PROVENANCE VARIATION IN NEW ZEALAND-GROWN *EUCALYPTUS DELEGATENSIS*. 2: INTERNAL CHECKING AND OTHER WOOD PROPERTIES

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ABSTRACT

A *Eucalyptus delegatensis* R.T.Baker provenance trial was evaluated at age 8 years for growth rate, internal checking within growth rings, and other wood properties. Internal checking, which occurs on drying, severely restricts the use of *E. delegatensis* for solid-wood products. Relationships were investigated between internal checking variables and the other wood properties (basic density, heartwood content, and moisture content) and stem diameter.

Neither the size nor the frequency of internal checks showed any marked association with any of the other disc variables or combination thereof. Internal checking features, however, differed strongly between two regional provenance groups, the Tasmanian provenances having less than half as many as the mainland Australian provenances. Heartwood was markedly less and basic density averaged 9 kg/m^3 higher in the Tasmanian material. The Tasmanian provenances were also superior, albeit marginally, in diameter growth. Accordingly, Tasmanian provenances are recommended over mainland ones for New Zealand plantations, even though tree form is not as good.

Keywords: provenance; wood properties; internal checking; *Eucalyptus delegatensis*.

INTRODUCTION

Eucalyptus delegatensis has proved to be well suited to parts of New Zealand because of its fast growth, easy establishment, frost tolerance, and relatively good tree form characteristics (for one of the ash group of eucalypts) (Wilcox 1980). The wood, however, exhibits severe internal checking on drying (Kininmonth *et al.* 1974). Present recommendations for cutting and drying *E. delegatensis* include: quarter-sawing; careful air-drying to under 30% moisture content (m.c.); reconditioning; and finally kiln drying. Despite such care, substantial internal checking is still very prevalent (Haslett 1988), and is of such concern with regard to value and end uses that widespread planting in New Zealand of *E. delegatensis* for sawn

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timber has recently been severely curtailed. Haslett identified the pattern of within-ring variation in wood density as a possible cause of the problem, because fast-grown plantations tend to give very wide bands of low-density earlywood, and the earlywood-latewood transition is often abrupt.

Provenance trials for *E. delegatensis* were established in New Zealand in 1978 from a large and comprehensive seed collection made available by CSIRO Division of Forest Research (D.J.Boland, pers. comm.). In this paper we report results from a detailed wood-properties assessment made at age 8 years on one of the sites of this provenance material. Our objective was to determine what relationships might exist between wood checking features on the one hand, and growth rate and other wood properties on the other.

MATERIALS AND METHODS

Materials

The material for this study (Boland & Moran 1979; Moran *et al.* 1990) was from a detailed rangewide collection which included Tasmania, Victoria, New South Wales (NSW), and the Australian Capital Territory (ACT). Each provenance lot comprised a bulked seed collection from 5–10 trees. Sampling for the wood property assessment was done in an 8-year-old trial of this material at Longwood Forest, Southland (lat. 46°30′S, alt. 230 m), in the part of New Zealand where *E. delegatensis* grows most promisingly. The material from the collection planted at Longwood, including New Zealand lots, is listed in Table 1, and details of this trial have been given by Wilcox *et al.* (1985). Briefly, the trial at this site was established as a randomised complete block design with 27 replicates of one tree per seedlot per replicate. After the growth and form traits were measured (King *et al.* 1993), destructive sampling of nine replicates (one-third of the trial) was carried out and disc samples were taken for detailed internal wood property analyses.

Wood Property Measurements at Longwood

On all trees felled (323 stems), two cross-sectional discs were cut at 1.4 m height. Measurements of diameter under bark, and of heartwood, as well as green weight, were made on site for one of these discs. Laboratory measurements of green volume and oven-dry weight enabled calculations of wood density, moisture content, and heartwood percentage. The second disc was used to assess internal checking. A radial cut was made in the disc before it was dried in a laboratory kiln at 70°C dry bulb and 60°C wet bulb for 4–5 days. After drying, one surface was sanded to facilitate assessment of checking (Fig. 1).

Observations after drying included:

- The angle to which the radial cut opened on drying because of differential shrinkage;
- Number of internal checks in each ring;
- Severity of the worst check.

