SCLEREIDS IN GYMNOSPERMS

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INTRODUCTION

A systematic study of the distribution, structure and ontogeny of sclereids in most of the groups of gymnosperms has not been made until now. The occurrence of sclereids has been mentioned under the names "idioblasts", "sclerenchyma cells", "thick walled cells", "stone-cells" etc., by SEWARD (1906) in *Araucaria*, BOWER (1881) in *Welwitchia*, RODIN (1958, 1962, 1963, 1966) in *Welwitchia* and *Gnetum*. MAHESHWARI (1961) described the sclereids of *Gnetum*. STERLING (1947) giving an account of sclereid formation in the shoot of *Pseudotsuga taxifolia* also refers to the report of sclereids in *Araucaria* by GRIFFITH (1950), by SACHER (1954) in *Pinus ponderosa* and by KITAMURA (1956) in *Sciadopitys*. KHALIL-H-AL-TALIB and TORREY (1961) have also described the distribution of sclereids in the leaves of *Pseudotsuga*. These are the only few stray references on the occurrence of sclereids in gymnosperms. The hitherto uninvestigated Indian gymnosperms and conifers were therefore studied from the sclereid point of view.

Some available members of the Cycadaceae, like *Cycas revoluta*, *C. circinalis*, *Zamia florinda*, *Z. mexicana*, *Encephalortos caffer*, and *E. villosus* were examined. But some of these showed no sclereids in the vegetative parts. The reproductive parts of *Cycas* also do not show any sclereids.

The reproductive parts of the other genera were not available and so could not be studied.

Ephedra foliata the available Indian species of Ephedrales, does not show sclereids in either vegetative or reproductive parts.

Several representative genera of the Indian conifers were investigated (RAO & TEWARI, 1961; RAO & MALAVIYA, 1963, 1964a, 1965a, 1965b, 1967a, 1967b, 1967c, 1967d), for their sclereid features in the vegetative as well as reproductive parts. The study though not exhaustive has brought out a number of interesting features about sclereids in conifers and this constitutes the subject matter of this paper.

A second objective of this study was to see the taxonomic importance if any, of sclereids in conifers. FOSTER (1944, 1945a, 1945b, 1946, 1947, 1955a, 1955b) and T. A. RAO (1950, 1951, a, b, c, 1952, 1954, 1957, 1961, 1963, 1964) have emphasized the importance of sclereids in the study of systematic botany. Our observations, though meagre, yet fully support the contentions of the above two authors as the various tables and charts included in this paper will show.

A few general observations on sclereids may not be out of place at this stage. According to HABERLANDT (1914), FOSTER (1949) and ESAU (1962), "Sclereids" are non-prosenchymatous in origin and are modified parenchyma cells of the ground tissue of the cortex or the mesophyll of the leaf. The initials are distinguishable from the neighbouring

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cells by a large prominent nucleus, dense protoplasmic contents, and a thin primary wall. These initials may elongate, or become more or less circular, or lobed, develop later into osteo, brachy and astrosclereids. In the development of all these three types of sclereids, generally the initial undergoes a general increase in size, looses its protoplasmic contents and the nucleus, and develops usually a thick, lamellated secondary wall often traversed by branched or unbranched pit-canals.

The type of sclereid that is formed is also to a large extent dependent upon the neighbouring tissues. Further the above development of sclereids is by "intrusive" and "symplastic" growths as discussed by Foster and T. A. Rao in a series of papers (op. cit.). The classification adoped in this paper is that of TSCHIRCH (1889) based on the form and morphology of adult sclereids.

MATERIAL AND METHODS

All the materials investigated in this paper were fixed in form-acetic alcohol. FOSTER's (1946) techniques of clearing and staining were used. In case of hard cones, concentric nitric acid was also used for maceration. Although lengthy, FUCH's (1963) technique of clearing and staining was very useful in some cases. Hand sections, microtome sections of 8-10μ thickness, macerations and cleared mounts, were all examined. Alcoholic safranin by itself or in combination with light-green and Haematoxylin-Orange-G combination were used. One percent safranin as recommended by Foster in 1/2 xylol and 1/2 absolute alcohol mixture gave excellent staining results. For temporary mounts Phloroglucin-concentric hydrochloric acid combination was used (FOSTER, 1949).

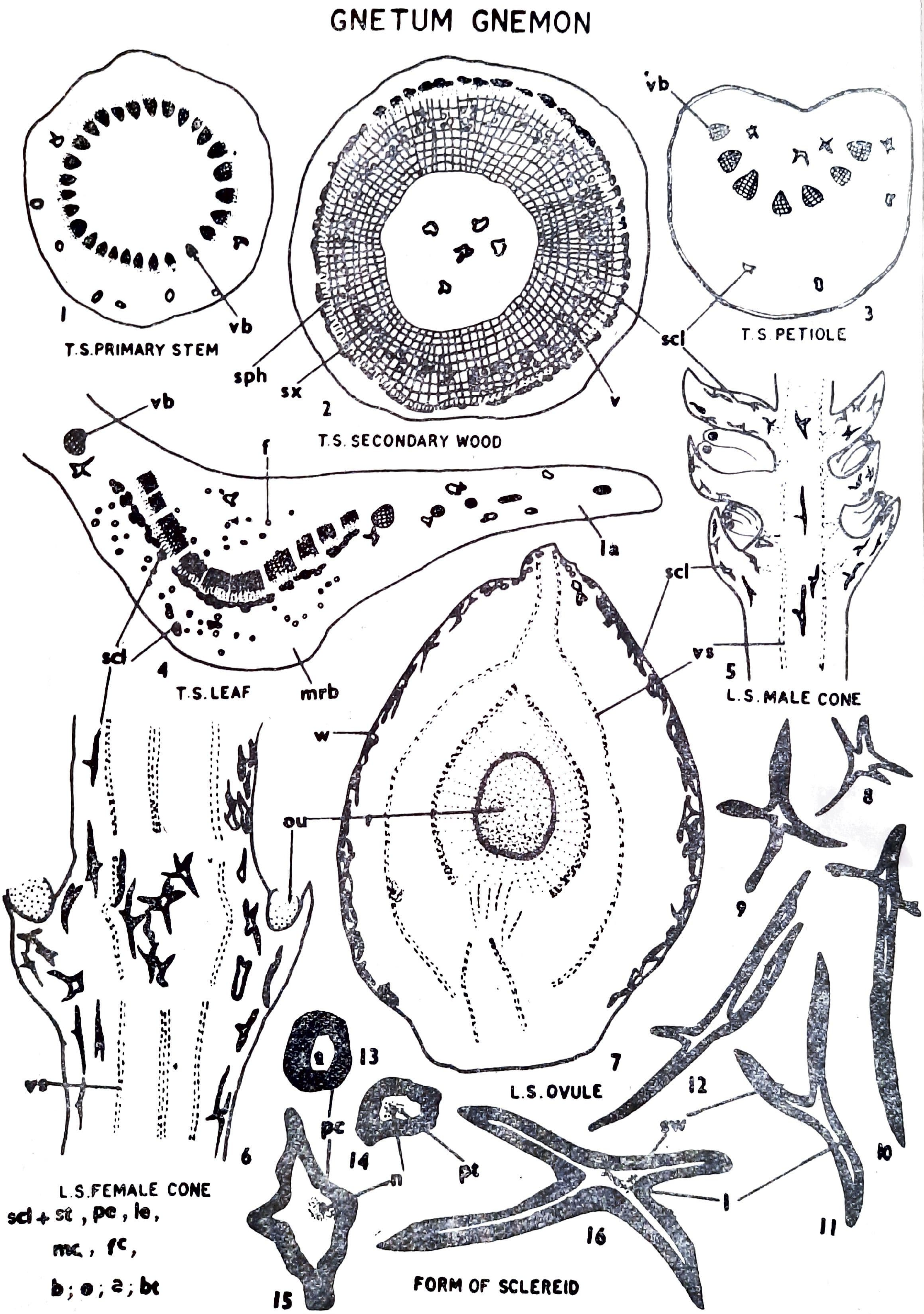
Mostly identified specimens from the departmental collections have been studied. The identifications and the specific names have been further confirmed by reference to DALLIMORE and JACKSON (1948) and Index Kewensis (1946).

DESCRIPTION

Gnetales

Text-Fig. 1

RODIN (1962, 1966) investigated the structure and distribution of sclereids in the American and African species of *Gnetum* and showed that the species could be classified according to sclereid characters. He also suggested that presence of sclereids reflects the primitive condition. In *G. schwackeanum*, he mentioned the largest sclereids ever reported in any plant. T. A. RAO (1961) also mentioned the occurrence of sclereids in all the Indian species of *Gnetum*. A detailed study of the structure, distribution and ontogeny of sclereids in *Gnetum gnemon* and *G. ula* was recently taken up by the authors (RAO & MALAVIYA, 1967d). It is found that in all the three species sclereids are present in stem, leaves, micro and megasporangiate cone-axes, micro-sporophylls, the ovule wall and the integument. Brachy, osteo and astrosclereids of various shapes and bizarre types with thick, lignified, lamellated, secondary walls traversed by pit-canals occur in various parts. The nucleus with some protoplasmic contents persists even in the adult sclereid lumen. In the stem, brachysclereids occur between the primary vascular bundles and above them. After secondary growth they occur along with the bast-fibres and thus contribute towards the building up of a mechanical tissue cylinder in the secondary wood. In the cortex, small


GNETUM GNEMON
vb
1
T.S. PRIMARY STEM
sph
sx
2
v
T.S. SECONDARY WOOD
vb
scl
3
T.S. PETIOLE
vb
f
la
scl
4
T.S. LEAF
mrb
scl
vs
5
L.S. MALE CONE
w
ou
vs
7
L.S. OVULE
8
9
10
11
12
ou
vs
6
L.S. FEMALE CONE
13
pc
14
pt
n
15
16
sw
l
FORM OF SCLEREID
scl + st, pe, le,
mc, f^c,
b; e; a; bc

Text-fig. 1.

astrosclereids occur as isolated cells. A few isolated sclereids are often found in the pith also.

In the leaf mesophyll, mostly astrosclereids are distributed in a diffuse manner. The sclereids occurring in reproductive parts are larger than those occurring in the vegetative parts.

So far as has been investigated, *Gnetum* sclereids do not possess the crystals which are reported in sclereids of *Welwitchia mirabilis* by RODIN (1958, 1963, 1966). The adult sclereids of *Gnetum* have a persistent nucleus while those of *Welwitschia* do not have. These two features may be added to the list of morphological and anatomical differences recognised between these two genera.

Coniferales

From the observations made on the species of Indian Conifers studied in this paper, it appears that although the development of sclereids is the same in all conifers, the nature of the sclereids and their distribution in the plant organs varies from genus to genus. Even in the development of sclereids certain minor differences have been noticed between some allied genera. Various types of sclereids and their distribution seem to be rather characteristic of the different genera of conifer. They may even furnish clues for the identification of the different families and genera, and even species (Table 1). These sclereid features so far observed, have been illustrated in a few charts and also arranged in a series of comparative tables which will be discussed below.

Taxaceae (1 species) have only brachy and osteosclereids with characteristic lumen and mostly a persistent nucleus with some remains of the original protoplast. Cephalotaxaceae (1 species) also have only brachy and osteosclereids, but with characteristic peg-like projections on the secondary wall. Podocarpaceae in which 17 species of *Podocarpus* have been studied are characterised by the presence of only simple brachysclereids. One species of *Dacrydium* has also been studied. It shows the presence of brachy, osteo and astro sclereids. Araucariaceae (2 genera, 7 species) have three types of sclereids, i.e. brachy, osteo and astrosclereids with numerous crystals of calcium oxalate. Cupressaceae (3 genera, 12 species) have all the three types, brachy, osteo and astrosclereids, occurring only in the fertile parts. Polymorphism of sclereids is exhibited to a maximum degree in this family. Taxodiaceae again have brachy, osteo or fusiform and astrosclereids, mostly with tannin present in the lumen of the sclereids. Pinaceae also have three types, i.e. brachy, osteo and astrosclereids, but mostly in the sterile parts with one exception *Picea morinda* where the sclereids are found in fertile as well as sterile parts.

Taxaceae

Text-fig. 2, Table 2.

