.4	2.48	20.1
	1.22	29.2	20.6	391	347	23.4	1.84	17.3	2.12	15.7
	2.44	27.4	14.4	359	328	14.9	1.87	10.9	2.00	11.6
	3.66	25.4	9.8	337	316	8.9	1.80	7.2	1.83	8.5
	4.88	25.2	7.4	323	304	7.3	2.07	7.0	2.08	8.9
	6.10	24.4	5.4	310	293	6.6	2.02	6.2	1.93	8.5
	7.31	24.0	5.2	305	289	5.4	2.01	5.0	1.88	7.1
	8.53	23.2	5.0	287	272	5.5	2.00	4.8	1.79	7.6
	9.75	22.2	4.4	273	259	5.3	2.25	4.4	1.91	7.7
	10.97	21.4	4.2	262	249	5.0	2.25	4.0	1.83	7.6
	12.19	20.6	3.8	248	236	4.8	2.34	3.7	1.82	7.8
	13.41	19.2	3.6	232	224	4.4	2.24	3.2	1.63	7.4
	14.63	18.6	3.0	211	208	3.9	2.38	2.7	1.64	7.3
	15.85	17.4	2.4	200	191	3.6	2.20	2.2	1.38	7.4
	17.07	16.0	1.8	180	170	3.6	2.40	2.1	1.38	8.2
	18.29	14.8	2.4	168	159	3.4	2.38	1.8	1.28	8.3
	19.51	13.0	2.2	143	135	3.1	2.38	1.4	1.10	8.9
Av.S.E.		-	-	17	17	9.1%	0.27	14%	0.34	9.6%
Age 45 yr.										
	0.15	45.0	38.8	441	372	38.6	1.59	30.4	1.88	21.8
	1.22	44.0	30.0	388	338	26.2	1.58	18.6	1.70	18.2
	2.44	43.2	21.6	369	333	18.6	1.71	13.1	1.83	13.0
	3.66	42.6	15.4	348	316	14.7	1.54	10.6	1.59	12.0
	4.88	42.4	10.6	325	301	10.2	1.66	7.5	1.60	9.6
	6.10	40.8	9.8	318	296	9.5	1.54	7.5	1.45	9.9
	7.31	40.0	8.4	310	288	8.3	1.61	6.3	1.48	8.8
	8.53	39.4	7.8	301	282	7.2	1.57	6.5	1.41	9.3
	9.75	38.2	7.4	292	274	6.7	1.61	5.9	1.40	9.0
	10.97	37.0	6.6	281	263	6.4	1.68	5.4	1.40	8.8
	12.19	36.4	6.8	271	254	6.3	1.65	5.1	1.34	8.9
	13.41	34.4	5.6	262	245	6.1	1.73	4.6	1.34	8.6
	14.63	33.4	5.4	247	232	5.7	1.66	4.2	1.21	8.9
	15.85	31.6	5.2	240	224	5.7	1.70	3.9	1.19	9.0
	17.07	30.0	4.6	230	214	5.5	1.70	3.8	1.15	9.4
	18.29	27.6	4.2	234	202	4.9	1.60	3.2	1.05	9.0
	19.51	25.6	3.8	201	187	4.6	1.74	2.8	1.04	9.2
	20.73	24.8	3.6	187	174	3.8	1.73	2.1	0.97	8.0
	21.95	22.8	3.0	175	161	4.0	1.78	2.0	0.91	9.3
	23.17	21.0	3.6	159	147	4.2	1.81	1.9	0.86	10.1
	24.38	18.4	2.6	134	125	3.5	1.96	1.4	0.80	10.5
Av.S.E.		-	-	11	10	8.2%	0.14	9.8%	0.14	5.6%