The severity of checking was also graded visually, ring by ring, on each disc as follows:

0 No checks in the ring
1 Small checks, entirely within the ring, and with width of 1–2 mm
2 Larger checks but still entirely within the growth ring
3 A check that crossed latewood boundary

TABLE 1–Set 1 provenances used in wood property analysis

No.	Region	Origin	Elevation (m a.s.l.)	Latitude (S)	Longitude (E)
73	NZ	Tapanui	–	–	–
101	ACT	Yaouk Bill	1400	35° 55′	148° 54′
104	NSW	Mt Bogong	1525	35° 36′	148° 28′
110	NSW	Youngal	1130	36° 24′	148° 08′
112	NSW	Pinnacle	1500	36° 20′	148° 14′
114	NSW	Mt Flinders	1360	35° 57′	149° 03′
116	NSW	Yarrangobilly	1260	35° 42′	148° 30′
119	NSW	Pilot Hill	1100	35° 37′	148° 09′
122	VIC	Mt Buffalo	1350	36° 43′	146° 48′
124	VIC	Mt Big Ben	1100	36° 24′	146° 56′
125	VIC	Currajong Ck	1280	37° 05′	146° 26′
126	VIC	Mt Buller	1050	37° 08′	146° 53′
127	VIC	Taggerty	960	37° 23′	145° 52′
129	VIC	Mt Macedon	945	37° 24′	144° 36′
130	VIC	Ada River	925	37° 48′	145° 49′
131	VIC	Mt Useful	1220	37° 40′	146° 31′
132	VIC	Mt Skene	1150	37° 24′	146° 21′
133	VIC	Mt Ewen	1230	37° 22′	147° 11′
135	TAS	Hartz Mts	560	43° 13′	146° 52′
137	TAS	Ben Lomond	1220	41° 31′	147° 39′
141	TAS	Maggs Mt	820	41° 46′	146° 11′
142	TAS	Surrey Hills	580	41° 20′	145° 40′
145	TAS	Heemskirk Riv	160	41° 48′	145° 12′
147	TAS	Miena	960	42° 01′	146° 47′
150	TAS	Lake Pedder	380	42° 58′	146° 22′
151	TAS	Russell Riv	500	42° 54′	146° 44′
154	TAS	Lake Tooms	600	42° 14′	147° 51′
160	ACT	Bulls Head	1125	35° 24′	148° 49′
161	NSW	Mt Delegate	900	37° 07′	148° 54′
162	VIC	Mt Ellery	–	37° 23′	148° 47′
163	VIC	Nunniong Plat	1320	37° 06′	147° 58′
168	NZ	Ex Bago NSW	–	–	–
169	NSW	Bago	–	–	–
171	VIC	Commercial	–	–	–
173	NZ	Rangataua	–	–	–
174	NZ	Southland	–	–	–

4 A check that crossed more than one latewood boundary
5 A severe check extending the full radius of the disk.

These grades were converted into composite ratings which are listed and designated, along with other variables studied, in Table 2.

Statistical Analyses

Four complementary approaches to statistical analysis were adopted using SAS Institute (1989) procedures:

- Analysis of variance for one variable at a time, primarily testing for differences among classes;