The distribution and form of the sclereids is shown in the four varieties of *Taxus baccata* named as var. I, var. II, var. III, var. IV. Sclereids occur in both vegetative and

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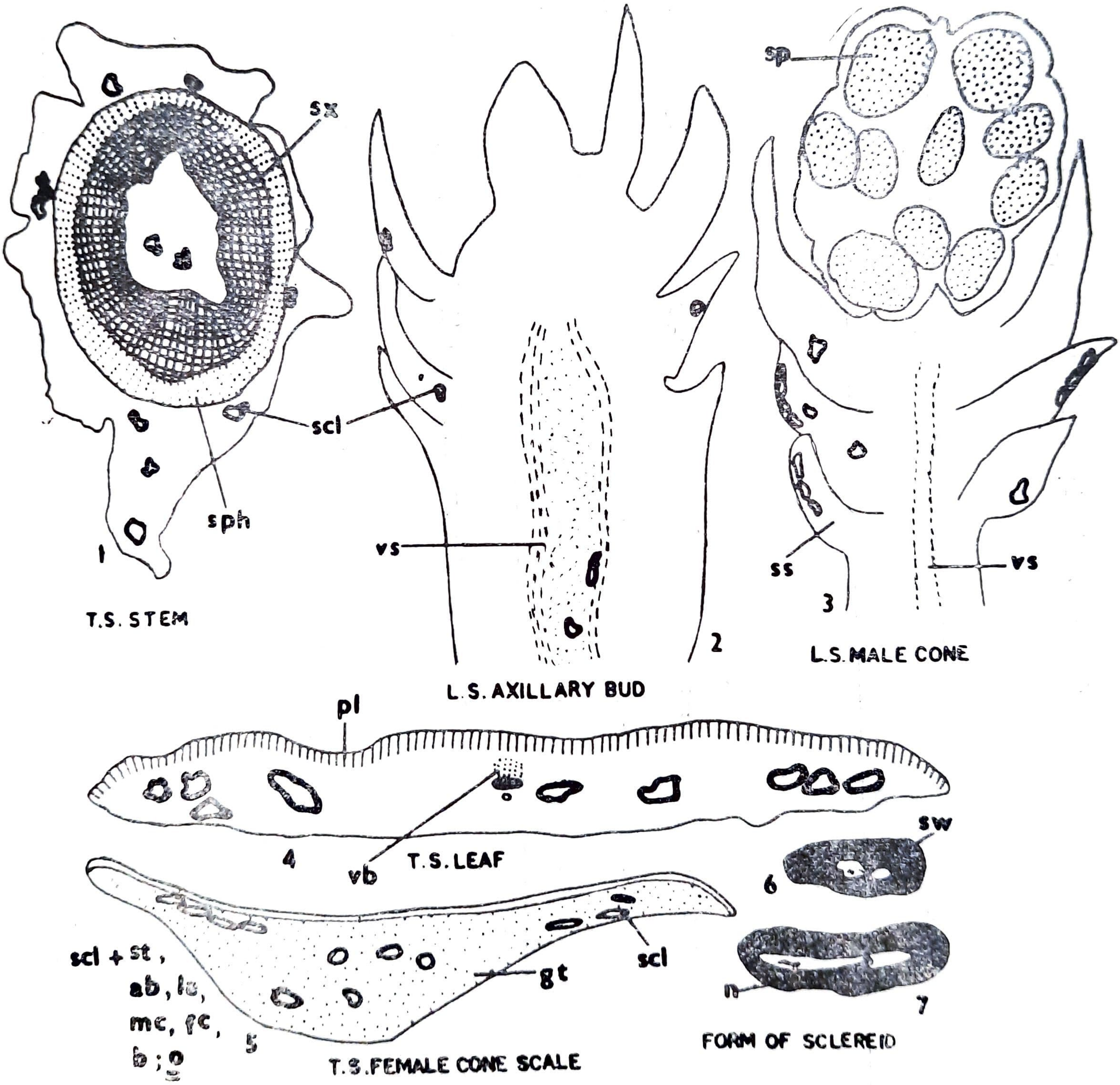
Text-Fig. 1—Gnetaceae (*Gnetum gnemon* & *G. ula*): *a*—astrosclereid; *b*—brachysclereid; *bt*—bizarre types; *f*—fibre; *fc*—female cone; *l*—lumen; *la*—lamina; *le*—leaf; *mc*—male cone; *mrb*—midrib; *n*—nucleus; *o*—osteosclereid; *ov*—ovule; *pc*—pit-canal; *pe*—petiole; *pt*—protoplast; *scl*—sclereid; *sph*—secondary phloem; *st*—stem; *sw*—secondary wall; *sx*—secondary xylem; *vb*—vascular bundle; *vs*—vascular supply; *w*—wall.

Table—1. CONIFERS

Plant organs in which sclereids occur	Names of the Families						
	1:1 Taxaceae	1:1 Cephalotaxaceae	2:18 Podocarpaceae	2:7 Araucariaceae	3:13 Cupressaceae	4:4 Taxodiaceae	4:10 Pinaceae
Stem	B, Very few O	B+O	B	B+O+A	Absent	B+O or also fusiform	B+O+A Absent in *Pinus*
Leaf	O Very few B	Absent	B, O+A	B+O+A B—few	Absent	Absent	Absent
Axillary bud	B	Absent	B	B+O+A	Absent	Absent	Absent
Micro-strobilus	B+O	B+O	B	B+O+A O+A few	B+O+A Polymorphic	B+O	Absent except *Picea B*
Mega-strobilus	B+O	B	B	B+O+A O+A few	B+O+A Polymorphic	B+O	Absent except *Picea B*
Special features of sclereids	Lumen variable in form, sometimes with a *persistent nucleus and protoplasmic remains*	Characteristic peg-like projections with empty lumen. Over the secondary wall, *empty lumen*	Simple sclereids with empty Lumen	Crystalliferous sclereids	Polymorphic sclereids either with contents and persistent nucleus or without contents	Sclereids mostly with tannin in their lumen	Polymorphic sclereids. Lumen varies in different genera

A: Astrosclereid, B: Brachysclereid, O: Osteosclereid.

reproductive parts, mostly brachysclereids with very few osteosclereids. The sclereids are present in one variety, i.e. *T. baccata* var. I in the leaves but are absent in the leaves of the other varieties. They are characteristic in having irregular form of the lumen with disorganised protoplast and a nucleus. The genus *Austrotaxus* was not studied for want of material.



Text-Fig. 2—Taxaceae (*Taxus baccata*): *ab*—axillary bud; *b*—brachysclereid; *fc*—female cone; *gt*—ground tissue; *le*—leaf; *mc*—male cone; *n*—nucleus; *o*—osteosclereid; *pl*—palisade; *scl*—sclereid; *sp*—sporangium; *sph*—secondary phloem; *ss*—sterile sporophyll; *st*—stem; *sw*—secondary wall; *sx*—secondary xylem; *vb*—vascular bundle; *vs*—vascular supply.

Table —2. Family TAXACEAE (See text-fig. 2)

(*Rao & Malaviya 1965 a*)

Name of the plant (*Taxus*)	Distribution of sclereids					Structure of sclereids	
	Stem	Leaf	Axillary buds	Micro-strobilus	Mega-strobilus	Secondary wall + Pit-canals	Lumen
T. baccata var. I.	B O very few	O	B	O+B	B+O	Lamellated, lignified, with deep running Pit-canals.	Shows great variation. Some disorganised protoplast and a nucleus.
T. baccata var. II	B O very few	Absent	B	O+B	B+O	same	same
T. baccata var. III	B O very few	Absent	B	O+B	B+O	same	same
T. baccata var. IV	B O very few	Absent	B	O+B	B+O	same	same

Table—3. Family CEPHALOTAXACEAE (See text-fig. 3)

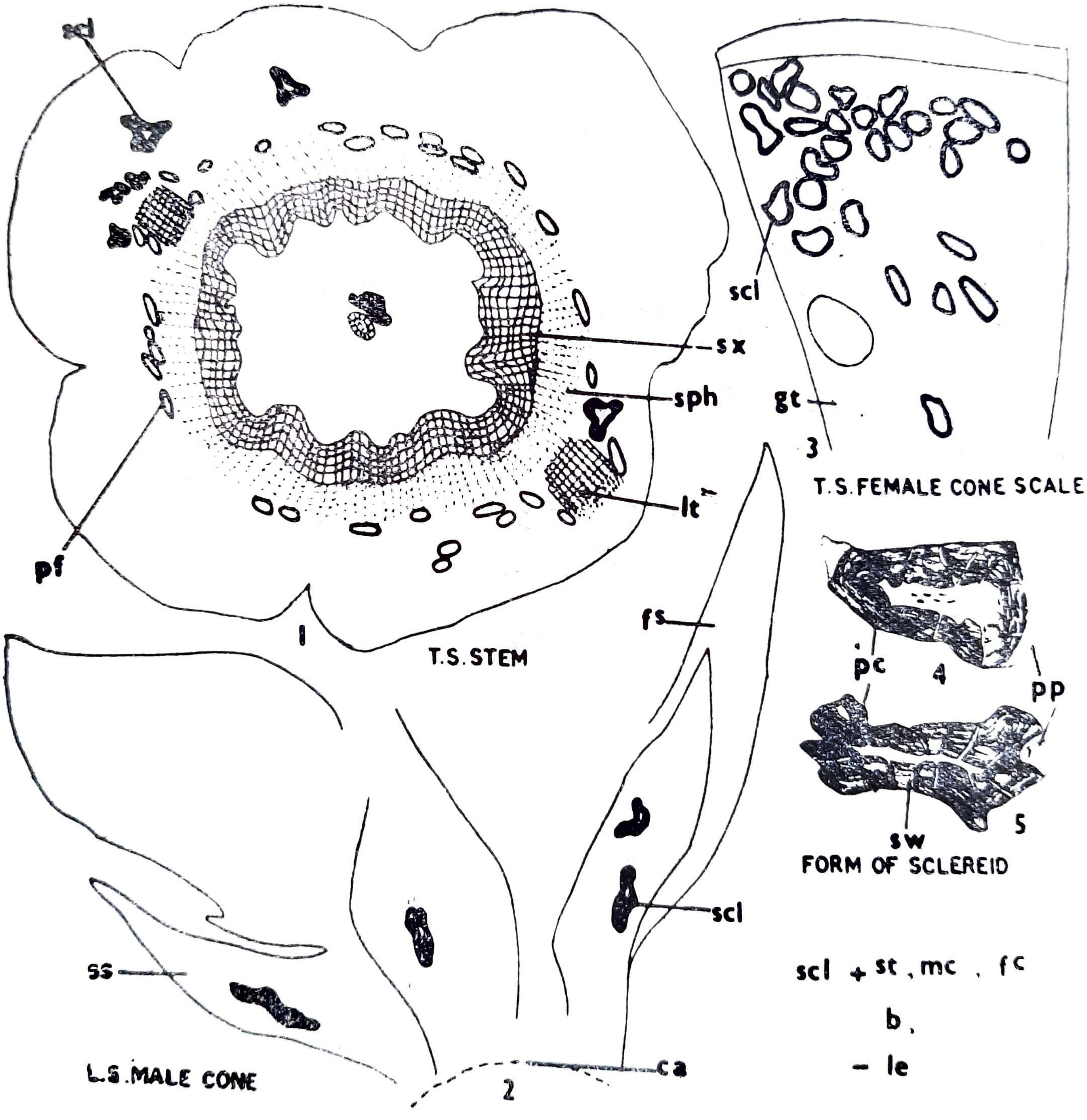
(*Rao & Malaviya 1964 b*)

Name of the plant (*Cephalotaxus*)	Distribution of sclereids					Structure of sclereids	
	Stem	Leaf	Axillary buds	Micro-strobilus	Mega-strobilus	Secondary wall + Pit-canals	Lumen
C. drupacea	B	Absent	Absent	B+O	B+O	Lamellated, thick lignified secondary wall, traversed by pit-canals. Small, pointed or blunt processes over the secondary wall. They appear to be original cell protoplast cornered during lignification.	Empty at maturity

Cephalotaxaceae

Text-fig. 3, Table 3

Sclereids differ very clearly from those of Taxaceae. They are totally absent from the leaves of *Cephalotaxus*, and are mostly of *brachysclereid type* with characteristic peg like projections on the secondary wall. These are the "left over" remains of the original cell protoplast which is cornered during lignification. These give the sclereids a very characteristic appearance.

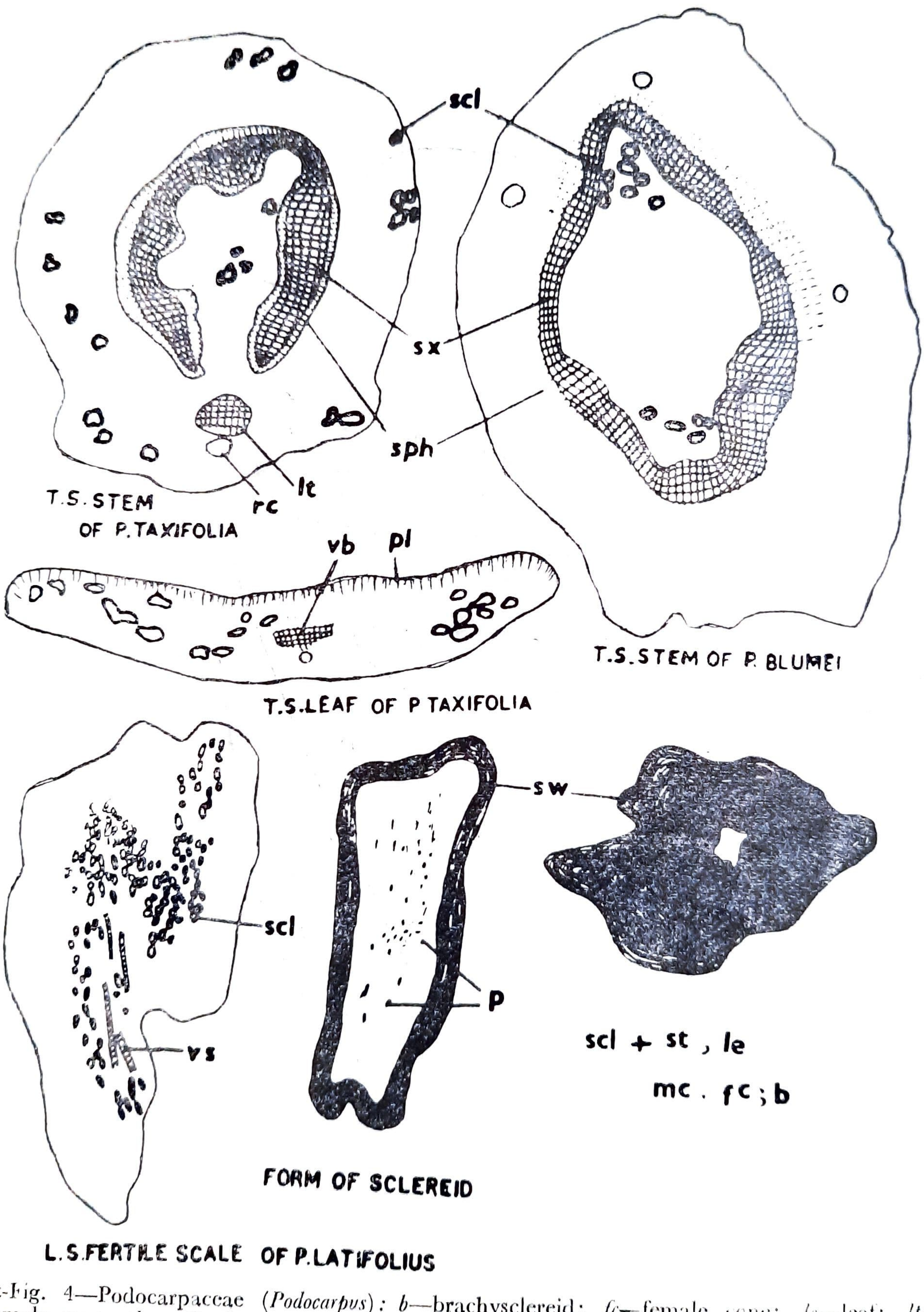


Text-Fig. 3—Cephalotaxaceae (*Cephalotaxus drupacea*): *b*—brachysclereid; *ca*—cone axis; *fc*—female cone; *fs*—fertile sporophyll; *gt*—ground tissue; *le*—leaf; *lt*—leaf trace; *mc*—male cone; *o*—osteosclereid; *pc*—pit-canal; *pf*—phloem fibre; *pp*—protoplasmic process; *scl*—sclereid; *sph*—secondary phloem; *ss*—sterile sporophyll; *st*—stem; *sw*—secondary wall; *sx*—secondary xylem.

