007111

THE ORIGIN AND DISTRIBUTION OF LATERITES IN SOUTH WESTERN AUSTRALIA AND THEIR IMPORTANCE IN DETERMINING IMPACT BY *PHYTOPHTHORA CINNAMOMI* IN THE NORTHERN JARRAH FOREST

BY

J. KINAL

Submitted as part of the LF5/6 examination

AUGUST 1985

Summary

The northern jarrah forest lies on an extensively lateritised landscape. Laterite has developed in situ but the profile may have been dissected. Each of the horizons may become a new soil parent material either in situ or as detritus. Soil fertility is in part determined by extent of weathering. Landform and soil development, and vegetation are closely related. Dolerite dykes have a major influence on weathering patterns and on the hydrological behaviour of a site. A connection between dolerite-influenced laterite development, soil fertility and P.cinnamomi activity is suggested.

Contemporary hardening of laterite is suggested. There appears to be a positive feedback between site degradation by hardening of laterite and P.cinnamomi activity. Current forestry cultural practices including logging, burning and clearing may have detrimental effects on the laterite-P.cinnamomi relationship.

There is a need to understand the hydrological processes of the laterite profile in relation to P.cinnamomi activity; and to understand processes that affect contemporary lateritisation.

Contents

List of Figures

The Origin and Distribution of Laterites in South Western Australia and their Importance in Determining Impact by *Phytophthora cinnamomi* in the Northern Jarrah Forest

Introduction

Recent research on jarrah dieback has resulted in a shift of emphasis in that program. It was shown that at specific site types vertical drainage was impeded, creating conditions suitable for fungal survival, production and transmission and infection of the vertical roots of jarrah (Shea et al 1983).

The discovery that disease impact at some sites could be related to specific characteristics of the lateritic soil profile was reason for optimism. The implication was that the forest managers had a potential tool for predicting disease impact.

Such a tool would, however, require understanding of the distribution, morphology and hydrologic properties of lateritic soils. Whereas knowledge of the formation of laterites could shed some light on the structure and distribution of present-day soil profiles, ideas about laterite formation continue to be controversial.

This report will consider the genesis, distribution and composition of laterites in south Western Australia and how these factors might relate to the activity of *Phytophthora cinnamomi* in the northern jarrah forest.

2 The Setting

The northern jarrah forest lies on the south western margin of the Great Plateau of Western Australia (Fig.1). The Plateau has been subjected to extensive lateritisation, peneplanation and uplift. The Darling Range marks the south western boundary of the Plateau.

Rejuvenated drainage, after uplift, resulted in dissection of the terrain.Stripping of the original soil mantle gave rise to new soil parent materials in eroded horizons and in deposits. The resulting landscape consists of landforms and soils that reflect the past interaction between climate, relief and geology (Churchward and Gunn 1983).

Superimposed on this landscape are vegetation complexes in patterns that are closely related to the underlying topography and soils (Havel 1975). Uplands and slopes, mantled with lateritic gravels and duricrust and comprising about 80% of the landscape, support a forest with jarrah as the dominant or codominant tree species (Shea et al 1983).

3 The Disease

3.1 Early Research

Research in Western Australia up until 1980 defined and confirmed which environmental factors affected the survival and pathogenicity of *P.cinnamomi*. It requires warm and wet soil conditions to form sporangia and free water for release and dispersal of zoospores.