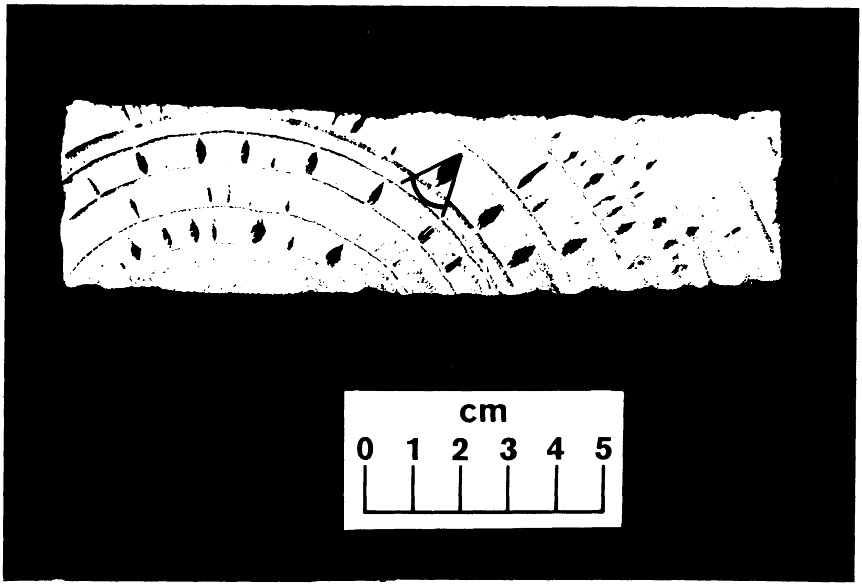

FIG. 1–Typical internal checking in *Eucalyptus delegatensis*. The checks shown are almost all of severity grades 1 and 2. The basis for measuring the angle to which the check opened is illustrated by the superimposed graphic.

TABLE 2–Variables reported.

Internal wood checking variables	
ΣCHECKS	Total number of checks on disc
CH/CM^2	Number of checks per square centimetre of disc
AVSEV	Mean severity score of checks per disc
MAXSEV	Maximum severity score of individual checks on disc
Σ(4–5)	Number of checks of grade 4 or more (crossing >1 latewood boundary per disc)
$(4–5)/CM^2$	Number of checks of 4 or more per square centimetre
ANGLE	Angle to which the radial cut opened on drying
Other disc variables	
RADIUS	Radius inside bark (cm)
HEART	Percentage of heartwood
MOIST	Moisture content (%)
DENSITY	Basic wood density (kg/m^3)

- Simple correlation analysis between pairs of variables;
- Multiple regression analysis, treating internal checking variables as dependent and including regions as a dummy variable;
- Analysis of covariance, focusing on tests for provenance differences after adjusting for a covariate.

The analysis of variance model (using SAS Proc GLM) incorporated the following effects: replicates, provenance groups, and provenances within groups. Provenance groups necessarily represented a fixed effect, but provenances within groups were treated (conservatively) as a random effect. Means and standard errors were thereby calculated for provenance groups with two alternative groupings:

(i) Australian states, namely New South Wales including Australian Capital Territory (NSW), Tasmania (TAS), and Victoria (VIC);

(ii) Tasmania (TASMANIA) *versus* Australian mainland (MAINLAND).

Pairwise comparisons were made between states using t-tests (Steele & Torrie 1980); otherwise, F-tests were used.

Simple correlations were calculated, at the individual-tree level, between the internal checking variables and the other disc variables.

Multiple regression models were initially run for the internal checking variables (including drying angle) on the other disc variables, SAS Proc STEPWISE (default codings), in order to see how much of the variance in wood checking could be explained by the basic variables of RADIUS, HEART, MOIST, and DENSITY (Table 2). Further stepwise models also included geographic variables (viz regions as a dummy variable, and latitude, longitude, and altitude) as independent variables.

While reservations exist about the stepwise analysis, the other analyses could be tested to confirm the results. The analyses of covariance (SAS Proc GLM) tested for provenance differences in internal checking after adjusting for individual-tree covariance on growth rate. The effects in the model thus included: replicates, individual provenances, and diameter under bark as the covariate, the last-mentioned having been indicated by preceding analyses.

RESULTS

Relationships Between Internal Checking Features and Other Disc Variables

Simple correlation coefficients are shown in Table 3 between internal checking variables relating to numbers and sizes of checks and drying angle, on the one hand, and the remaining disc variables (viz radius inside bark (RADIUS), percentage heartwood (HEART), moisture content (MOIST), and basic density (DENSITY)), on the other. The correlation of RADIUS with total number of checks ($\sum$CHECKS) was significant ($r=0.345$; $p<0.0001$), but that with checks per square centimetre (CH/CM^2) was non-significant ($r=-0.096$; $p>0.05$). This trend was also evident in respect of checks in visual grades 4 and 5, i.e., checks crossing two or more growth rings (variables $\sum$(4–5) and (4–5/CM^2)). Thus, faster-growing trees are not inclined to produce more checks per unit volume of wood than slower-growing trees. Larger trees did produce greater numbers of severe checks, but this may be a scale effect, and we could not get any accurate assessment of total volume of check space per unit volume of solid wood.

Basic density showed significant ($p<0.05$) negative correlations with most of the internal wood checking variables but the coefficients of determination were low ($R^2<4\%$).