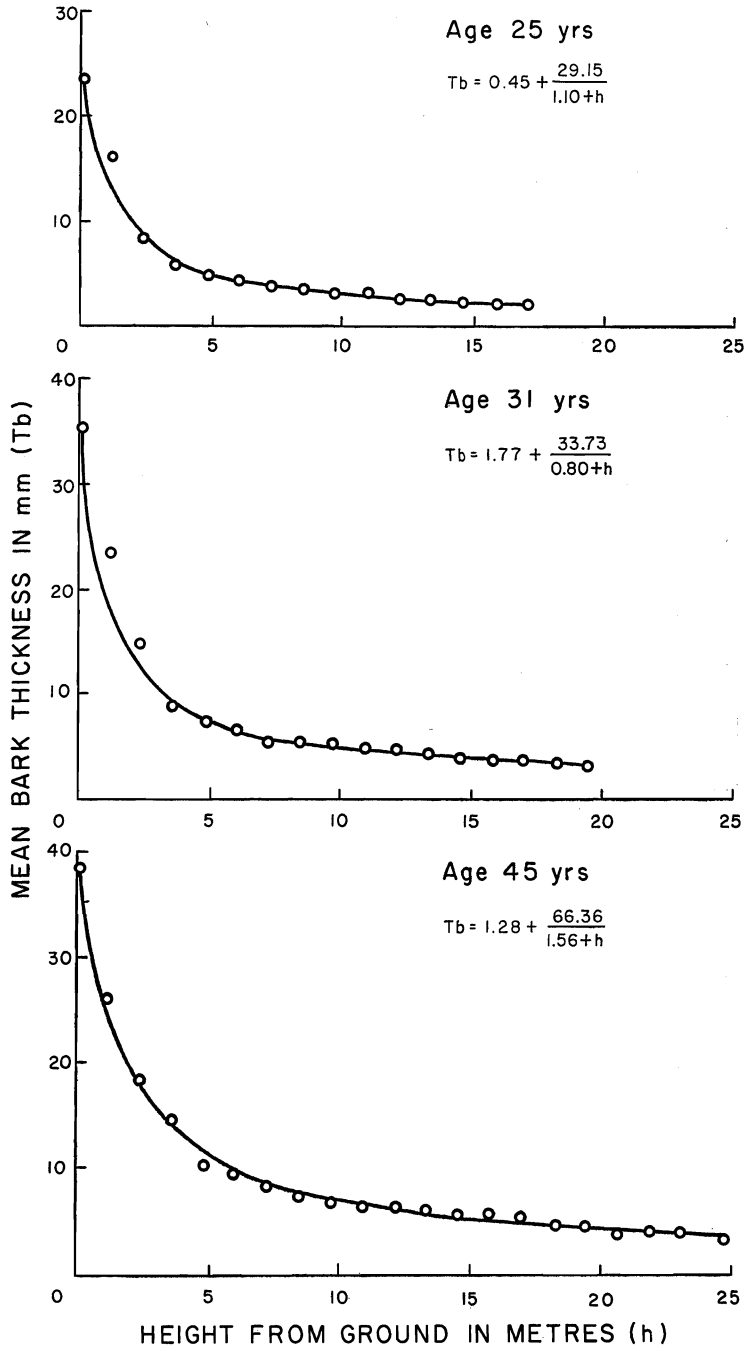

FIG. 1—Relation between mean bark thickness and height in **P. radiata** stems aged 25, 31 and 45 yr.