Podocarpaceae

Text-fig. 4, Table 4

Table 4 shows the distribution and type of sclereids in the *Podocarpaceae*. Seventeen species of Podocarpus were studied and the sclereids are exclusively of the brachysclereid type in all the species. In some species, i.e. 1-10, sclereids occur in large numbers in the stem and leaves. All the micro and mega sporangiate cones could not be examined for want



Text-Fig. 4—Podocarpaceae (*Podocarpus*): *b*—brachysclereid; *fc*—female cone; *le*—leaf; *lt*—leaf-trace; *mc*—male cone; *pl*—palisade; *rc*—resin canal; *scl*—sclereid; *sph*—secondary phloem; *st*—stem; *sw*—secondary wall; *sx*—secondary xylem; *vb*—vascular bundle; *vs*—vascular supply.

Table—4. Family PODOCARPACEAE (See text-fig. 4)

(*Rao & Malaviya* 1965*b*)

Name of Plant (*Podocarpus*)	Distribution of sclereids					Structure of sclereids	
	Stem	Leaf	Axillary buds	Micro-strobilus	Mega-strobilus	Secondary walls & Pit-canals	Lumen
PODOCARPUS							
1. *P. falcatus*	+	+	×	×	×	THICK, LAMELLATED, NUMEROUS PIT-CANALS SIMPLE OVAL OR ROUNDED APERTURES OF PITS	EMPTY AT MATURITY.
2. *P. taxifolia*	+	+	×	×	×		
3. *P. gracilior*	+	+	×	×	×		
4. *P. littoralis*	+	tt	×	×	×		
5. *P. chilinus*	+	+	×	×	×		
6. *P. blumei*	+	+very few	×	×	×		
7. *P. sps.*	+	+	×	×	×		
8. *P. javanicus*	+	+	×	×	×		
9. *P. neglectans*	+	+	×	×	×		
10. *P. coriaceous*	+	+	×	—	×		
11. *P. elatus*	—	tt+	×	×	×		
12. *P. chinensis*	—	tt+	×	×	×		
13. *P. macrophyllus*	—	tt+	×	×	×		
14. *P. neriifolius*	—	tt+	+	—	×		
15. *P. alifolius*	—	tt+	+	—	+		
16. *P. sp.* (Calcutta)	—	tt+	—	—	—		
17. *P. sp.* (,,)	—	tt+	—	—	—		
DACRYDIUM *Dacrydium sp.*	+	+	×	—	×	Brachy, osteo and astro sclereids with comparatively thinner secondary walls than in the sclereids of *Podocarpus*.	

of material. Other species from 11-17 show no sclereids in either stem or leaves, but have transfusion tissue in the leaves. One unidentified species of *Dacrydium* has only brachy-sclereids in the stem, brachy, osteo and astrosclereids in the leaves and no sclereids in cones.

A point of interest is that these species of *Podocarpus* which show transfusion tissue in the leaves do not show any foliar sclereids, and those with foliar sclereids show no transfusion tissue. This feature splits the genus *Podocarpus* into two sections. All the species studied show exclusively simple brachysclereids.

Araucariaceae

Text-figs. 5, 6, Table 5

Table 5 shows the distribution and form of sclereids in the family Araucariaceae. In *Araucaria* (Text-Fig. 5) as well as *Agathis* (Text-Fig. 6) the sclereids are present in the stem, leaves, micro and megasporangiate cones. The sclereids are characterised by the presence of numerous crystals of calcium oxalate in the secondary wall and also in the lumen. The sclereids of both the genera are very similar, except for a minor difference, i.e. there are no pit-canals in the secondary wall of the sclereids of *Araucaria*, while they are present in *Agathis*. Another point is that osteosclereids are very few in *Agathis* while in *Araucaria* all three of them occur abundantly. These sclereid differences although of a minor nature do help to distinguish these two genera to some extent.

Cupressaceae

Text-figs. 7, 8, Table 6

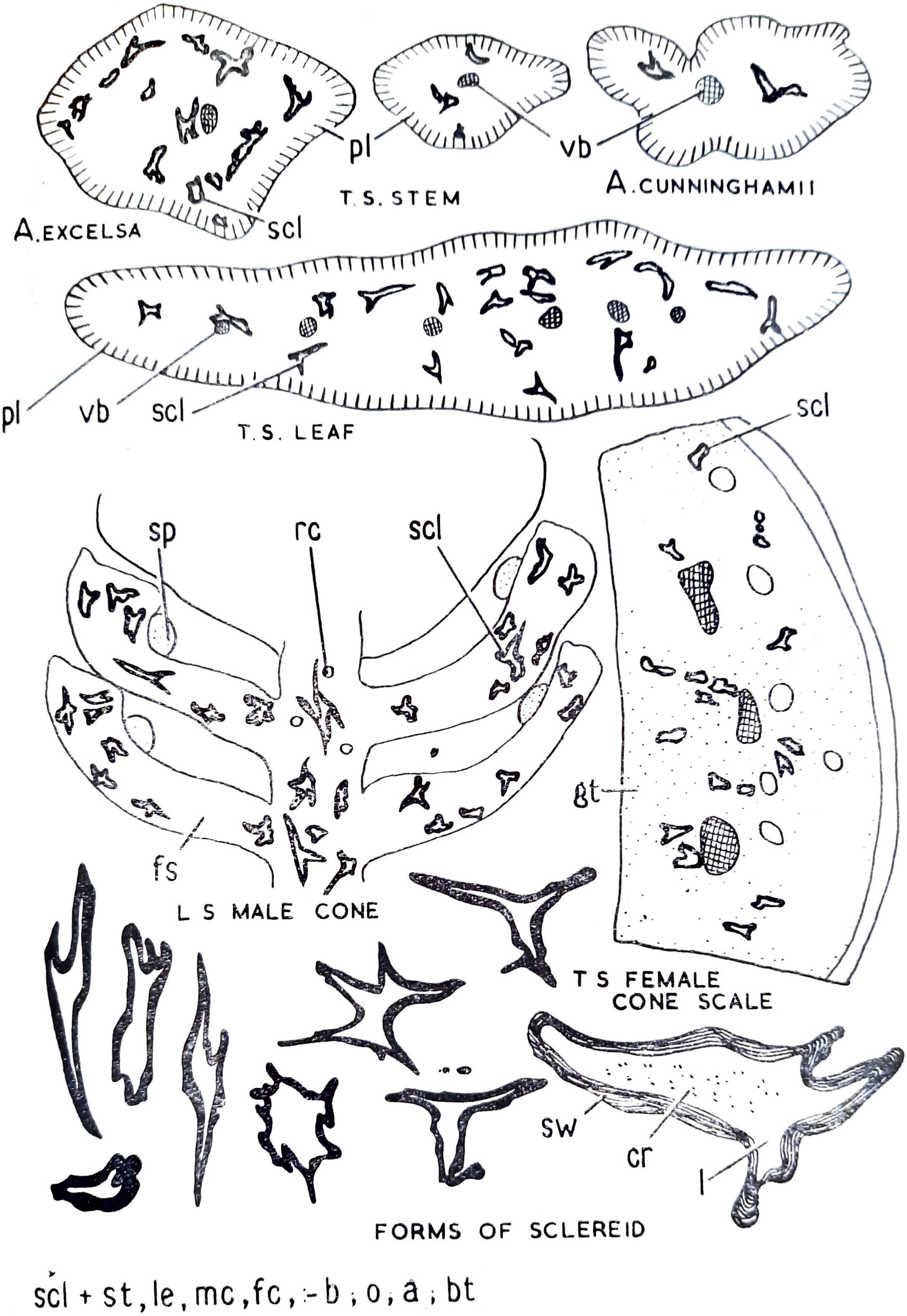
In table 6 are shown the sclereids of the family Cupressaceae. In the 7 species of *Cupressus* studied, all three types of sclereids are present in the micro and megasporangiate cones, while they are absent in the stem and leaves. The sclereids are characterised by the presence of a persistent nucleus, either one or two in the lumen, along with some disorganised protoplast. In the four species of *Juniperus* studied, the sclereids have no nuclei which is a distinguishing feature. In the two species of *Thuja* (Text-fig. 8) also there are no nuclei in the adult sclereid. In *Thuja* in addition to the brachy, osteo and astrosclereids, bizarre types either H-shaped, Y-shaped, or of various other peculiar forms, are also found. Polymorphism of sclereids is rather a characteristic feature of the two species of *Thuja* and it helps to distinguish them from the other members of the family.

Taxodiaceae

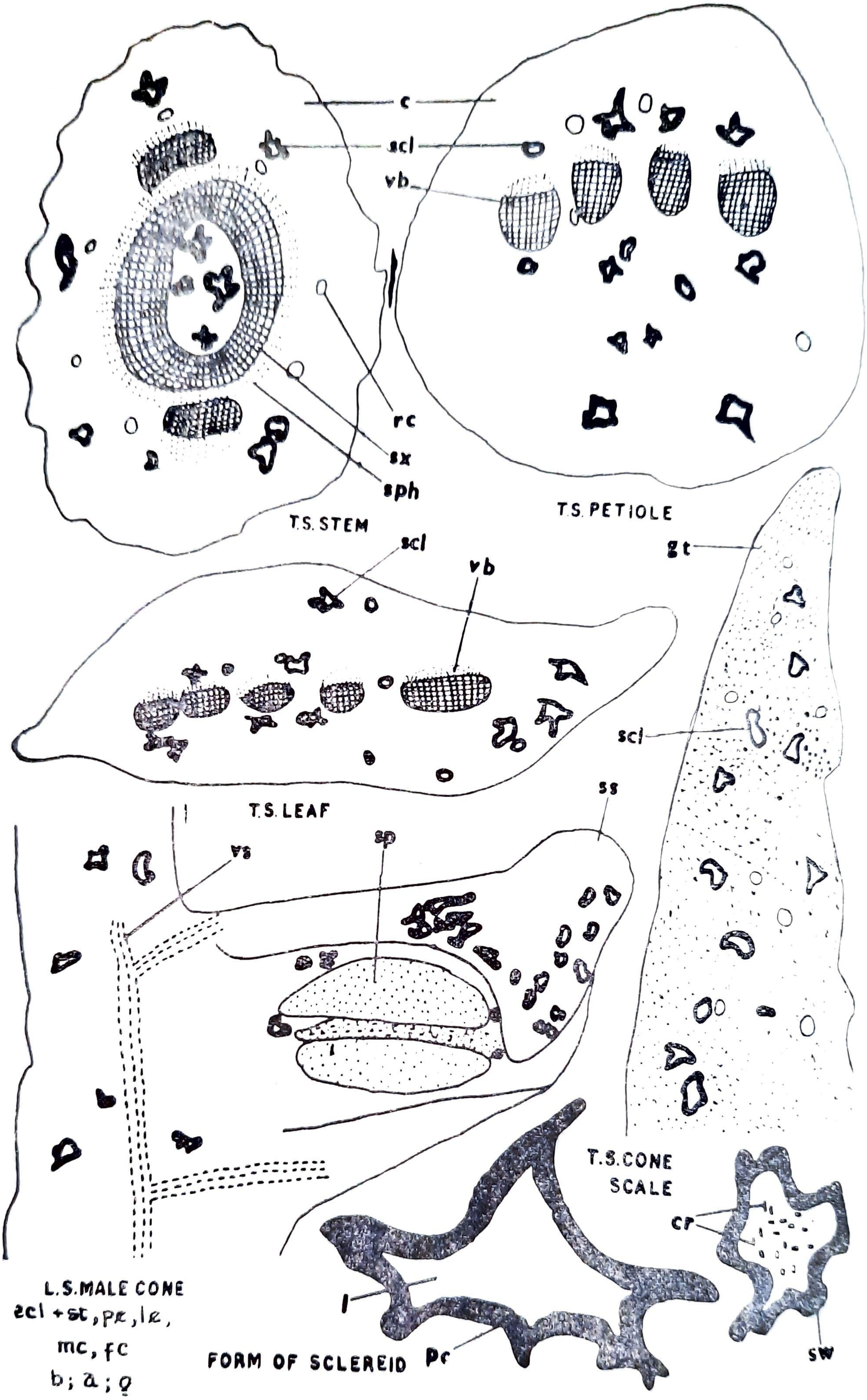
Text-figs. 9, 10, Table 7

Table 7 show the form and distribution of sclereids in Taxodiaceae. In *Cryptomeria japonica* sclereids are present in the stem and micro megasporangiate cones. Sclereids are of the brachysclereid type or fusiform types. They have tannin lobules present in their lumen sometimes also along with a nucleus.

In *Cunninghamia lanceolata* (Text-fig. 10) we find both brachy and osteosclereids, also having tannin in their lumen. In *Taxodium distichum* sclereids are only of the fusiform type with very few brachysclereids. In *Sciadopitys verticillata* only astrosclereids with empty lumen occur in the leaves and in the stem there occur thick walled, empty brachysclereids. No sclereids are present in the male and female cones. Thus in this family the above mentioned genera can be distinguished from each other on sclereid basis.



Text-Fig. 5—Araucariaceae (*Araucaria cookii*): *a*—astrosclereid; *b*—brachysclereid; *bt*—bizarre type; *cr*—crystal; *fc*—female cone; *fs*—fertile sporophyll; *gt*—ground tissue; *l*—lumen; *le*—leaf; *mc*—male cone; *o*—osteosclereid; *pl*—palisade; *rc*—resin canal; *scl*—sclereid; *sp*—sporangium; *st*—stem; *sw*—secondary wall; —vascular bundle.