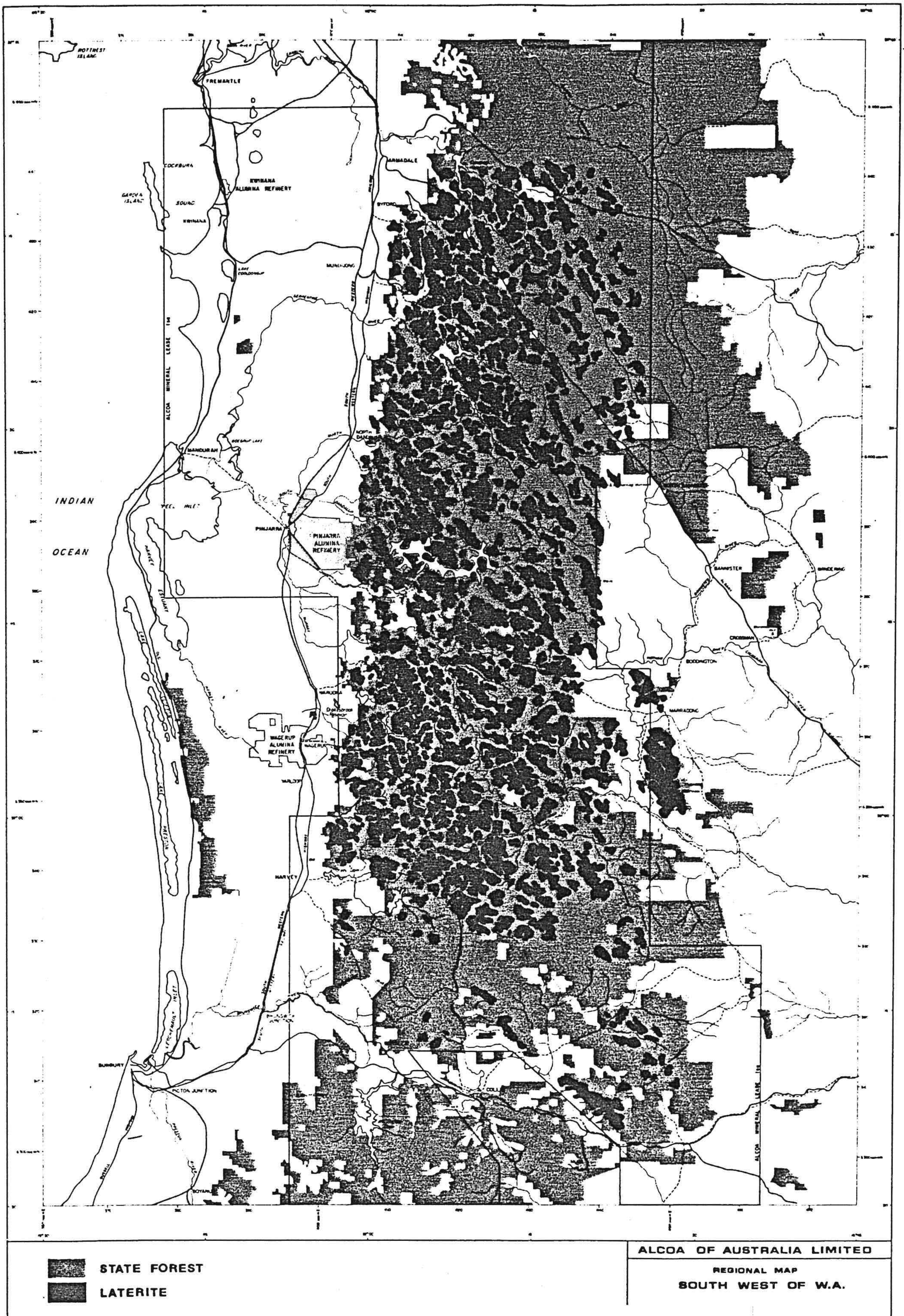

Fig.1. Distribution of aluminous laterite in relation to the northern jarrah forest.

Moisture-gaining valleys provide an environment suitable for fungal survival and activity throughout the year. But disease impact is limited on these sites due to the presence of resistant species. However, the environment of surface soils in upland sites is considered marginal for sporulation and survival. In summer the soil is generally too dry for survival. Depending on the timing of opening or closing rains, warm moist conditions that favour sporulation may occur in autumn or spring. In winter, although temperatures are suboptimal for sporulation, moist conditions favour survival. Accordingly, recovery of inoculum was usually sporadic (Shea 1975).

The bias towards surface soils was in keeping with the commonly held belief that they had optimal levels of aeration and temperature (Podger 1972) and from consistent recovery of P. cinnamomi from feeder roots of jarrah growing in diseased areas (Shea et al 198Ø).

Podger (1972) recognized an association between some areas of dieback with soil profiles containing massive laterite or dense clay at shallow depth but concluded that it was not universal and hence not diagnostic. Shea (1975) qualified his interpretation of soil properties in situ stating that they could be reflecting topographic and vegetational characteristics of the site.

3.2 Recent Developments

The dilemma facing researchers was that it seemed inconceivable that areas of mass collapse of jarrah could be caused by fine feeder root attrition in upper topographical positions where the surface soils were only marginally favourable to P. cinnamomi and in which distribution of inoculum levels were usually low and randomly distributed in localized foci.

This quandary was partly resolved when it was shown that the environment immediately above a laterite impeding layer extended the periods suitable for activity of P. cinnamomi on upland sites. Lateral transport of inoculum could occur in subsurface flows above the layer infecting jarrah roots which pass through vertical channels in the layer (Shea et al 1983).