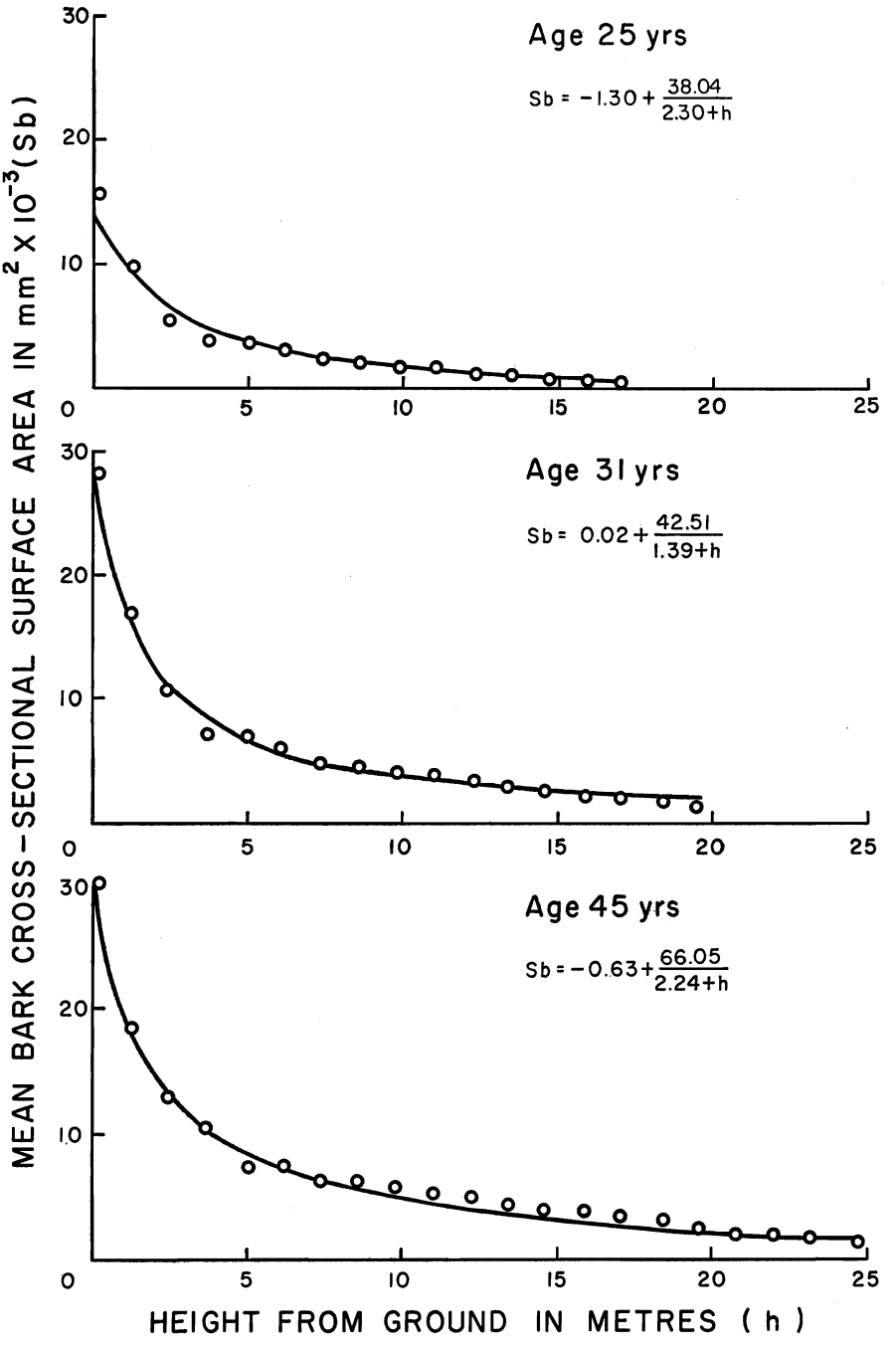

FIG. 2—Relation between mean bark cross-sectional surface area and height in **P. radiata** stems aged 25, 31 and 45 yr.

TABLE 2. Total height (h), transition point height (h_t), phloem thickness (T_p) and per cent bark of total stem volume (B%) in *P. radiata* stems aged 25, 31 and 45 yr.

Age	h (m)	h_t (m)	T_p (mm)	B%
25	21.90	2.16	1.97	11.2
31	25.90	3.84	2.14	10.1
45	30.86	6.00	1.67	9.4
Av.S.E.	0.64	0.50	Grand Mean ± S.E. 1.93 ± 0.10	10.2 ± 0.39

measured, h_t was linearly related to h. Although the number of annual rings decreased steadily with increasing h, the maximum number of periderms, like T_b, decreased rapidly initially after which the rate of decrease declined (Table 1).

ANATOMY

The anatomy of pine bark has been described (Chang, 1954; Srivastava, 1963; Martin, 1969; Howard, 1971). Pine bark lacks fibres and therefore, unlike bark from other species, cannot be used as a fibre source. The main emphasis in this study is on the amount and distribution of periderm components, particularly phellem (cork) cells.