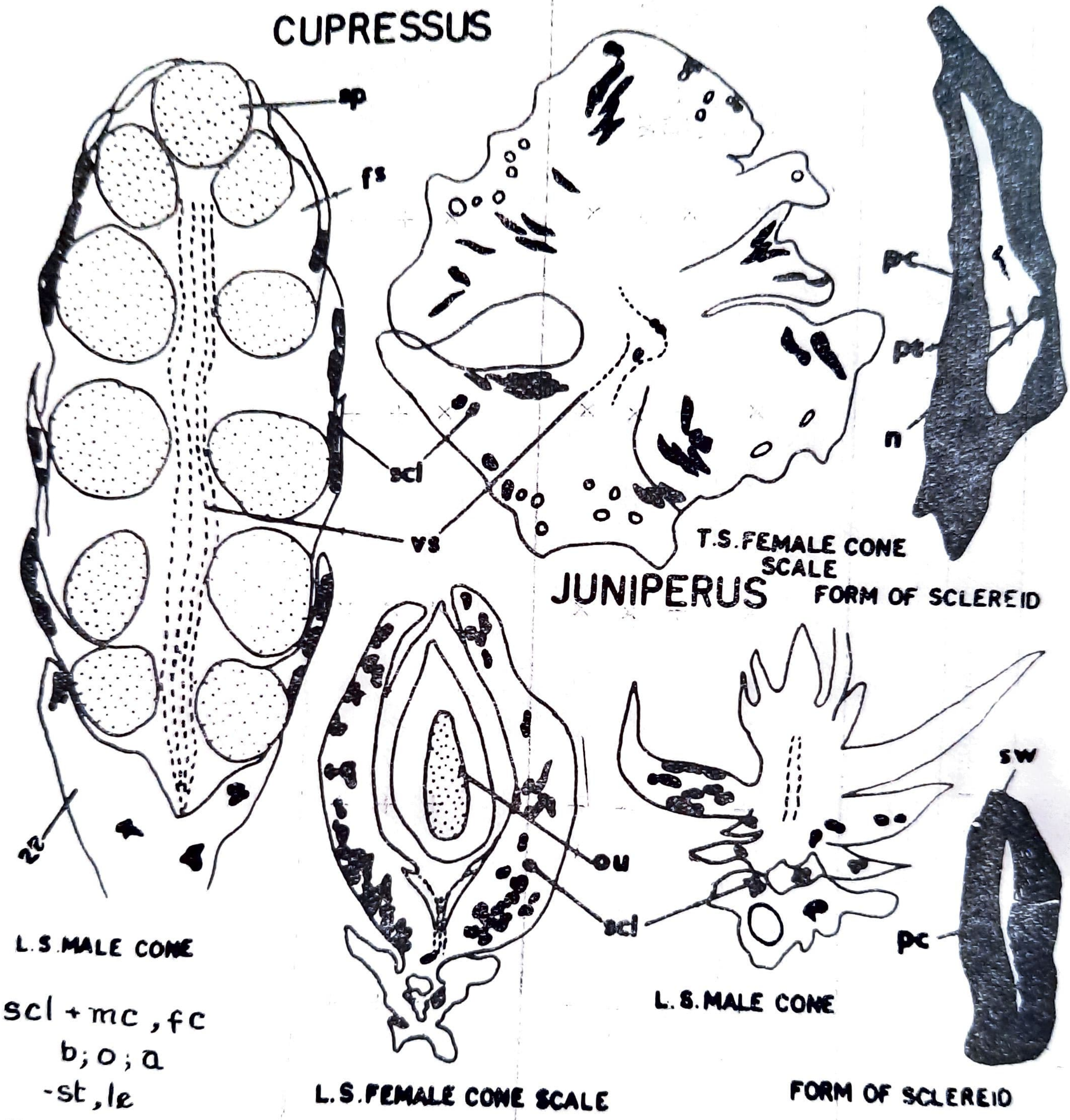


Text-Fig. 6—Araucariaceae (*Agathis loranthifolia*, *A. robusta* & *A. obtusa*): *a*—astrosclereid; *b*—brachysclereid; *c*—cortex; *cr*—crystal; *fc*—female cone; *gt*—ground tissue; *l*—lumen; *le*—leaf; *mc*—male cone; *o*—osteosclereid; *pc*—pit-canal; *pe*—petiole; *rc*—resin canal; *scl*—sclereid; *sp*—sporangium; *sph*—secondary phloem; *ss*—sterile sporophyll; *st*—stem; *sw*—secondary wall; *sx*—secondary xylem; *vb*—vascular bundle; *vs*—vascular supply.

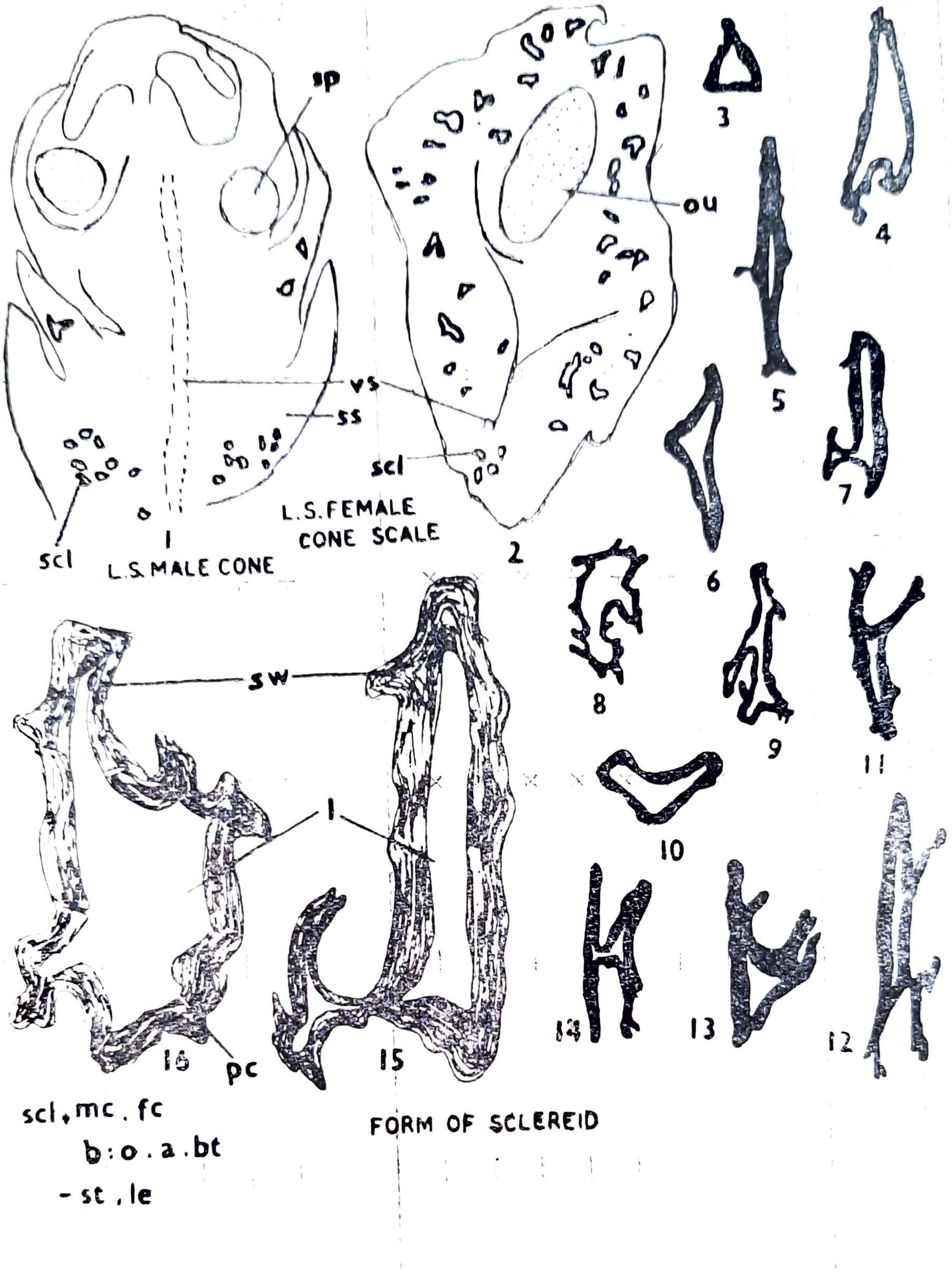
Table—5. Family ARAUCARIACEAE (See text-figs. 5 & 6)

(*Rao & Malaviya* 1964*a*, 1968)

Name of the Plant	Distribution of Sclereids					Structure of Sclereids	
	Stem	Leaf	Axillary buds	Micro-strobilus	Mega-strobilus	Secondary wall & Pit-canals	Lumen
ARAUCARIA							
1. *A. cooki*	+ Only in cortex	+	×	×	×	CRYSTALLIFE ROUS ($Ca_2G_2O_4$) SCLEREIDS; THICK, LAMEL-LATED *NO PIT-CANALS.*	LUMEN EMPTY EXCEPT SOME CRYSTALS.
2. *A. bidwilli*	+	+	+	+	×		
3. *A. excels*	+	+	×	×	×		
4. *A. cunninghami*	+	+	×	×	×		
AGATHIS							
1. *A. loranthifolia*	+	+	×	×	×	Do.	Do.
2. *A. robusta*	+	+	×	+	+	PIT CANALS PRESENT O—	
3. *A. obtusa*	+	+	×	+	+	VERY FEW	



Text-Fig. 7—Cupressaceae (*Cupressus* & *Juniperus*) *a*—astrosclereid; *b*—brachysclereid; *fc*—female cone *s*—fertile sporophyll; *le*—leaf; *mc*—male cone; *n*—nucleus; *o*—osteosclereid; *ov*—ovule; *pc*—pit-canal; pt—protoplast; *scl*—sclereid; *sp*—sporangium; *as*—sterile sporophyll; *st*—stem; *sw*—secondary well; *vs*—vascular supply.

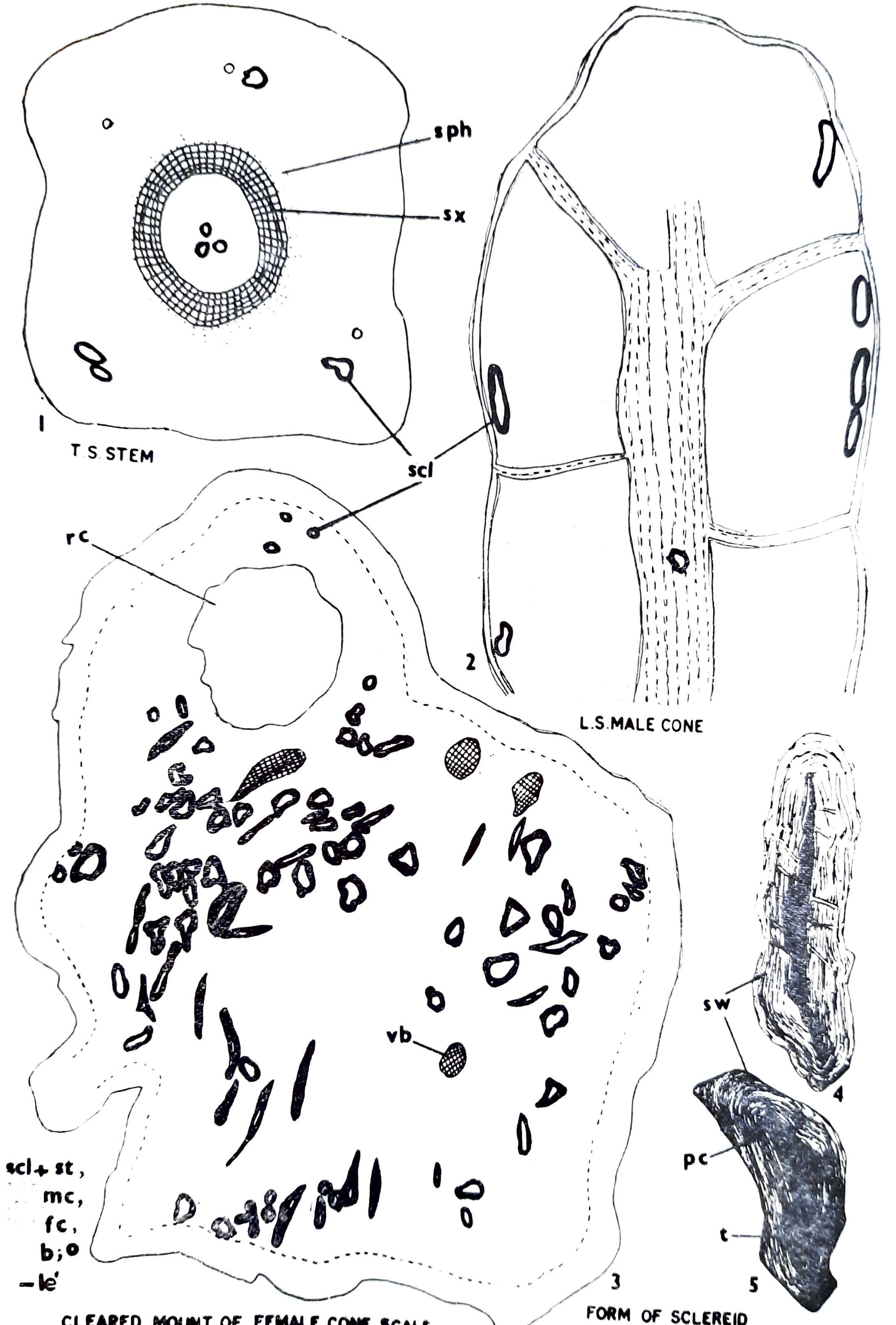


Text-Fig. 8—Cupressaceae (*Thuja occidentalis* & *T. orientalis*): *a*—astrosclereid; *b*—brachysclereid; *bt*—bizarre type; *fc*—female cone; *l*—lumen; *le*—leaf; *mc*—male cone; *o*—osteosclereid; *ov*—ovule; *pc*—pit canal; *scl*—sclereid; *sp*—sporangium; *ss*—sterile sporophyll; *st*—stem; *sw*—secondary wall; *vs*—vascular supply