Other questions about jarrah's susceptibilty to P. cinnamomi were unanswered. Lesion extension in inoculated jarrah roots and stems was found to be seasonal (Shea unpublished). Fungal activity was intermittent, at times being arrested by the jarrah host and at other times apparently breaking out and girdling stems or roots (Tippett et al 1983). Tippett and Hill (1983) showed that rate of lesion extension was related to inner bark moisture content. Futhermore, the relative hydration of jarrah bark, differed with site type which suggest differences in soil moisture availability to trees during summer (Tippett unpublished).

It appears that particular sites have hydrological characteristics which permit continued hydration of jarrah into periods when temperature is close to optimal for fungal growth.

4 Laterite

4.1 What is Laterite ?

Since the term "laterite" was first coined by Buchanan in 1807 to describe deposits in India, it has taken on many different meanings (Schellman 1981). Commonly laterites are defined as "highly weathered materials (1) rich in secondary forms of iron, aluminium or both; (2) poor in humus; (3) depleted of bases and combined silica; (4) with or without nondiagnostic substances such as quartz, limited amounts of weatherable primary minerals, or silicate clays; and (5) either hard or subject to hardening upon exposure or to alternate wetting and drying (Sivarajasingham et al 1962).

A laterite may be a solid mass, vesicular or consist of nodules or concretions mixed with sand and clay (Maignien 1966).

Hardness ranges from scarcely coherent to blocks broken only by a hammer. A laterite horizon may have a hard crust overlying softer material although each has the same chemical composition. The most consistent characteristics of hard laterite crusts (also called duricrust, caprock or hardcap) are the greater crystallinity and the continuity of the crystalline phase of the iron-oxide minerals. Alternate wetting and drying also appears necessary for hardening (Alexander and Cady 1962).

4.2 Laterite Formation

Laterites form through intensive weathering, by water, of silicate rocks. Only the newly formed secondary minerals, principally haematite (Fe_2O_3), goethite ($FeOOH$), gibbsite($Al_2O_3.3H_2O$), and kaolinite ($Al_2(Si_2O_5)(OH)_4$) and the most resistant primary minerals remain in the mantle of weathered material (Maignien 1966). Alumina-rich (Al_2O_3) are termed bauxites.

Geidans (1973) summarized the principal factors that determine the character of laterites.

- Structural characteristics of the parent rock such as its texture the presence of joints and fractures, and the differential weatherability of the minerals determine its porosity and hence the movement of water through it.

- Rainwater carrying dissolved carbon dioxide is the initial solvent in the weathering process and provides the medium for removal of the solutes.

- Sufficient relief is essential to ensure adequate drainage of saturated solutions.

- Vegetative cover minimizes erosion and excessive runoff and supplies organic acids to infiltrating water.

- Warmer temperatures accelerate the chemical process. Laterites are widely distributed but occur mostly in tropical and subtropical regions.

4.3 Laterite Profile

Typically laterites are underlain by a saprolite weathering mantle. A vertical section of a standard profile is illustrated in Fig.2. Usually the term "soil" is resricted to mean surface material with biological activity, however, in practice the total laterite profile above basement rock is often considered a soil (Aleva 1981). Each of the horizons of the laterite profile and the parent rock, if exposed by truncation, provide a substrate for new soil formation. Soils may also develop from detrital materials transported downslope following dissection of older surfaces (Stephens 1946).