Materials and Methods

Phloem tissue was fixed and dehydrated using the technique of Feder and O'Brien (1968), and embedded in butyl methacrylate. Sections were stained in 0.05% (w/v) Toluidine Blue in 0.25M phosphate buffer pH 5.6.

The sites of resins and polyphenols in bark sections were determined by staining with 7.0% w/v cupric acetate and 7.0% w/v ferric chloride respectively. Normal alcohol dehydration would possibly shift these extractives. To minimise this effect, tissue was initially placed in ethylene glycol (under vacuum) which was successively replaced by polyethylene glycol of increasing molecular weight until embedded in polyethylene glycol 1500 from which sections were cut. The sections were cleared with water, stained and mounted in glycerol.

Rhytidome proved difficult to infiltrate using standard histological procedures, presumably because of the presence of suberin. The best sections for cell wall examination were those cut dry by hand and immersed overnight in 1N NaOH prior to washing and mounting in glycerol. This procedure was used for the quantitative study of periderm described below.

Five random sections were cut from both inner and outer rhytidome positions at 0, 6 and 12 m heights in five 45-yr-old trees. Similar sections were cut at 0 m in five, and at 6 m in three, 25-yr-old trees. There was insufficient periderm to sample the extra two trees at 6 m. Sections were cut so that the second innermost or second outermost periderm could be identified under the microscope and observations were made on the first complete radial tier of cells from the top of the microscopic field of view and the

30th tier thereafter. For each tier were recorded the number and total width of both phellem and phelloderm cells, and the radial distance X from the phellem/phelloderm boundary of the periderm on one side to that on the other side of the periderm under observation (see Fig. 3). From this the per cent volume occupied by phellem and phelloderm was calculated.