In the multiple regression of $\sum$CHECKS (total number of checks) on measured disc variables (Table 4), HEART was the first variable to come into the equation and accounted for 13% of the variation of $\sum$CHECKS. The total model (Table 4), with a $p<0.15$ entry level, also included RADIUS (5% partial R^2) and DENSITY (1% R^2), and accounted for 19% of

TABLE 3–Correlations (bold type) between internal checking variables and other disc variables (321 d.f.). Probabilities *p* = 0 in ordinary type.

Internal checking variables	Other disc variables			
	RADIUS	HEART	MOIST	DENSITY
ΣCHECKS	**0.34**	**0.36**	**0.16**	**–0.15**
	0.0001	0.0001	0.003	0.006
CH/CM²	**–0.09**	**0.17**	**0.11**	**–0.14**
	0.085	0.002	0.046	0.009
AVSEV	**0.50**	**0.30**	**0.23**	**–0.19**
	0.0001	0.0001	0.0001	0.0007
MAXSEV	**0.36**	**0.21**	**0.20**	**–0.17**
	0.0001	0.004	0.0003	0.002
Σ(4–5)	**0.27**	**0.16**	**0.14**	**–0.13**
	0.0001	0.004	0.010	0.016
(4–5)/CM²	**0.11**	**0.076**	**0.14**	**–0.15**
	0.043	0.17	0.013	0.007
ANGLE	**0.07**	**0.10**	**0.09**	**–0.07**
	0.19	0.066	0.080	0.17

TABLE 4–Results of stepwise regression analysis of internal checking variables* on other disc variable features, showing partial (marginal) and total R^2† values in parentheses and F-ratio for model.

Internal checking variable	Wood property variables entering equation (at p<0.15)			Total R^2‡	F ratio
	First variable	Second variable	Third variable		
ΣCHECKS	HEART (13%)	RADIUS (5%)	DENSITY (1%)	(19%)	25.7
CH/CM²	HEART (3%)	RADIUS (3%)	DENSITY (2%)	(8%)	9.3
AVSEV	RADIUS (26%)	DENSITY (2%)	HEART (1%)	(29%)	43.3
MAXSEV	RADIUS (13%)	DENSITY (2%)		(15%)	29.2
Σ(4–5)	RADIUS (7%)	DENSITY (1%)		(9%)	15.1
(4–5)/CM²	DENSITY (2%)	RADIUS (1%)		(3%)	5.4
ANGLE	HEART (1%)	MOIST (1%)		(2%)	3.2

Total degrees of freedom = 322.
* Variables explained in Table 2.
† Ignoring marginal R^2 of variables that disappear from fitted regression in later steps.
‡ Partial R^2 values may not sum to values in this column because of rounding errors.

the variance in ΣCHECKS. For the number of checks per square centimetre (CH/CM²) HEART, RADIUS, and DENSITY jointly accounted for a significant but small (8%) amount of the variance (Table 4).

Percentage heartwood was the first explanatory variable in the equation for numbers of checks (ΣCHECKS and CH/CM²) whereas diameter was the first explanatory variable for the check-size variables (AVSEV and MAXSEV). Wood basic density (DENSITY) also came into the equations with negative coefficients but on the basis of partial R^2 could never account for more than 1 or 2% of the variance for internal checking features including angle

(Table 4). Moisture content (MOIST) entered the regression equations only for drying angle. The explanatory regression for drying angle, although significant ($p<0.05$), was very weak (R^2=2%).

Influence of Seed Origin on Wood Internal Checking

Although there were significant ($p<0.05$) but slight associations (Tables 3 and 4) between the number of internal checks and certain of the other disc variables (HEART, RADIUS, and, to a lesser extent, DENSITY), the major result was the strong and significant difference between MAINLAND and TASMANIAN *E. delegatensis* in total number of checks (ΣCHECKS) and number of checks per square centimetre (CH/CM^2) (Table 5). Regions (TASMANIA and MAINLAND) represented an extremely significant ($p<0.0001$) source of variation for ΣCHECKS and CH/CM^2, whereas provenances within regions were non-significant ($p>0.05$). Tasmanian sources had less than half as many checks as mainland sources.

TABLE 5–Means ± standard errors for internal checking features and other disc variables of Tasmanian and mainland Australian regions, plus probability levels for tests for differences between regions and between provenances within regions.