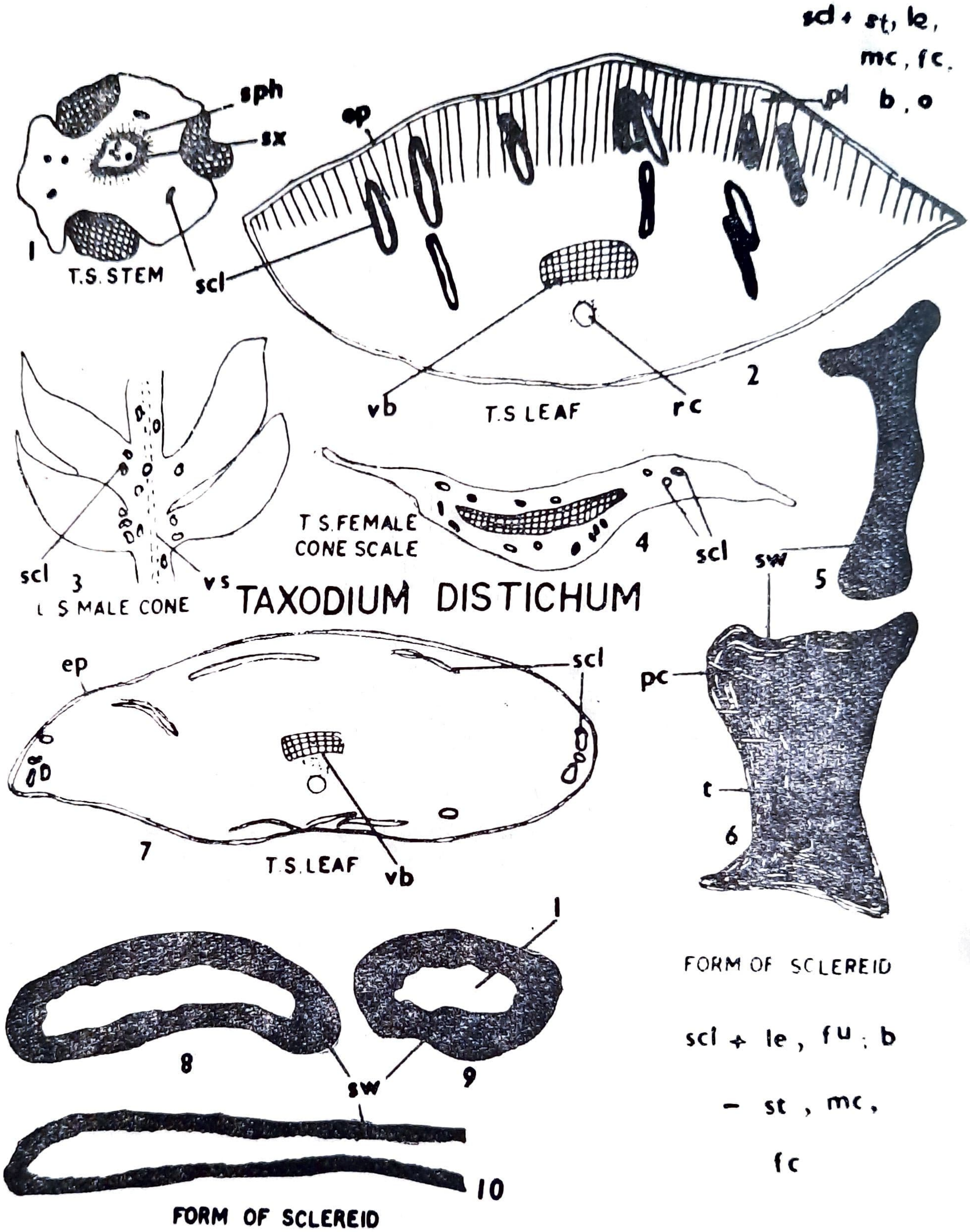
Table—6. Family CUPRESSACEAE (See text-fig. 7 & 8)

(*Rao & Malaviya* 1967, 1970)

Name of plant	Distribution of sclereids					Structure of sclereids	
	Stem	Leaf	Axillary buds	Micro-strobilus	Mega-strobilus	Secondary wall & pit-canals	Lumen
CUPRESSUS							
1. *C. macrocarpa*	—	—	×	+	+	B. O. AND A POLYMORPHIC; THICK, LAMELLATED, PITS CANALS NUMEROUS	PERSISTENT NUCLEUS OR 2, 3, NUCLEI & DIS-ORGANIZED CELL PROTO-PLAST.
2. *C. goveniana*	—	—	×	+	+		
3. *C. funebris*	—	—	×	+	+		
4. *C. lusitanica*	—	—	×	+	×		
5. *C. sempervirens*	—	—	×	×	×		
6. *C. torulosa*	—	—	×	×	×		
7. *C. lindleyi*	—	—	×	×	×		
JUNIPERUS							
1. *J. chinensis*	—	—	×	+	+	B, O AND A POLYMORPHIC VARIATION GREATER	NUCLEUS ABSENT, EMPTY AT MATURITY
2. *J. formosana*	—	—	×	+	+		
3. *J. procera*	—	—	×	+	+	DO.	
4. *J. sp.*	—	—	×	+	+		
THUJA						B, O AND A BIZZARRE TYPES MAXIMUM POLY MORPHISM NOT DISTINCTLY LAMELLATED, NO PITS	In ♂ Granular protoplasmic contents In ♂ empty
1. *T. occidentalis*	—	—	—	+	+		
2. *T. orientalis*	—	—	—	+	+		



Text-Fig. 9—Taxodiaceae (*Cryptomeria japonica*) *b*—brachysclereid; *fc*—female cone; *le*—leaf; *mc*—male cone *o*—osteosclereid; *pc*—pit-canal; *rc*—resin canal; *scl*—sclereid; *sph*—secondary phloem; *st*—stem; *sw*—secondary wall; *sx*—secondary xylem; *t*—tannin; *vb*—vascular bundle.



Text-Fig. 10—Taxodiaceae (*Cunninghamia lanceolata*): *b*—brachysclereid; *ep*—epidermis; *fc*—female cone; *fu*—fusiform sclereid; *l*—*lumen*; *le*—leaf; *mc*—male cone; *o*—steosclereid; *pc*—pit-canal; *pl*—palisade; *rc*—resin canal; *scl*—sclereid; *sph*—secondary phloem; *st*—stem; *sw*—secondary wall; *sx*—secondary xylem; *t*—tannin; *vb*—vascular bundle; *vs*—vascular supply.

Table—7. Family TAXODIACEAE (See text-figs. 9 & 10)

(*Rao & Malaviya* 1963, 1967c, 1968
Rao & Tewari 1961)

Name of Plant	Distribution of sclereids					Structure of sclereids	
	Stem	Leaf	Axillary buds	Micro-strobilus	Mega-strobilus	Secondary wall & pit-canals	Lumen
Cryptomeria iaponica	+ (few)	—	×	(+)	(+)	THICK, LA-MELLATED, NUMEROUS PIT-CANALS B & FUSIFORM	Tannin (PHLO-BAPHENES) LUMPS OR OCCUPYIN ENTIRE LUMEN *NUCLEUS ALSO PRESENT*
Cunninghamia lanceolata	+ (more)	(+)	×	(+)	(+)	THICK LA-MELLATED, NUMEROUS PIT-CANALS	TANNIN PRE-SENT ONLY in few sclereids.
Taxodium distichum	—	+	—	—	—	HOMOGENOUS-LY THICK WALLED: NO PIT-CANALS SOME SORT OF INCLUSIONS IN THE LUMEN FUSIFROM	
Sciadopitys verticillata	+	+	×	—	—	Leaf sclereids exclusively of astro-sclereid types with empty lumen, pointed arms stem sclereid ex-clusively of brachysclereid types with an empty lumen.	

Pinaceae

Text-figs. 11, 12, Table 8

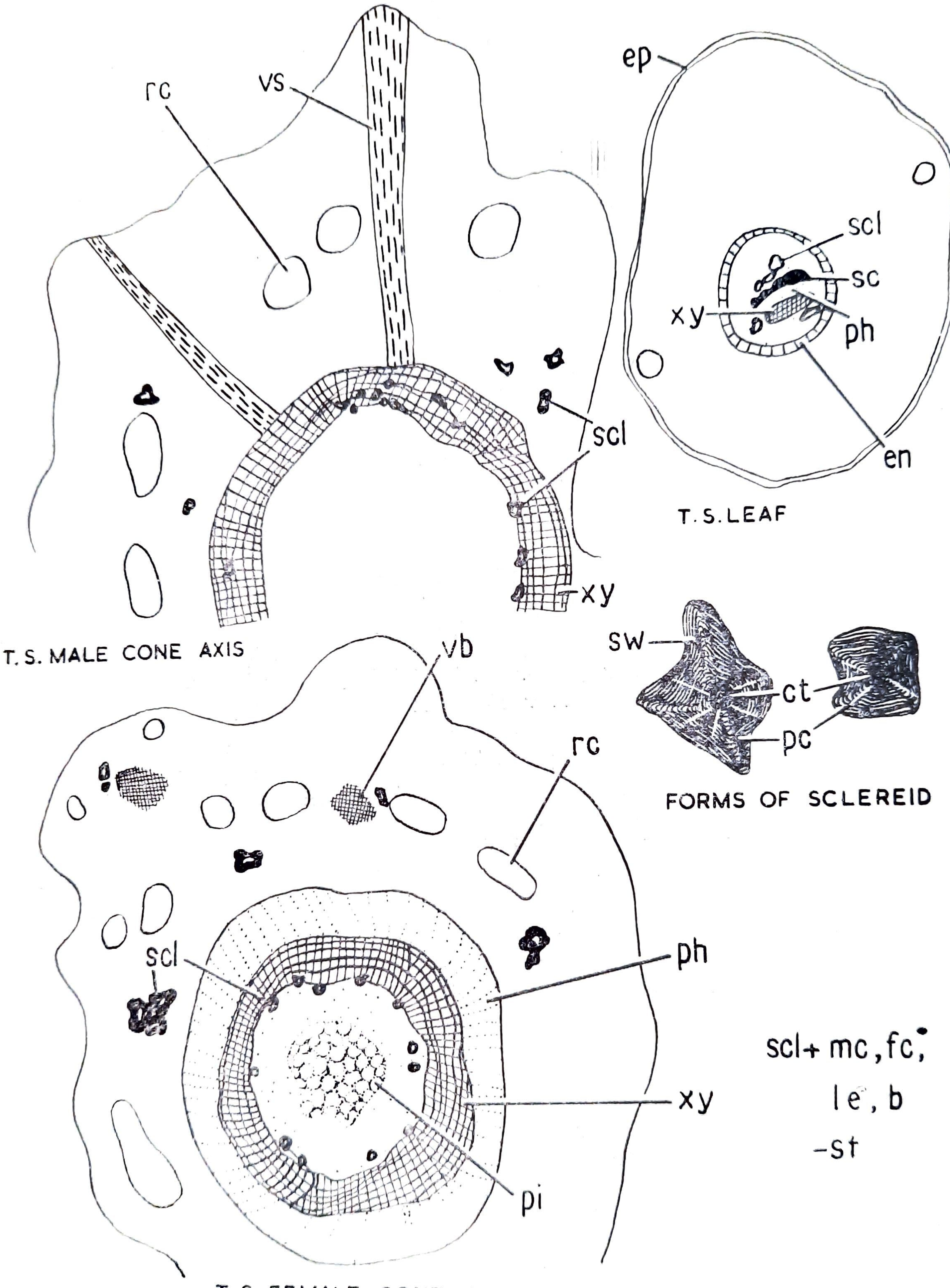
The family Pinaceae shown in table 8 also has characteristic sclereid features for different genera. *Picea morinda* (Text-Fig. 11) is characterised by the presence of mostly squarish brachysclereids in micro and megasporangiate cones, and very few in the leaves. No sclereids occur in stem. In the two species of *Cedrus* and 3 species of *Abies* (Text-fig. 12) studied so far only *cauline* sclereids are present. They are of brachy, osteo and astrosclereid type. Hence these two genera differ from *Picea* very clearly. In *Cedrus* some sclereids have their lumen partitioned off into several lumina giving the appearance of septate lumen. But actually this is not a true cellular condition. These partitions seem to be the disorganised remains of the protoplast mixed with the wall substance. In *Abies* the sclereid lumen is continuous. In the three species of *Pinus* studied here, no sclereids occur in any part of the sporophyte although SACHER (1954) records the occurrence of sclereids in the cortex of the shoots of *Pinus ponderosa*. Thus all four genera, i.e. *Pinus*, *Cedrus*, *Abies* and *Picea* can be distinguished easily on sclereid basis.

DISCUSSION

A detailed study of the structure, distribution and ontogeny of sclereids in a number of Indian conifers, has brought out the fact that the sclereid features are not uniform in all of them. This will be evident from a careful study of all the tables included in this paper. Each family and each genus seems to have its own peculiarity of sclereid structure and arrangement. This observation has been a little encouraging. Although it is not possible at this stage to state categorically that the sclereids are of the first rate taxonomic value. Yet they do help to some extent in taxonomy, perhaps when considered along with other morphological and anatomical criteria. This aspect assumes some importance when one has to deal with fragmentary conifer materials, living or fossil, particularly the latter. For example the fossil shoot of *Brachyphyllum* found in Jurassic (Rajmahal) India and regarded generally as araucarian shows sclereids exactly like those found in the living genus *Araucaria* (RAO, MALAVIYA & MENON, 1965).

A perusal of the different tables included in this paper shows that to some extent sclereid characters may help in the identification of conifers at the generic level. But the same degree of usefulness of sclereid characters does not present itself at the specific level. Still in some genera like *Podocarpus*, *Araucaria* and *Abies* the pattern of distribution and structure of sclereids seem to differ even at specific level. For example in the genus *Podocarpus* the first ten species (see Table 4) have sclereids in stem and leaves. Other species from 11-17 have no sclereids at all. Hence the two groups can be easily distinguished from each other. *P. latifolius* has no sclereids in stem and leaves, but sclereids are present in the megastrobilus. It is possible that the megastrobilate cones of other species also have sclereids but due to non-availability of the material they could not be examined.