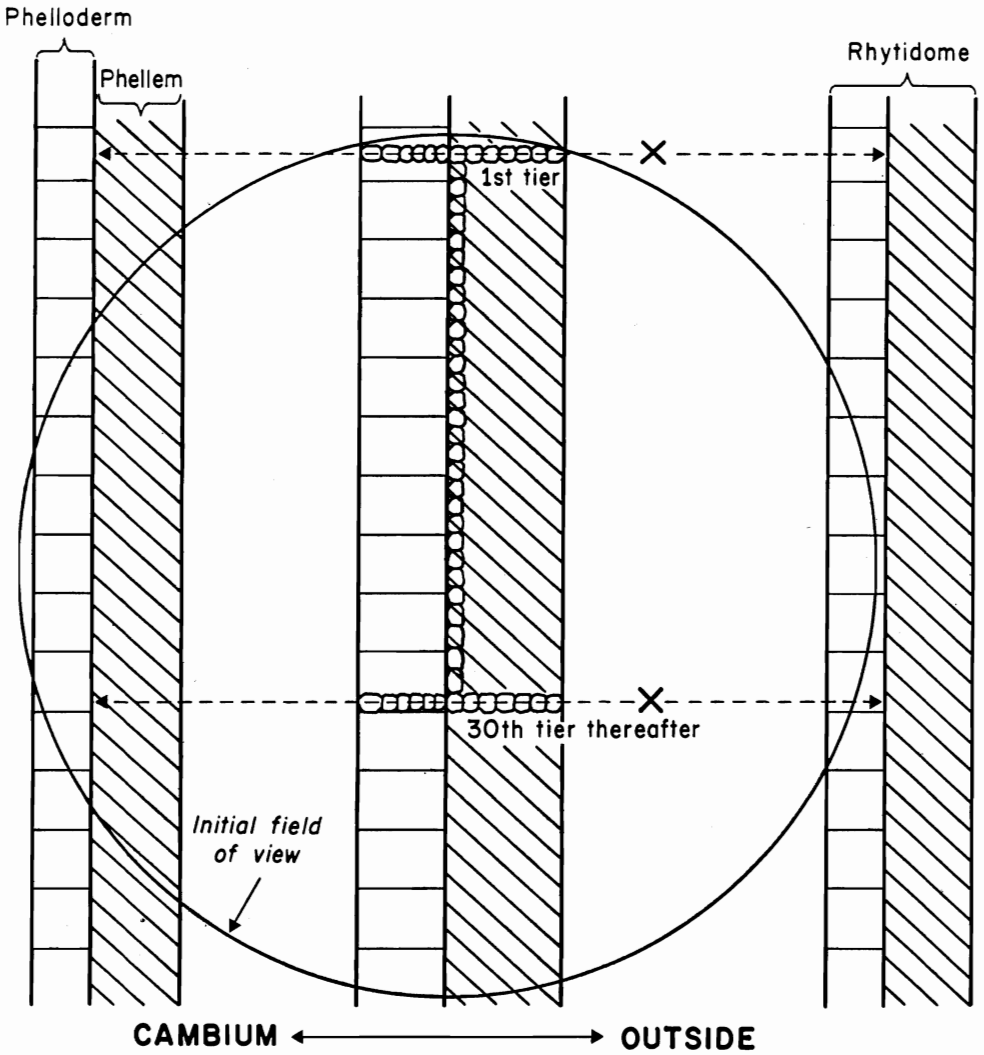

FIG. 3—Diagram showing measurement details for quantitative study of periderm.

Results

Sections of *P. radiata* rhytidome and phloem are shown in Figs. 4 and 5 respectively.

Both copper acetate and ferric chloride stained all periderm components as well as phloem axial parenchyma. Ray parenchyma and sieve cells were unstained.

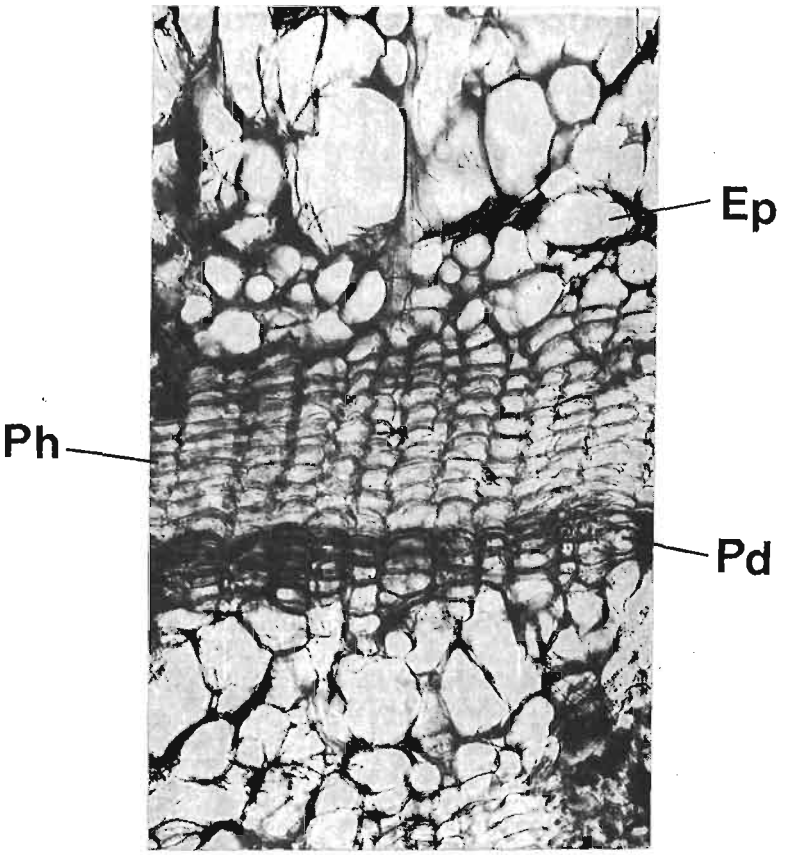

FIG. 4—**P. radiata** rhytidome showing phellem (Ph), phelloderm (Pd), and enlarged parenchyma (Ep). R.L.S. 80x.

The number of cells, width and per cent volume of phellem and phelloderm are given in Table 3.