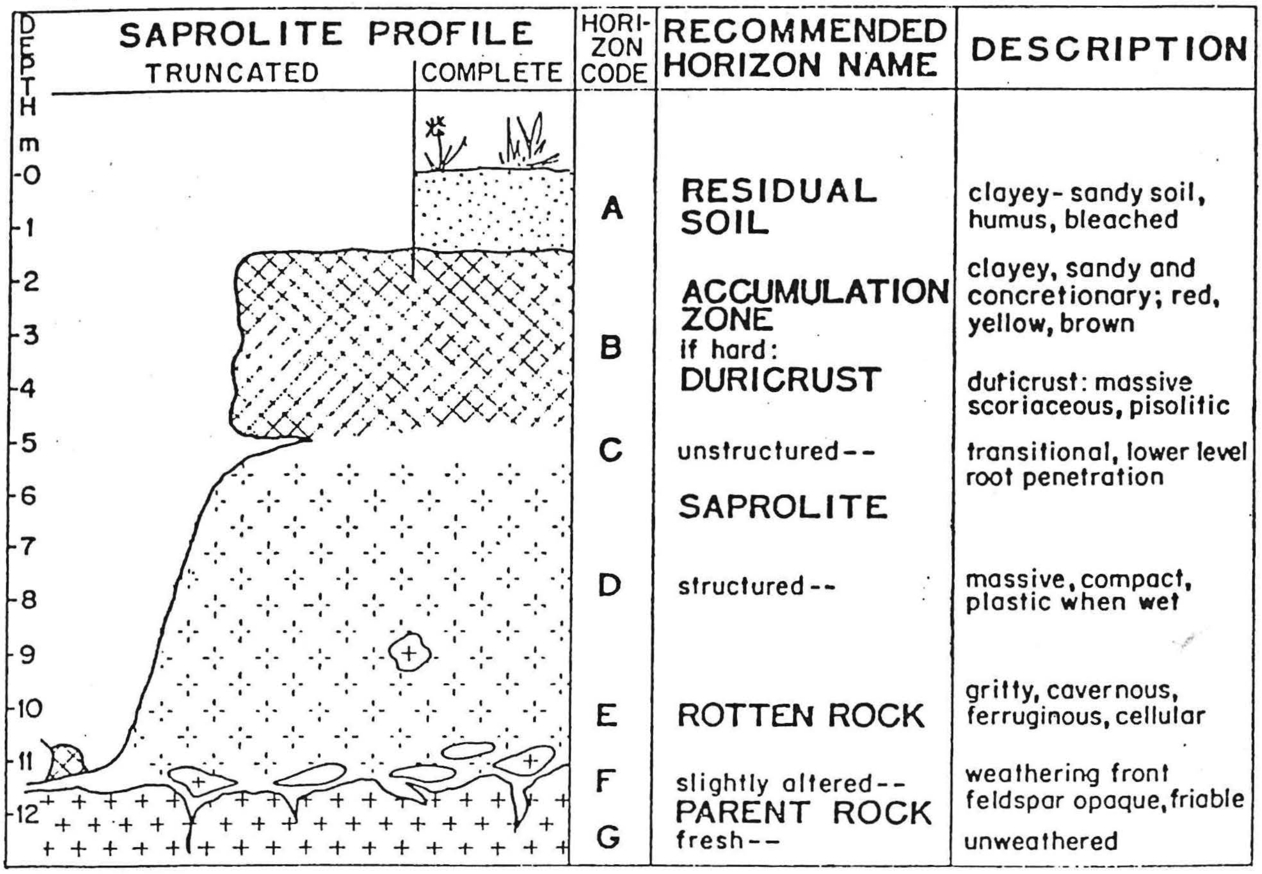

Fig.2. A standard laterite weathering profile (Aleva 1981).

5 South Western Australian Laterites

Early reports indicated that disease occurrence was restricted to specific topographic situations (cited in Podger 1972). Shea et al (1983) approaching the problem from a different perspective came to a similar conclusion : the jarrah forest is distributed over a range of site types of differing susceptibility to P. cinnamomi infection.

What forces could be responsible for having influenced such a distribution of sites? Two geomorphological features of an appropriate scale are potential candidates :

1. Dolerite dykes , 2. Landforms and Soils.

5.1 The Dolerite Influence

Thin sheet-like intrusions of dolerite occur throughout the granite basement. Because of their relative resistance to weathering, dolerites frequently remain prominent in the landscape as divides or as basement ridges between areas of more deeply weathered granites (Bettenay et al 1980) so influencing the movement and composition of infiltrating rainfall and groundwater.

Isovolumetric weathering of pallid clay derived from dolerite and granite has preserved their texture (Anand et al 1985, Johnston et al 1983). Weathering occurs around the rigid framework provided by the more resistant quartz grains. Consequently granite with more abundant and coarser quartz (ca. 20%) weathers to a saprolite with coarser texture and greater permeability than dolerite saprolite (ca. 8% quartz) (Bettenay et al 1980). This property is reflected in the water retention capacity of the two clay types. Maximum water content of dolerite saprolite (54% by volume) is considerably greater than that of granite saprolite (36%) (Johnston et al 1983).