Variable	Region		Significance level (p)	
	TASMANIAN	MAINLAND	Between regions	Between provenances
Internal checking variables				
ΣCHECKS	13.9 ± 2.28	31.5 ± 1.541	<0.0001	0.55
CH/CM^2 ($\times10^{-2}$)	8.43 ± 1.51	21.2 ± 0.94	<0.0001	0.46
AVSEV	0.82 ± 0.060	1.03 ± 0.037	0.005	0.13
MAXSEV	2.53 ± 0.137	2.68 ± 0.085	0.33	0.022
Σ(4–5)	0.413 ± 0.123	0.543 ± 0.076	0.33	0.10
$(4–5)/CM^2$ ($\times10^3$)	2.25 ± 0.843	3.32 ± 0.523	0.29	0.019
ANGLE	56 ± 2.50	36 ± 1.6	<0.0001	0.014
Other disc variables				
RADIUS	148.2 ± 4.46	144.6 ± 2.77	0.53	0.008
HEART	35.3 ± 1.78	43.5 ± 1.10	0.0002	<0.0001
DENSITY	401 ± 4.64	391 ± 2.9	0.084	<0.0001
MOIST	170 ± 3.4	173 ± 2.1	0.45	<0.0001

Variables explained in Table 2.

In the multiple regression models, with region along with the other wood disc variables as independent variables in the model, REGION was the first explanatory variable for ΣCHECKS and CH/CM^2 respectively (Table 6). In the model for CH/CM^2, REGION, as the first explanatory variable in the stepwise procedure, accounted for 15% of the variance. With region accounting for 15% of the variance in this model, the combined marginal R^2 of wood density and diameter accounted for only a further 2%.

The actual importance of REGION is far greater than the partial R^2 values would suggest, because those R^2 values are constrained by the proportion of phenotypic variance contributed by provenance differences overall. Indeed, REGION accounted for essentially all the

TABLE 6–Results of stepwise regression analysis of internal wood checking features on region and other disc variable features showing partial (marginal) and total R^2* values in parentheses and F ratio for model.

Internal checking variable	Wood property variables entering equation (at p<0.15)			Total R^2†	F ratio
	First variable	Second variable	Third variable		
ΣCHECKS	REGION (13%)	RADIUS (11%)	HEART (1%)	(26%)	24.3
CH/CM^2	REGION (15%)	DENSITY (1%)	RADIUS (1%)	(17%)	19.8
AVSEV‡	RADIUS (23%)	REGION (5%)	DENSITY (2%)	(30%)	40.2
MAXSEV‡	RADIUS (13%)	DENSITY (3%)		(15%)	25.7
Σ(4–5)‡	RADIUS (8%)	DENSITY (4%)	MOIST (1%)	(12%)	13.2
(4–5)/CM^2‡	DENSITY (7%)	MOIST (1%)	RADIUS (2%)	(10%)	10.3
ANGLE	REGION (19%)	HEART (7%)	MOIST (2%)	(28%)	28.0

Total degrees of freedom = 322
REGION = (mainland, Tasmania), other variables as explained in Table 2
* Ignoring marginal R^2 of variables that disappear from the fitted regression in later steps.
† Partial R^2 values may not sum to values in this column because of rounding errors.
‡ Results not identical to those in Table 4 because of omission of New Zealand provenances.

between-provenance variation in ΣCHECKS, CH/CM^2, and AVSEV, and most of that variation in ANGLE. The contributions of the other explanatory variables were not so constrained.

AVSEV, which is a measure of the average severity of the checks in discs, showed individual checks in the Tasmanian provenances to be significantly less severe on the whole than in mainland provenances (Table 5). The difference between regions in shrinkage characteristics on drying was also clearly shown by a large difference in average drying angle. With significantly higher wood density, lower heartwood percentages, different checking characteristics, apart from different bark features (not reported here), the wood of Tasmanian *E. delegatensis* is quite different from that of the mainland provenances (Table 5).