For phellem the average number of cells, width and per cent volume were highly significantly greater at 0 m than at other heights; per cent volume of phellem in inner rhytidome was highly significantly greater than in outer rhytidome at 0 m only; and, because of large between-tree variation, all other differences were not significant.

Average number of cells and width of phelloderm at 25 yr were highly significantly greater than at 45 yr; average width in the outer rhytidome was significantly greater than in the inner rhytidome, and was highly significantly greater at 0 m than at other heights; and all other differences were not significant.

CHEMISTRY

Bark usually contains more extractives than the associated wood (Martin and Crist, 1971) and, except for tannins (Humphreys and Martin, 1966), the extractive content and distribution in *P. radiata* bark is largely unevaluated. The bark shows con-

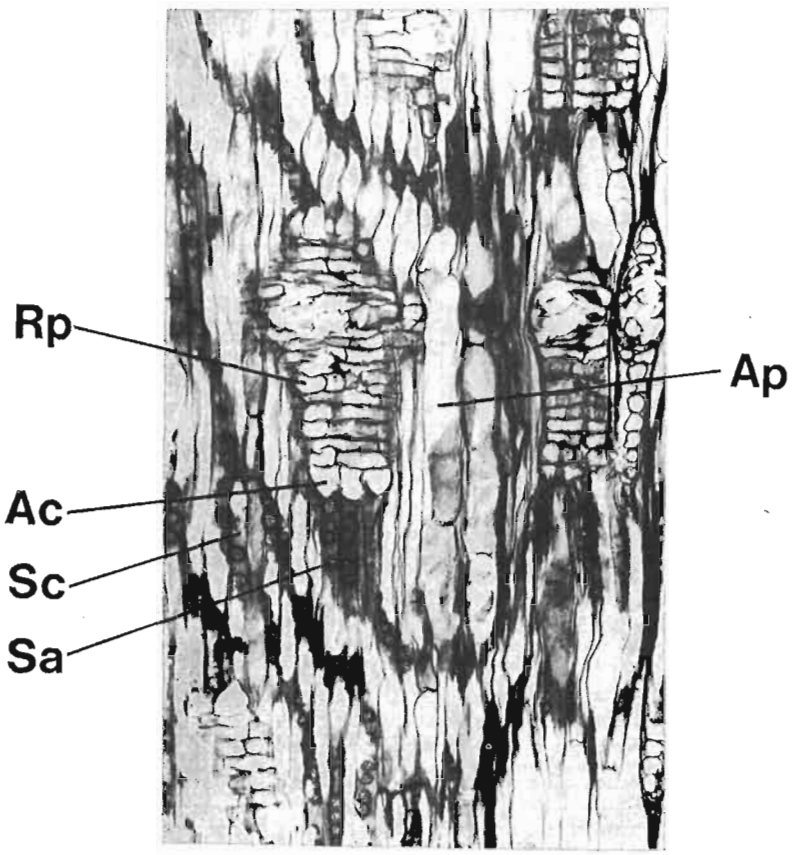

FIG. 5—**P. radiata phloem** showing ray parenchyma (Rp), axial parenchyma (Ap), albuminous cell (Ac), sieve area (Sa), and sieve cell (Sc). R.L.S. 80x.

siderable promise as a source of phenols which, with formaldehyde, form an adhesive suitable for plywood and particle board manufacture (Booth, Herzberg and Humphreys, 1958; Herzberg, 1960; Plomley, 1966, 1973). The amount and distribution of various gross extractives is here examined.

Materials and Methods

Bark samples for extraction were taken from 3 cross-sectional positions (phloem, inner rhytidome, outer rhytidome) at 3 tree heights (0, 6, 12 m) from 3 trees of each of 2 ages (25 and 45 yr). Inner and outer rhytidome comprised material containing the inner and outer 3 periderms respectively. Twenty-five-yr-old trees at 12 m had 3 or less periderms and inner and outer periderm were here treated as one. Bark was stored in plastic bags at −10°C.