The iron (Fe_2O_3) content of dolerite (14-18%) is significantly greater than that of granite (2-5%) (Bettenay et al 1980). Dolerite outcrops and ferruginious laterite above dolerite basements may provide iron in solution by lateral movement to contribute to cementation of crusts of adjacent profiles. Sadleir and Gilkes (1976) attributed the ferruginous crust at Jarrahdale to this process.

5.2 Influence of Landforms and Soils

Woolnough (1927) considered that peneplain conditions of low relief were necessary for lateritisation to occur. This concept has since been challenged by Mulcahy (1960) who postulated laterite formation concurrent with and following uplift. This has the important implication that contemporary relief in the dissected Darling Plateau is not limiting to ongoing laterite formation.

Following periods of uplift, dissection of the Plateau exposed horizons of the laterite profile, each becoming a distinctive soil parent material either in situ or as transported sediments (Stephens 1946). Exposed horizons may have become hardened. According to Mulcahy (1960), inclusions of pallid zone in the ferruginous horizon of the Kauring surface suggested laterite formation in already weathered material. Discolouration and incipient hardening within 30 years of the exposure of a pallid zone at Jarrahdale is evident in Fig.3.

Fig. 3. Hardening and red staining of pallid clay by iron, within 30 years of exposure, at Jarrahdale.

Fertility of lateritic soils,is in part determined by the extent of weathering (Wild 1950). The angular brecciated appearance of the ferruginous nodules in Fig.4 indicates a history of fragmentation and recementation. The marked infertility of Australian lateritic soils is overlain by a general trend of levels of nutrients, exchange capacities and exchangeable ions increasing from the oldest to the youngest surfaces (Mulcahy 1960). Phosphates that have not been depleted by weathering have been largely fixed by iron in the ferruginous horizon (Prescott and Pendleton 1952).

Fig. 4.Brecciated nodules in caprock at Jarrahdale indicating detrital origin.

Deposition of detritus over a variety of underlying materials may give rise to complex soil patterns with contrasting textural horizons e.g. the Balkuling surface is characterized by a shallow layer of sand over a dense mottled clay (Turton et al 1962).

Local relief will affect the pattern of erosional activity. Hence localized channelling of sediments into depressions may occur (Mulcahy 1960). In the Darling Range, quality of bauxites is related to slope gradient (Baker 1975).

Fig.5. Fragmented caprock.

Fig. 6. Sheet caprock.

6 The Laterite Connection

6.1 Pathogen - Environment Interaction

P. cinnamomi requires particular conditions for production, survival and transmission of spores and the infection of jarrah at depth in the soil profile. These conditions are met by duplex soils whose upper horizon is sufficiently porous to permit passage of fungal propagules; whose lower horizon is of sufficiently contrasting texture to perch water, at least after heavy rain; and with defined root channels which intersect the perching layer (Shea et al 1983).

The northern jarrah forest overlies a range of duplex laterite soils, (Churchward and McArthur 1980) but not all meet these requirements.

Potentially, water may perch at several horizons within the laterite profile:

1. over duricrust (Shea et al 1983),
2. over clay (Throssell 1984),
3. layered within clay (Tyskin pers. comm.).

Water may infiltrate through the matrix of the layer, or via discrete channels, or a combination of both. Figs 5 and 6 contrast fragmented and sheet caprock surfaces respectively. The hydraulic conductivity and the areal distribution of the pathways will determine the relative amount of vertical and lateral water flow.

Duricrust which is massive and continuous is most likely to impede infiltrating water. At a number of diseased sites, Smurthwaite and Shearer (1983) found the duricrust to consist of massive blocks with cracks partially occluded by cemented pisolites (Fig. 7).

Fig.7. Massive caprock with cemented pisolites in crevice. Note black iron inclusions in caprock.

At most of those sites the laterite was of doleritic origin. The relation of highly ferruginous laterite to a NW trending dolerite dyke is clearly evident in Fig. 8.