The major influence on the expression of most internal checking variables was the regions effect. However, it was shown that maximum check size (MAXSEV) and number of large checks per square centimetre ((4–5)/CM^2) had significant components of variance attributable to provenance effects within region rather than region effects (Table 5). Multiple regression models were investigated using geographic origin variables (altitude – ALT, latitude – LAT, and longitude – LONG) within regions as independent variables on MAXSEV and (4–5)/CM^2. Significant effects were demonstrated within the mainland region (Table 7), especially of ALT. Within the Tasmanian region, ALT was the only such variable to be significant (R^2 = 12%, p = 0.002) for ANGLE. Thus, provenances from higher altitudes were less likely to have large checks and altitude could account for up to 10% of the variance within mainland sources. This in itself might only reflect the slower growth of such provenances, but in fact altitude, while statistically significant (p<0.05), was observed to be only a minor determinant of individual-tree RADIUS (R^2 = 0.03).

Analysis of covariance with AVSEV, MAXSEV, and (4–5)/CM^2 for provenance effects within the mainland region, using RADIUS as a covariate, indicated that there were significant (p<0.05) differences between provenances for large-check features, even taking

TABLE 7–Results of stepwise regression analysis of internal checking features on geographic origin variables within the Australian mainland, showing partial (marginal) and total R^2 values in parentheses F ratio for model.

Internal checking variable	Source variables entering equation (at p<0.15)			Total R^2	F ratio
	First variable	Second variable	Third variable		
MAXSEV	ALT (10%)			(10%)	18.8
Σ(4–5)	ALT (8%)			(8%)	15.8
(4–5)/CM^2	ALT (7%)	LAT (1%)	LONG (4%)	(12%)	8.4

Total degrees of freedom = 287
ALT = altitude, LAT = latitude, LONG = longitude; other variables as explained in Table 2

into account basic growth differences. This effect was not evident within the Tasmanian region, suggesting that provenance selection among Tasmanian provenances may not be as effective as it would be among mainland provenances.

DISCUSSION AND CONCLUSIONS

Our original working hypothesis, that internal checking might be explained by vigorous growth and measured wood properties, was not strongly supported. The stepwise regression models showed only weak predictive powers for internal checking features using such variables. Percentage heartwood and disc radius could account for nearly 20% of the variance in number of internal checks per disc, but when tree size was taken into account by expressing the variable as number of checks per square centimetre, the predictive power of the regressions dropped considerably.

Fast growth by itself appears to have only a small influence on the number of checks but does affect both the mean and maximum sizes of internal checks. Heartwood formation, along with growth rate, does appear to have a minor but statistically significant impact on the production and size of checks, and wood density would appear to have only a very slight impact. A follow-up study on a pilot sample of 30 discs of detailed density profiles failed to reveal any further statistically significant relationships between internal checking and wood properties. It would appear, therefore, that none of the "other" disc features, either singly or in combination, had any major impact on the size or incidence of internal checks assessed in this study.

Unlike the "other" disc features, regional differences had very marked effects on the expression of internal checking features. In particular, Tasmanian provenances had less than half the total number of internal checks that mainland ones had. In terms of large internal checks (those crossing two or more growth rings), however, there were no clear regional differences. These large checks occurred in low frequencies (less than 5% of total checks) and their frequency distribution (with many zero occurrences) makes statistical interpretations less reliable. Nevertheless, there were indications of significant provenance differences within the mainland region for incidence of large checks.

The much lower incidence of checking in Tasmanian *E. delegatensis*, together with significantly lower heartwood percentages and higher wood density, shows its wood to be very different from that of mainland *E. delegatensis*. This adds to the marked genetic differences that have been noted between mainland and Tasmanian *E. delegatensis* (Boland 1985; Boland & Dunn 1985; King *et al.* 1993). With the generally favourable growth rates of Tasmanian provenances (their slight superiority was more evident in the larger sample studied by King *et al.* 1993), it would be advisable to concentrate on seed sources of Tasmanian origin for New Zealand *E. delegatensis* plantations. There are indications of markedly poorer form characteristics in Tasmanian *E. delegatensis* (King *et al.* 1993) but it is likely that this would be more readily improved in a tree improvement programme than internal wood characteristics, because these wood properties will be so expensive to evaluate in candidate trees . Moreover, the superior form of mainland material is of no advantage for producing sawn timber if the wood is unsatisfactory. Certainly, the total genetic resource afforded by these provenance trials would form a valuable base to provide selections for further plantations of *E. delegatensis* in New Zealand.

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