Approximately 2.5 gm of finely broken bark sample was oven-dried (80°C) and successively soxhlet extracted for 12 hr in each of petroleum ether (BP 40°C-50°C),

TABLE 3. Cell count, width and per cent volume of phellem and phelloderm in inner rhytidome (IR) and outer rhytidome (OR) at various heights in *P. radiata* stems aged 25 and 45 yr.

	PHELLEM						PHELLODERM					
	CELL COUNT		WIDTH (mm)		%		CELL COUNT		WIDTH (mm)		%	
	IR	OR	IR	OR	IR	OR	IR	OR	IR	OR	IR	OR
AGE 25 YR												
Height 0 m	16.4	14.3	0.566	0.503	37.6	28.8	6.1	6.3	0.203	0.237	14.2	13.2
Height 6 m	9.1	8.1	0.335	0.266	21.5	17.5	5.3	4.5	0.176	0.157	11.5	10.3
AGE 45 YR												
Height 0 m	12.4	11.5	0.441	0.449	35.9	27.7	4.2	4.2	0.143	0.156	12.0	9.9
Height 6 m	8.8	8.6	0.310	0.317	22.6	22.3	3.6	4.3	0.118	0.146	8.9	10.5
Height 12 m	8.2	9.0	0.289	0.302	20.4	20.3	3.8	4.0	0.129	0.135	9.3	9.4

ether, ethanol and hot water. The percent of vacuum-dried or freeze-dried (hot water) extract was determined.

Results

Per cent extractives are given in Table 4. Conclusions below were based on analyses of variance of log transformed data for each age separately.

(1) *Petroleum ether.* The mean rhytidome extract was highly significantly greater at 12 m than at 0 and 6 m in 25-yr-old stems, and was greater than the phloem extract in both 25-yr-old stems (highly significant) and 45-yr-old stems (significant).

(2) *Ether.* The mean rhytidome extract was highly significantly greater than the phloem in both ages.

(3) *Ethanol.* The mean phloem extract decreased significantly with increasing height in 45-yr-old but not in 25-yr-old stems, and the mean rhytidome extract decreased highly significantly with increasing height in both ages. The mean extract from inner rhytidome was greater than from outer rhytidome in both 25-yr-old stems (significant) and 45-yr-old stems (highly significant), and the difference between inner and outer decreased with increasing height .

(4) *Hot water.* The mean extract from inner was greater than from outer rhytidome in both 25-yr-old stems (significant) and 45-yr-old stems (highly significant). The mean phloem extract significantly decreased with increasing height and was highly significantly greater than rhytidome extract in 45-yr-old stems.

DISCUSSION

For trees in this study, bark shape and volume distribution were well described, within age classes, by an empirical equation. Should bark utilisation become important enough to warrant it, use of such equations as predictors appears promising.

Irrespective of age the butt log is preferable as a source of bark because:

(1) Bark volume was concentrated in the lower part of the stem. (The butt log (5 m) contained 61, 51 and 45% of the total bark in 25, 31 and 45-yr-old stems respectively; and the butt log of 25-yr-old stems had twice the bark of the log of equivalent centre-girth in 45-yr-old stems).

(2) Bark per cent was greatest in the butt log. Therefore for the butt log less wood as well as a lesser number of logs need be handled to yield a given volume of bark than in any other part of the stem.

As a source of Stiasny polyphenols (see Wissing, 1955) for adhesives, the butt log has further advantages:

(3) Ethanol extractives were greatest at the base of the stem.

(4) The proportion of phloem to bark was least in the butt log. Although phloem has a large hot water extractive content (which includes phloem sugars) (Table 4), its proportion of Stiasny polyphenols is small compared to that in rhytidome (Palmer, R. E., pers. comm.). Therefore, all things being equal, Stiasny polyphenol content would be expected to decrease progressively up the stem as the proportion of phloem to bark decreased. This has been shown to occur (Palmer, R. E., pers. comm.).

In many milling operations the butt log is singled out for special treatment and therefore preferential use of this log for bark utilisation becomes a practical proposition.