Araucaria cooki has sclereids only in the cortical region of the stem and not in the pith while the *A. bidwilli* and *A. cunninghamia* (see Table 5) have sclereids in cortical as well as pith regions. Turning to the genus *Abies*, *A. alba* has only very few brachysclereids in the pith regions of the stem, while *A. webbiana* and *A. balsamea* have all the three types of sclereids. Thus, though primarily helpful in generic identifications, sclereid features may in some cases be helpful in specific identifications also. After all, the data collected in this paper


rc
vs
ep
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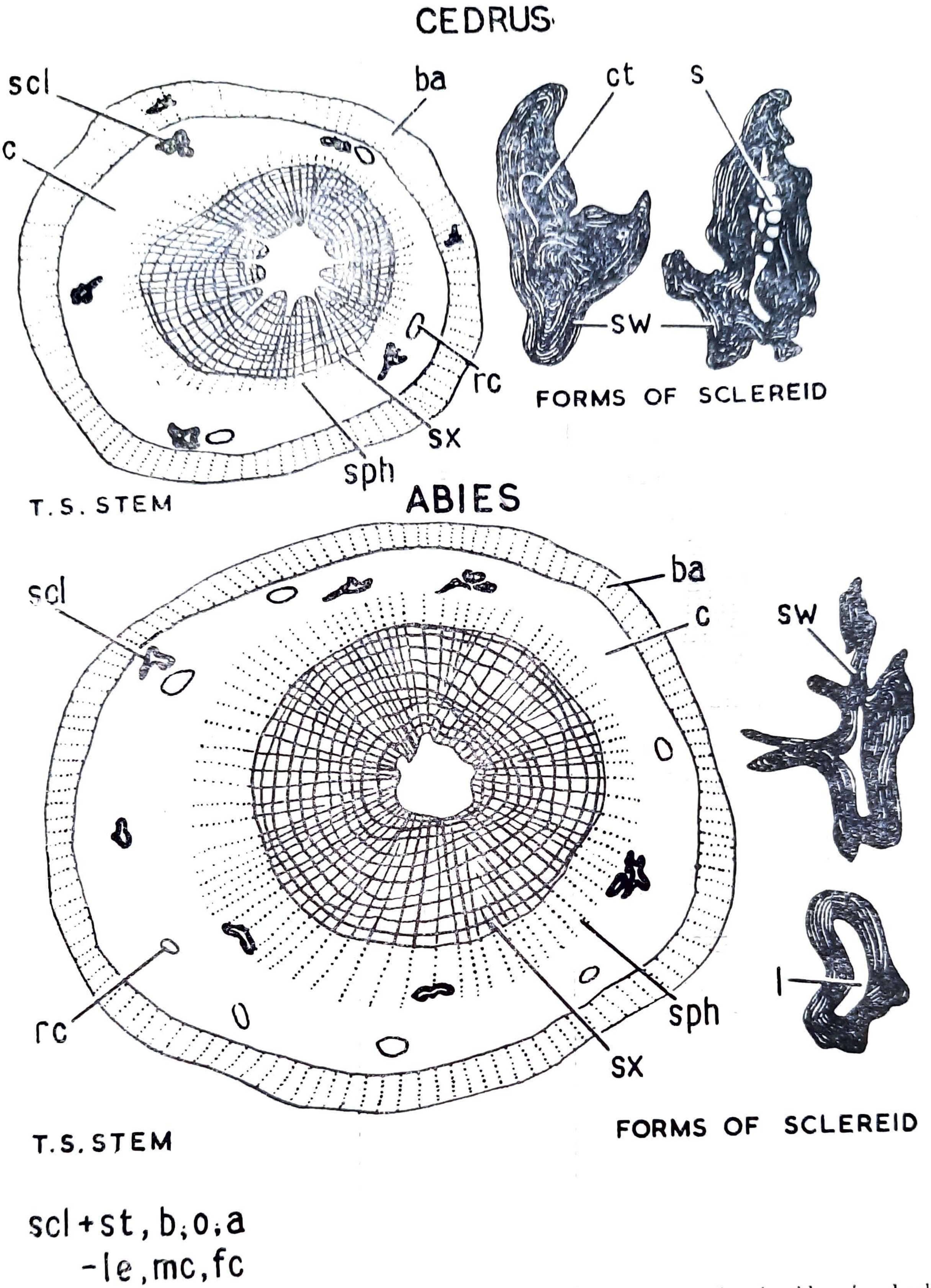
T. S. LEAF
scl
xy
T. S. MALE CONE AXIS
vb
sw
ct
pc
FORMS OF SCLEREID
rc
scl
ph
scl+ mc, fc,
le, b
-st
xy
pi
T. S. FEMALE CONE AXIS

Text-Fig. 11.



Text-Fig. 12—Pinaceae (*Cedrus* and *Abies*): *a*—astrosclereid; *b*—brachysclereid; *ba*—bark; *c*—cortex; *ct*—cell content; *fc*—female cone; *l*—lumen; *le*—leaf; *mc*—male cone; *o*—osteosclereid; *rc*—resin-canal; *s*—sep um; *scl*—sclereid; *sph*—secondary phloem; *sw*—secondary wall; *sx*—secondary xylem.

Table—8. Family PINACEAE (See text-figs. 11 & 12)

(*Rao & Sharma* 1967 *b* & *c*)

Name of Plant	Distribution of sclereids: Stem	Leaf	Axillary buds	Micro-strobilus	Mega-strobilus	Structure of sclereids: Secondary wall & pit-canals	Lumen
PICEA							
P. morinda (DIETRICHUS)	—	+ few near vascular bundles	×	(+)	(+)	*THICK LAMELLATED PIT-CANALS DEEP*	♂ -*CONTENTS PRESENT* ♀ -*EMPTY AT MATURITY*
CEDRUS							
1. *C. deodara*	+ (in bark)	—	—	—	—	B, O AND A THICK, LA-MELLATED, PITTED	*LUMEN PARTITIONED* BY DIS-ORGANIZED PROTOPLAST +LIGNIN
2. *C. libanii*	+ (in bark)	—	—	—	—		
ABIES							
1. *A. alba*	+ (only *B* few)	—	—	—	—		
2. *A. webbiana*	+	—	—	—	—	MORE VARIABLE	LUMEN CONTINUOUS NO CONTENTS
3. *A. Balsamea*	+	—	—	—	—	DO.	
PINUS							
1. *P. excelsa*	NO SCLEREIDS IN ANY PART OF THE SPOROPHYTE						
2. *P. Longifolia*							
3. *P. girardiana*							

FUNCTIONS OF SCLEREIDS IN CONIFERS

Sclereids seem to be mostly of the nature of mechanical tissue giving rigidity and strength to the plant parts in which they occur. A function which has been attributed to them by HABERLANDT (1914), FOSTER (1949), RAO (1957) and ESAU (1962). In most of the woody cones their rigidity may be due either to the presence of sclereids or fibres as in *Pinus* or exclusively to the presence of sclereids as in *Cryptomeria* and *Cunninghamia* or due to the presence of both tissues as in *Cupressus* and *Juniperus*. Thus it appears that both the sclereids and bast fibres may contribute to the rigidity of woody cones in conifers.

It is rather interesting to note that in *Podocarpus* and *Taxus* sclereids occur in the leaves of those species where transfusion tissue is not present. Sclereids are totally absent in the leaves of those species where transfusion tissue is present. This raises a doubt as to whether one of the functions of the sclereid may be as a minor alternative to translocatory tissue. This is further supported by the presence of pits and pit-canals in the secondary wall of the adult sclereid which perhaps play some part in lateral diffusion of materials. But in the leaves of a species of *Dacrydium* investigated both sclereids and transfusion tissue are present although the latter is very little. But on the side where sclereids are present very little or no transfusion tissue is present.

The presence of crystals in the walls and lumen of the adult sclereids of genera like *Agathis* and *Araucaria* or the occurrence of tannin in the lumen of the genera Cryptomeria and Cunninghamia, suggest that they function as repositories of excretory or secretory products as the idioblasts of plants (FOSTER, 1956; ESAU 1962).

Whatever may be the structure, taxonomic importance or function of the sclereids it is evident from the present study that the sclereids are no longer to be considered insignificant, or unimportant plant cells to be simply referred to as sclerenchyma cells, fibres, stone-cells; idioblasts, etc. They constitute definite, fixed, significant entities in the patterns of plant anatomy.

A key for the identification of the different genera of conifers studied so far, on the basis of sclereid form and distribution.

A. OSTEOSCLEREIDS OR FUSIFORM SCLEREIDS

(1) Only foliar sclereids; Secondary wall homogenous; devoid of pits; some stainable contents in lumen .. .. *Taxodium distichum*

B. BRACHYSCLEREIDS

(1) Foliar, cauline and strobilar sclereids; lumen empty, simple sclereids .. .. *Podocarpus*

(*a*) Cauline and foliar sclereids .. .. *P. falcatus, P. taxifolia, P. gracilior, P. littoralis, P. chilinus, P. blumei, P. sps., P. javanicus, P. neglectans, P. coriaceous*

(*b*) Only strobilar sclereids .. .. *P. latifolius*

(*c*) Foliar and cauline sclereids totally absent .. *P. elatus, P. chinensis, P. macrophyllus, P. neriifolius, P. latifolius, P. sp.* 1, *P. sp.* 2

(2) Mostly strobilar and a few foliar sclereids squarish in form with contents .. .. *Picea morinda*

C. BRACHY AND OSTEOSCLEREIDS

(1) Foliar, cauline and strobilar sclereids.

(*a*) Sclereids with irregular lumen and persistent nucleus .. .. .. *Taxus baccata*

(*b*) Sclereids with tannin in lumen; peg-like processes over the secondary wall .. .. *Cunninghamia lanceolata*

(2) Strobilar and cauline sclereids, foliar sclereids absent

(*a*) Peg-like protoplasmic processes over the secondary wall; empty lumen .. .. *Cephalotaxus drupacaea*

(*b*) No peg-like processes; tannin present in lumen .. .. .. *Cryptomeria japonica*

D. BRACHY AND ASTROSCLEREIDS

(1) Foliar and cauline sclereids, strobilar sclereids absent .. .. *Sciadopitys verticillata*

E. BRACHY, OSTEO AND ASTROSCLEREIDS

(1) Foliar, cauline and strobilar sclereids; numerous crystals of calcium oxalate present in the secondary wall and lumen

(*a*) Secondary wall devoid of pits and pit-canals *Araucaria*

(i) Sclereids in the cortex and pith regions of stem .. .. .. *A. bidwillii*, *A. excelsa*, *A. cunninghamii*

(ii) Sclereids only in cortex, none in pith .. *A. cookii*

(*b*) Secondary wall with pits and pit-canals .. *Agathis loranthifolia*, *A. robusta*, *A. obtusa*

(2) Only strobilar sclereids, foliar and cauline sclereids absent

(*a*) Adult sclereids with persistent nucleus 1 or 2, and some contents in lumen .. *Cupressus macrocarpa*, *C. goveniana*, *C. funebris*, *C. lusitanica*, *C. sempervirens*, *C. torulosa*, *C. lindleyi*

(*b*) Adult sclereids with empty lumen .. *Juniperus chinensis*, *J. formosana*, *J. procera*, *J. sp.*

(*c*) Sclereids of bizarre types also present in addition to the astro, brachy and osteosclereids; maximum polymorphism .. .. *Thuja occidentalis*, *T. orientalis*

(3) Only cauline sclereids, foliar and strobilar sclereids absent

(*a*) Sclereids only in pith, cortex and bark regions; lumen interrupted .. .. *Cedrus deodara*, *C. libanii*

(*b*) Sclereids in pith and cortex, absent in bark; lumen continuous .. .. .. *Abies*

(i) Astro, brachy and osteosclereids in pith and cortex .. .. .. *A. webbiana*, *A. balsamea*

(ii) Only few brachysclereids in pith .. *A. alba*

(4) Only foliar and cauline sclereids, strobilar sclereids absent .. .. .. *Dacrydium*

F. NO SCLEREIDS IN ANY PART

Foliar, cauline and strobilar sclereids absent .. *Pinus excelsa, P. longifolia, P. girardiana*

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METAMORPHISM OF COAL MACERALS

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ABSTRACT

The chemical, structural and optical changes undergone by the coal macerals with increasing rank or metamorphism have been discussed in this paper. When properties of macerals are plotted against rank, it is found that the different macerals follow separate path. Abrupt and significant change in the properties of the macerals takes place at about 82-83, 89-90 and 92 percent carbon levels. At about 89-90 percent carbon content the track of exinite merges with the track of vitrinite and with further progress in rank at about 92 percent carbon content the latter meets the track of inertinite. At about 92 precent carbon level the chemical and structural differences between the macerals become almost negligible. Though fusinite attains a more or less stable chemical composition and structure in the early stage of coalification (diagenetic phase), other macerals of inertinite group show changes in the later stage (geochemical phase) of coalification. The difference in the chemical composition of the macerals decreases with increasing reflectance and becomes nil or negligible when reflectance (in oil) of vitrinite of coal reaches a value of about 1.80 or more. Present study also reveals that an estimation of chemical composition of pure macerals can be made from their reflectance values.

INTRODUCTION

It is well known that the coal macerals differ in their physical, chemical and optical properties. The differences are significant in low rank coals and the individual maceral follow different metamorphic paths which ultimately merge at higher rank. In an earlier paper the present author (Ghosh, 1971) discussed certain changes in the properties of the macerals with rank. Some more significant facts regarding metamorphism of coal macerals, encountered in course of further studies, have been discussed in this paper.

The present study is based on the data obtained on the chemical composition, structural and optical properties of macerals isolated from Indian coals and the data published by several other workers (referred to with the explanation of figures) of the different countries on coal macerals. Properties of the macerals isolated from Indian coals are given in tables 1 and 2.

RESULTS

Elementary composition: The primary difference in chemical composition of macerals is in their carbon, hydrogen and oxygen contents. With increasing rank carbon content of the macerals increases and oxygen and hydrogen content decreases. In a coal inertinite contains maximum carbon followed successively by exinite and vitrinite. Hydrogen content is maximum in exinite and minimum in inertinite.

Sulphur and nitrogen contents of the macerals do not show any appreciable change with rank. Usually nitrogen is maximum in vitrinite and followed by exinite and inertinite. Sulphur content of Tertiary coals of Assam and Jammu is higher than that recorded in Lower Gondwana (Permian) coals of India. From the studies of Roy (1963) as well as from

Table—1

Ultimate composition, aromaticity, hydroaromaticity, distribution of reactive oxygen groups and reflectance of coal macerals.

Coal and its Geological age	Maceral*	Ultimate composition (D.A.F.)					Aromaticity	Hydro-aromaticity	Reactive oxygen groups			R_o (Reflectance)
		C	H	N	S	O			O(OH)	$O_{(CO)}$	$O_{(COOH)}$	
1 Daranggiri Assam, Eocene	V	76.2	5.7	1.0	3.2	13.9	0.70	0.22	8.65	2.11	0.23	0.48
	E	78.5	10.3	0.7	4.5	6.0	0.65	0.28	2.48	2.38	0.25	0.15
	I	88.5	3.2	0.6	1.3	6.4	0.88	0.06	2.06	3.33	0.21	1.70
2 Tandur Permian	V	78.2	5.4	1.9	0.8	13.7	0.72	0.23	9.43	1.30	0.20	0.55
	E	82.5	7.4	1.5	0.7	7.9	0.66	0.26	2.93	3.42	0.21	0.18
	I	88.1	4.2	1.2	0.8	5.7	0.90	0.06	1.67	3.19	0.20	1.75
3 Samla Permian	V	80.8	5.3	2.1	0.7	11.1	0.74	0.22	6.52	2.65	0.22	0.55
	E	82.3	6.9	1.8	0.7	8.3	0.65	0.27	2.89	3.37	0.19	0.20
	I	86.6	4.7	1.3	0.7	6.7	0.88	0.07	2.12	3.40	0.20	1.67
4 Sanctoria, Permian	V	84.7	5.4	1.6	0.6	7.7	0.76	0.18	3.72	3.04	0.15	0.87
	E	88.6	5.8	1.3	0.7	3.6	0.74	0.20	1.08	1.73	0.14	0.40
	I	89.3	4.2	1.1	0.8	4.6	0.91	0.05	0.95	2.73	0.10	1.81
5 Ramnagar, Permian	V	85.8	5.3	1.8	0.7	6.4	0.78	0.17	2.55	3.17	0.14	0.52
	E	89.2	6.9	1.3	0.7	1.9	0.76	0.19	0.52	1.19	0.06	0.92
	I	91.0	4.2	1.2	0.8	2.8	0.91	0.05	0.71	1.48	0.10	2.13
6 Laikdih, Permian	V	86.6	5.3	1.5	0.8	5.8	0.82	0.14	1.91	2.77	0.08	1.02
	E	88.2	6.5	1.3	0.6	3.4	0.80	0.15	0.94	1.81	0.10	0.55
	I	91.8	4.0	1.0	0.8	2.4	0.93	0.03	0.52	1.53	0.08	2.25
7 Ghanuadih Permian	V	89.4	5.5	1.6	0.5	3.0	0.82	0.14	0.83	1.83	..	1.28
	E	89.7	5.7	1.2	0.6	2.8	0.80	0.15	0.64	1.79	..	0.77
	I	91.8	3.6	1.1	0.7	2.8	0.93	0.03	0.53	2.05	..	2.88
8 Chakkar, Jammu, Eocene	V	91.1	4.4	0.8	2.0	1.7	0.91	0.05	0.43	1.19	..	1.80
	I	93.2	2.8	0.6	1.7	1.7	0.98	..	0.31	1.37	..	4.02

*V—Vitrinite; E—Exinite; I—Inertinite.

Table 2**—Ultimate composition and reflectance of macerals from Tindharia coal, Darjeeling District, Eastern Himalaya.

Sample No.	Maceral*	Ultimate composition (D.A.F.)					Ro (Reflectance)
		C	H	N	S	O	
D—12	V	78.3	5.1	1.4	0.4	14.8	0.65
	I	87.8	3.8	1.3	0.5	6.6	1.81
D—13	V	86.9	4.9	1·0	0.5	6.7	1.10
	I	89.8	3.7	1.0	0.5	5.0	2.12
D—14	V	88.0	4.9	1.4	0.5	5.2	1.44
	I	90.3	3.5	1.2	0.4	4.6	2.60
D—15	V	89.0	5.0	1.1	0.5	4.4	1.57
	I	90.9	3.5	0.9	0.6	4.1	3.12

*V—Vitrinite; I—Inertinite.
** Data not plotted in the figures of this paper.

the present investigation it is seen that the sulphur content is maximum in exinite and is minimum in inertinite. Organic sulphur constitutes the major part of the total sulphur of the Tertiary coals of India (Table 3).

Table 3—Total and organic sulphur content in coal macerals.

Coal	Maceral*	Total sulphur	Organic sulphur
1	V	3.16	2.63
Daranggiri	E	4.51	4.24
	I	1.26	0.64
8	V	2.04	1.03
Chakkar	I	1.67	0.37

*V—Vitrinite; E—Exinite; I—Inertinite.

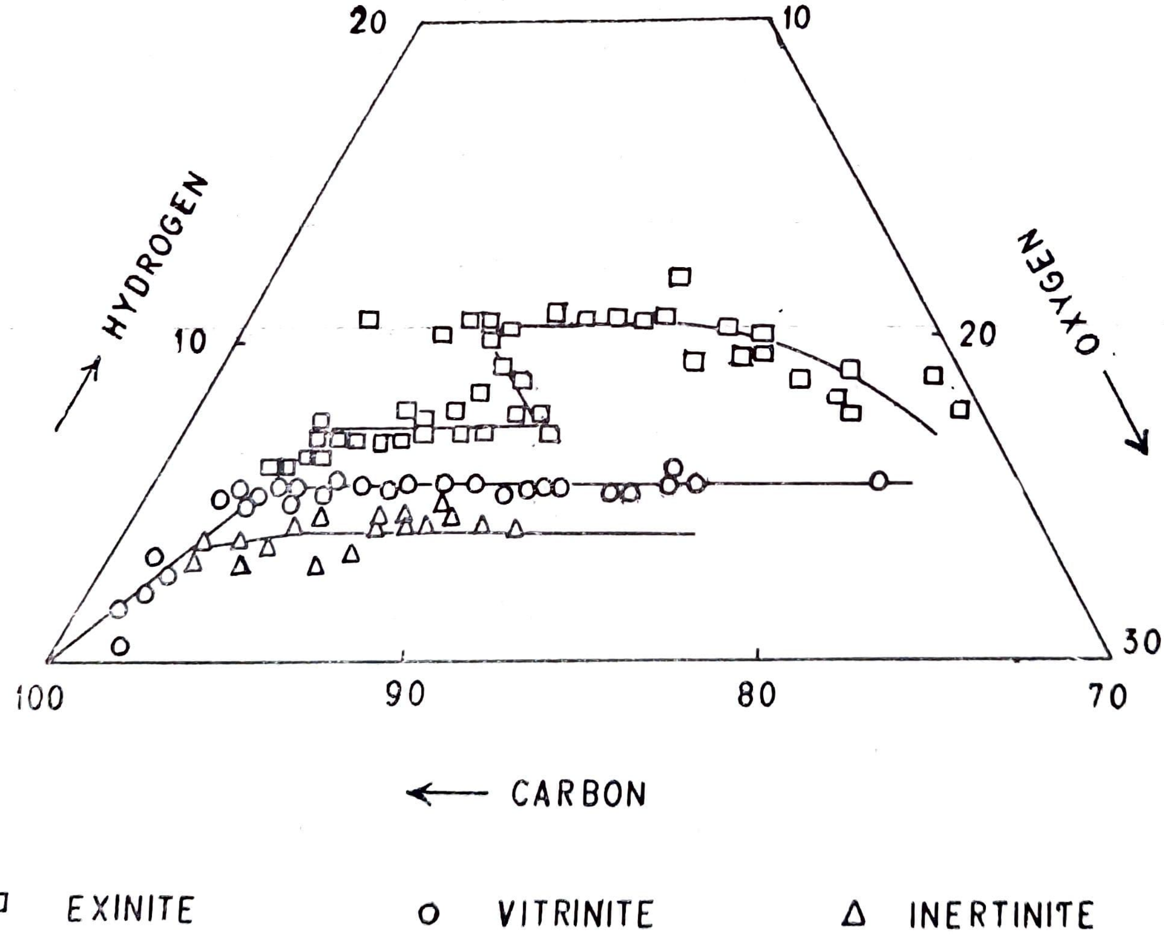
Reactive oxygen groups: Reactive oxygen constitutes a significant part of the total oxygen content of the macerals. The total reactive oxygen content (as percent of total O) of the macerals increases with rank. Amongst the macerals, it is highest in exinite and lowest in inertinite. Of the reactive oxygen groups, the (OH) groups decrease and the (CO) groups increase with rank. In a coal both the (OH) groups and (CO) groups are maximum in vitrinite and are minimum in inertinite.

Structural parameters: Aromaticity of macerals increases from exinite to inertinite and also with rank. The hydroaromaticity increases in the reverse order to that of aromaticity. In the same rank coal hydroaromaticity as well as distribution of hydrogen decrease in the order of exinite, vitrinite and inertinite. From the IR and PSR studies TSCHAMLER *et al.* (1966) have proved that the "exinite possesses the biggest aliphatic position with highest relative amount of CH_2 groups and micrinite possesses the smallest aliphatic position with lowest relative amount of CH_2 groups."

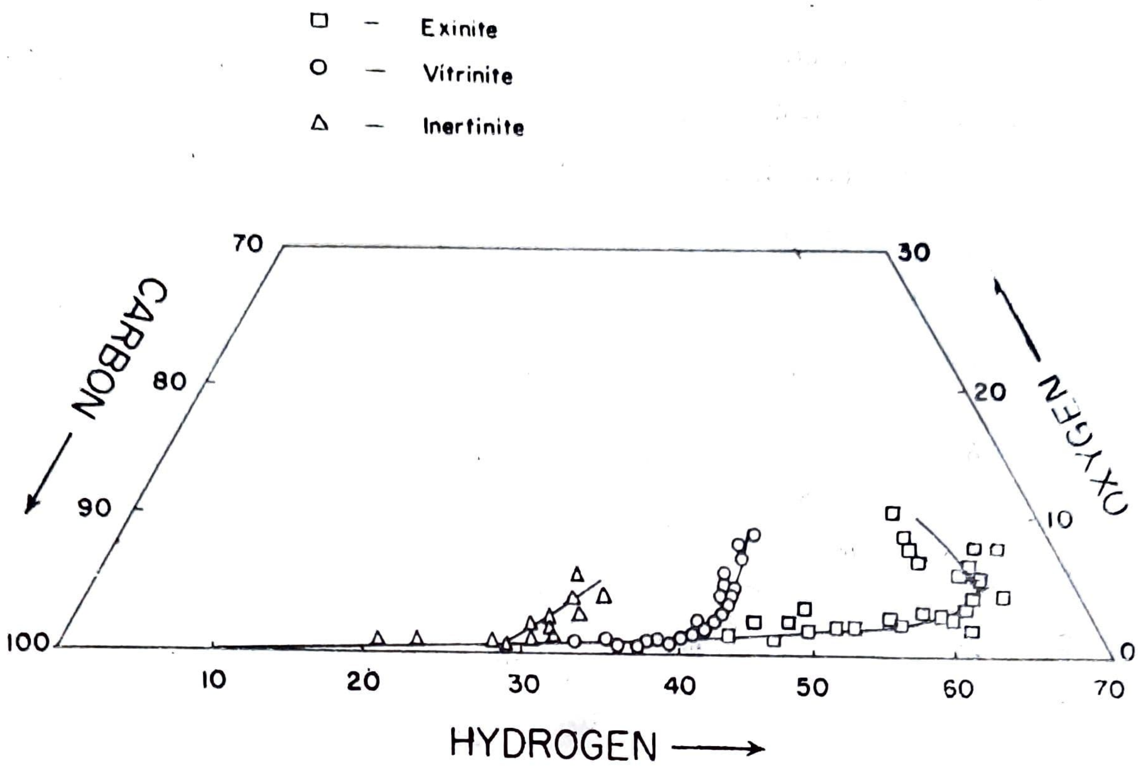
DISCUSSION

The nature of the metamorphic changes undergone by the coal macerals has been shown in figures 1 to 5. The difference in the properties of the macerals is significantly high in low rank coals and decreases with increase in rank and ultimately merge together at higher rank. This shows that in low rank coals the relative proportion of the different macerals can considerably influence the bulk chemical composition of a coal and therefore the average analyses of coal sample can not be used in ascertaining its rank and properties. This is particularly true in case of many low rank Indian coals which are rich in inertinite (SEN, 1968; GHOSH, 1969).