P. radiata bark appears very persistent as there is little evidence of sloughed-off stem bark on the plantation floor. Therefore, if periderms are formed annually (or at least periodically) over the whole stem, as is wood, then periderm and annual ring numbers should decrease in a similar manner up the stem. The results in Table 1 showed this was not so. While at the base of the tree the number of periderms approached that of annual rings, periderm number (like bark thickness) decreased much more rapidly with height than did annual ring number.

The proliferation of bark towards the base of the tree means (assuming uniform bark persistency) the duration or rate of cambial activity was greater here. A small part of this was due to increased phellogen activity as reflected in greater production of phellem and phelloderm (Table 3), but most was due to increased vascular cambial production of phloem elements. The innermost periderm was continuous over the whole length of measured stem delimiting a constant width of phloem. Periderms were formed at a greater frequency towards the base of the stem, delimiting phloem which on average was younger than elsewhere.

Techniques for separating cork from the bark of Douglas fir (5-50% cork) and white fir (5-60% cork) have been described (Dedrick & Firth, 1957; Collins & Williston, 1958). Cork from these species is formed in wider bands than in *P. radiata* and, unlike *P. radiata,* their barks have fibres (Chang, 1954). It is not known whether these differences would exclude the possibility of cork separation from *P. radiata* bark. *P. radiata* rhytidome in this study contained 17.5-37.6% phellem (cork) (Table 3). The butt log is preferable as a source of cork, because it has the greatest phellem content

TABLE 4. Per cent extractives in phloem (P), inner rhytidome (IR), outer rhytidome (OR) and mean rhytidome (R) at various heights (h) in *P. radiata* stems aged 25 and 45 yr.

		25 YR				45 YR			
	h (m)	P	IR	OR	R	P	IR	OR	R
Petroleum ether	0	1.27	1.88	3.47	2.68	1.46	1.41	1.28	1.34
	6	0.81	1.65	2.56	2.10	1.29	2.07	1.81	1.94
	12	0.97			5.88	0.91	1.78	1.71	1.75
Ether	0	0.71	1.15	1.89	1.52	0.78	1.15	2.17	1.66
	6	0.62	1.30	3.71	2.50	1.11	2.14	2.03	2.08
	12	0.58			3.46	0.68	1.16	1.96	1.56
Ethanol	0	3.91	19.13	7.96	13.54	6.89	18.78	4.56	11.67
	6	3.33	8.07	6.64	7.35	5.79	8.52	3.89	6.20
	12	3.50			4.25	5.12	5.40	3.46	4.43
Hot Water	0	11.10	10.52	7.41	8.96	14.73	8.81	5.51	7.16
	6	10.30	11.33	8.07	9.70	13.00	8.36	5.39	6.88
	12	10.43			9.65	10.10	8.93	5.71	7.32
Total	0	16.99	32.68	20.72	26.70	23.85	30.16	13.52	21.84
	6	15.07	22.35	20.98	21.66	20.81	20.27	12.69	16.48
	12	15.48			23.24	16.82	17.28	12.85	15.06

in the rhytidome (Table 3) and the smallest proportion of phloem (which contains no phellem) to bark.

P. radiata rhytidome contains considerable amounts of very highly polymerised phenols which are soluble only in alkali (Markham and Porter, 1973; Porter, 1974). Possibly a reason for reduced ethanol and hot water extractives in the outer rhytidome in this study is that increased exposure to light and/or oxygen increases polyphenol polymerisation, consequently reducing their ethanol and hot water solubility. This could be age-dependent with ethanol extractives, as the difference between inner and outer rhytidome decreases with height and is less in 25- than 45-yr-old stems. Although some variation in extractive content in rhytidome could be due to observed differences in proportion of cell types (Table 3), the large differences (particularly in ethanol extractives) suggest considerable variation in extractive content of similar cell types.

ACKNOWLEDGMENTS

The technical assistance of K. Galbally is gratefully acknowledged. Softwood Holdings Pty. Ltd (Mt. Gambier, South Australia) kindly provided the trees used in this study. Sincere thanks are expressed to N. Ditchburne, CSIRO Division of Mathematical Statistics, who did the statistical analyses and curve fitting.

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