The constituent macerals of the exinite group differ from each other in chemical composition particularly below the bituminous rank level. In the same level of carbon content, sporinite contains more H and less O compared to resinite, cutinite and alginite. The macerals semifusinite and fusinite of inertinite group also differ in chemical composition. The inertinite starts its track at considerably higher C level compared to the other two groups of macerals. This reflects that inertinite undergoes the major metamorphic



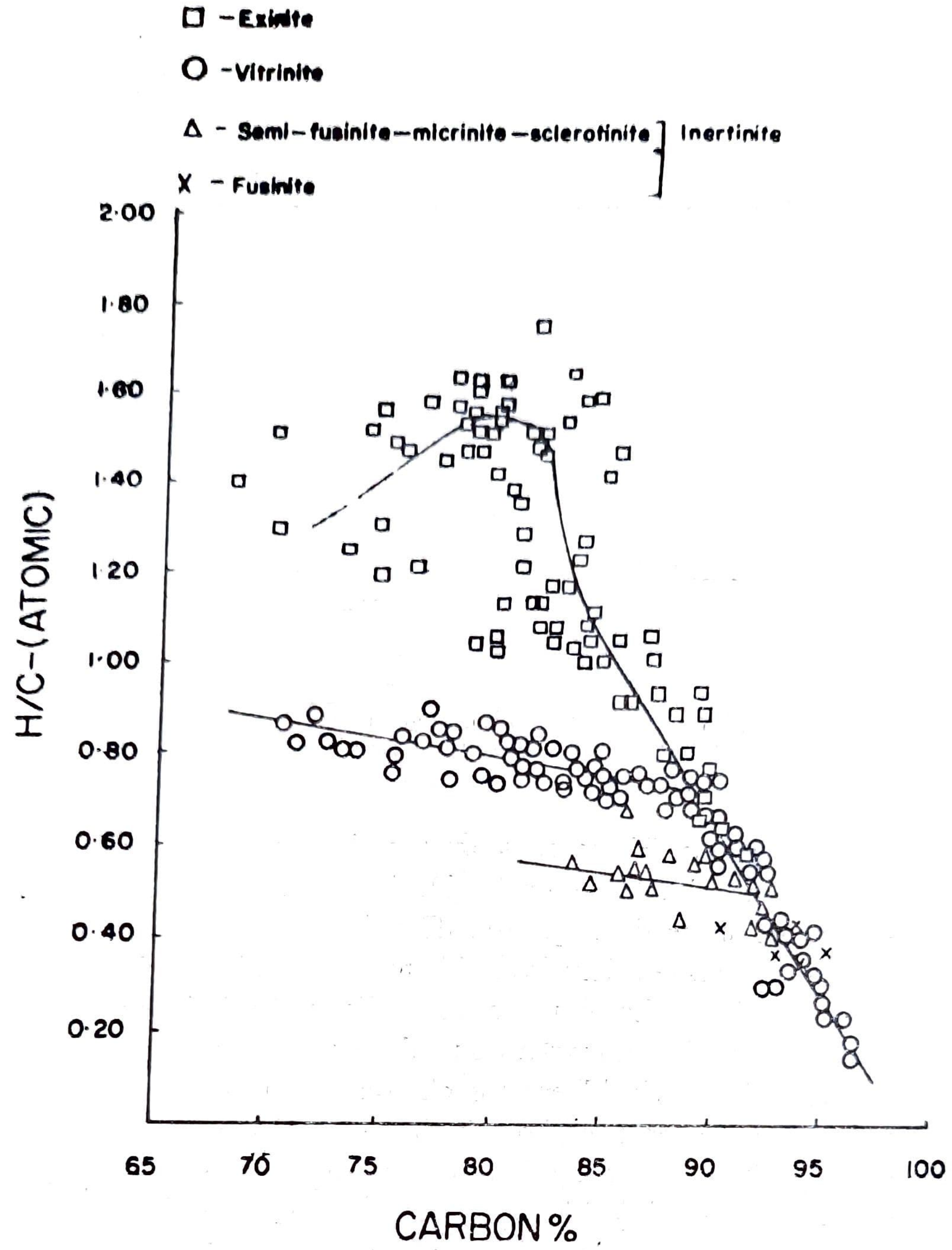
Text-fig. 1. Relationship between C, H and O (D. A. F.—basis, C+H+O=100 percent by weight) Based on the data of MACRAE (1943), CRICK (1951), KUHLWEIN (1951), KROGER *et al.* (1956), ALPERN (1956), DORMANS *et al.* (1957), MURCHISON (1957), ERGUN *et al.* (1959, 1960), FRIDEL & QUEISR (1959), GIVEN *et al.* (1960), FRANCIS (1961), LADNER & STACNY (1963), MURCHINSON & JONES (1964), TSCHAMLER *et al.* (1966), AUSTEN *et al.* (1966) and present author.



Text-fig. 2. Change of carbon, hydrogen and oxygen content (on atomic percentage basis) of coal macerals with rank (C+H+O=100 atoms). Based on the data used in Text-fig. 1.

change in the diagenetic phase. However, from the chemical and reflectance data of the macerals isolated from the Tindharia coal (Darjeeling District, Eastern Himalaya) it appears that the macerals of inertinite group suffer changes in the geochemical phase due to tectonism (Table 2). It is also evident from the text-figures 1 to 4 that the rate of chemical change with rank of the different macerals is distinctly different.

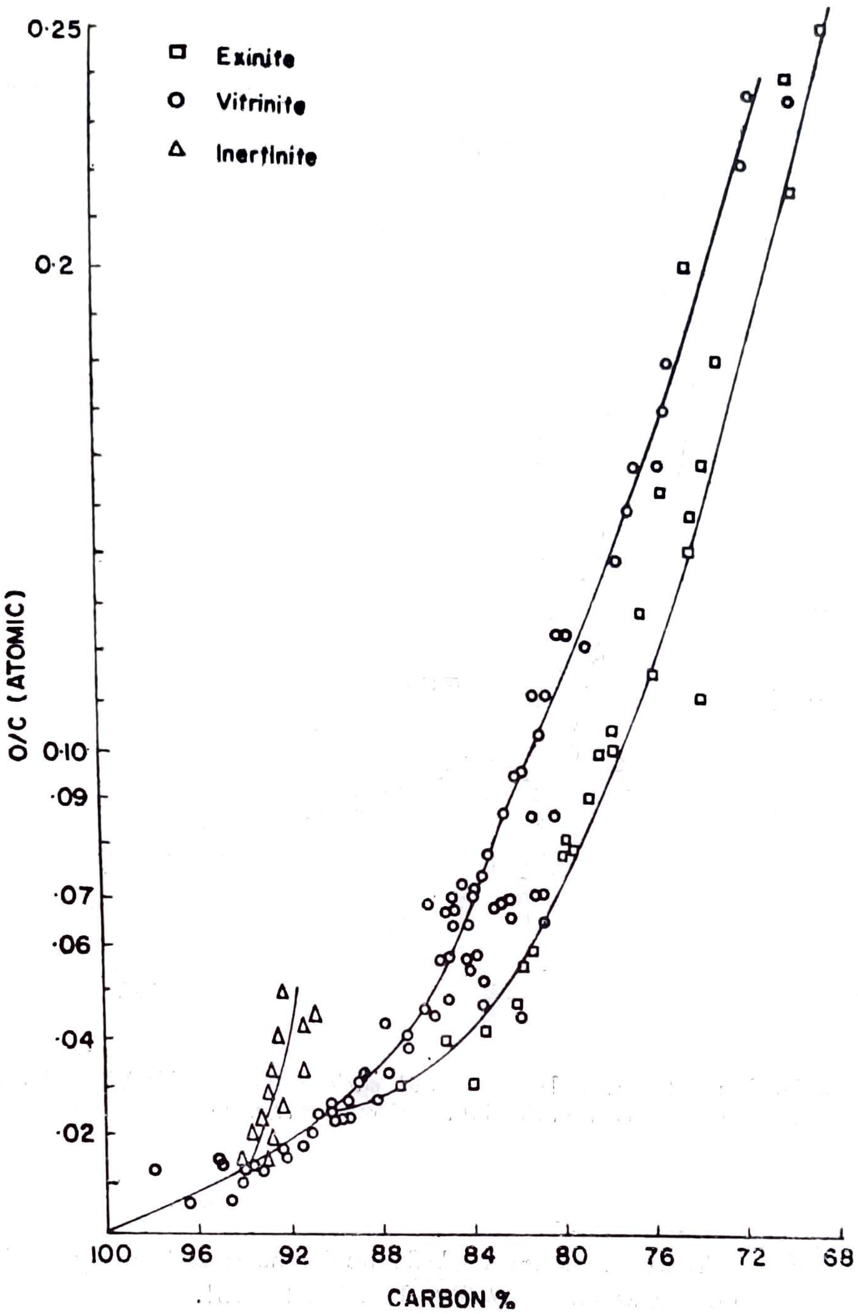
It is mentioned earlier that nitrogen and sulphur contents of macerals do not show any systematic change with rank. Therefore change in the quantitative distribution of the three major chemical elements, carbon, hydrogen and oxygen, of the macerals with rank has been examined by plotting the data on a triangular diagram (Text-fig. 1) (basis C+H+O=100 percent by weight). The net change in the macerals with rank is removal of H and O and enrichment in C. Though oxygen is removed throughout the entire range of rank increase, however, major part of it is removed at the first stage (Text-figs. 1 and 2). Hydrogen content of macerals remains almost constant over certain rank ranges and dehydrogenetation takes place abruptly and in steps. The rank level for the initiation of dehydrogenation is not same for all the macerals. Dehydrogenation of exinite starts first at 82-83 percent carbon level and is followed by vitrinite (91 percent carbon level) and inertinite (94 percent carbon level). Hydrogen content of exinite remains steady (H-10.2 percent) between 76 and 82-83 percent carbon content and below 76 percent carbon content the exinite track shows increase in H and decrease in O with increase in carbon content (Text-fig. 1.). Furthermore, at 82-83 percent carbon content exinite track also shows an increase in O and decrease in H. After having a drastic increase of oxygen and decrease of hydrogen at 82-83 percent carbon content, hydrogen content of exinite once again remains constant (H=7.2 percent) up to 89 percent carbon content and thereafter falls again till it meets the track of vitrinite. Hydrogen content of vitrinite (H=5.3 percent) and inertinite (H=3.8 percent) also remains almost constant up to 91 and 94 percent carbon contents respectively. Deoxygenation of macerals takes place through the removal of reactive oxygen groups and



Text--fig. 3. Relationship between C (D.A.F.) and H/C (atomic) of coal macerals. Based on the data used in Fig. 1. (Basis C+H+O+N+S=100 percent by weight).

during dehydrogenation the hydroaromatic and/or aliphatic side chains or side groups are removed. Dehydrogenation of inertinite takes place through demethanation.

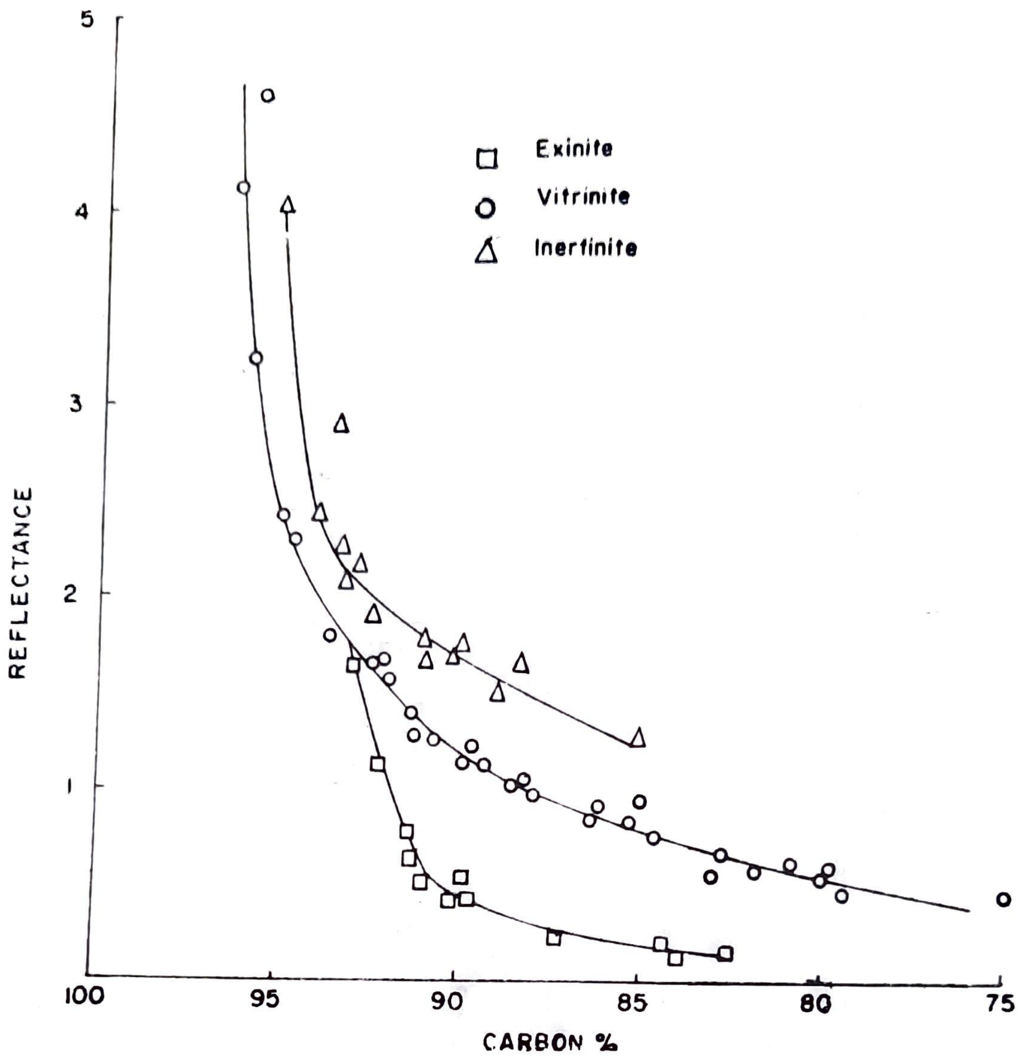
The changes in the atomic hydrogen-carbon (Text-fig. 3) and oxygen-carbon (Text-fig. 3 & 4) with C or rank (calculated on the basis of C+H+O+N+S=100 percent by weight) have also been studied to get an idea about the nature of the structural changes undergone by the macerals with rank. The line of best fit of exinite shows an increase in H/C with increasing C up to 82-83 percent carbon level. Upto this carbon level O/C falls significantly till it reaches a value of about 0.06. Thereafter exinite track takes a sharp bend and H/C begins to fall rapidly with rank till it reaches the metamorphic track of vitrinite at about 89-90 percent carbon content. At this carbon content the track of exinite also takes a sharp bend and follows that path till the end. Prior to this vitrinite track shows a gradual fall in H/C though O/C falls steadily. The inertinite track meets track of vitrinite at about



Text-fig. 4. Relationship between C (D.A.F.) and O/C (atomic) of coal macerals. Based on the data used in Fig. 1. (Basis C+H+O+N+S=100 percent by weight).

92 percent carbon content which corresponds with H/C=0.30 and O/C=0.015. It is evident from the above findings that abrupt change in the chemical structure of the macerals takes place at 82-83, 89-90 and 92 percent carbon contents.

Reflectance of macerals also increases with rank. Text-figure 5 shows that the difference in the optical property of macerals decreases with rank and the track of exinite merges with the track of vitrinite at about 1.80 Ro. From the nature of the tracks of the macerals it is evident that the difference in the chemical composition of the macerals becomes nil or negligible when reflectance (in oil) of vitrinite of a coal becomes 1.80 or more. In other words Ro value alone is sufficient in ascertaining the chemical composition of overall sample when Ro of vitrinite of the coal sample is 1.80 or more. An estimation of chemical composition (C, H and O on D.A.F. basis) of pure macerals can be made from their reflectance with the help of the text-figures 1 and 5.



Text-fig. 5. Relationship between reflectance and carbon content (D.A.F.,—basis, C+H+O=100 percent by weight) of coal macerals. Based on the data of DORMANS *et al.* (1957), ERGUN *et al.* (1959, 1960), and present author.

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