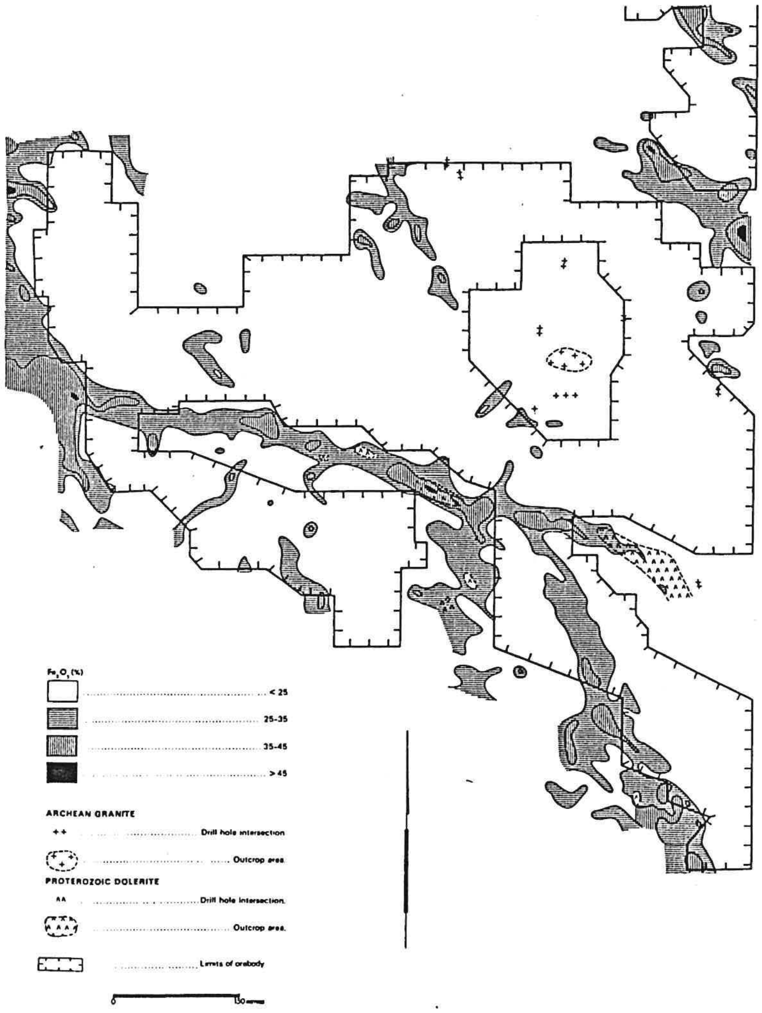

Fig. 8. Relation of highly ferruginous laterite to underlying dolerite dyke (Baker 1975).

There is widely documented evidence of the association between removal or thinning of vegetation and subsequent hardening of laterite (Alexander and Cady 1962). Early reports associated dieback with forest of poor quality on infertile soils (cited in Podger 1972). It is possible that the infertility of sites, expressed through a sparse canopy, has facilitated hardening.

Duricrust may appear to perch water because of an immediately underlying relatively impermeable clay layer (Throssell 1984).

Clay formed from different parent materials may have markedly contrasting hydrological properties. Infiltration of rainfall would be slower through the more compact, fine textured dolerite saprolite than through the matrix of granite-derived clay. An area of doleritic clay situated high in the landscape could perch water during rainfall that exceeded its infiltration capacity. Although areas downslope might have more permeable soils, the effect of each rain event would be magnified by the laterally moving water.

One possible origin of shallow clays overlain by hardened caprock is truncation of a mottled or pallid clay zone followed by hardening of the surface horizon.

Alternatively, aluminous laterites may become rekaolinized from a high water table resulting from subdued erosion (Baker 1975).

By contrast, in the Darling Range, laterites that qualify as mineable bauxite ore have a deep - 2m to 10m - earthy, often friable zone underlying a hard cap, and passing down into mottled and pallid clay (Baker 1975) (Fig. 9).

Fig.9. Deep bauxite profile at Del Park.

The thickness and grade of bauxite is related to the extent of drainage and leaching - conditions which favour the rapid removal of iron and silica in solution (Plumb and Gostin 1973). In the Darling Range, Croton and Tierney (1985) found a direct relationship between the depth of mined bauxite and the permeability of pallid clay.

According to Grubb (1970) vegetative cover is possibly the most important factor of all in bauxitisation. Under reducing conditions the solubility of iron is increased over that for aluminium, hence the iron is preferentially leached (Petersen 1971). The most likely source of reducing agents are organic decomposition products; or the iron may be mobilized by the formation of complexes with soil organic matter (Taylor et al 1983). The relative iron content between high grade and low grade bauxite caprock is contrasted in Figs 10 and 11 respectively.

In the northern jarrah forest, Havel found that significantly greater volumes of biomass were produced in the more fertile sites (cited in Abbott and Loneragan 1983). It is reasonable then to expect a close relationship between fertility and relative permeability and depth of the lateritic layer.

Vertical channels passing through laterite and into lower horizons and acting as preferred paths for rapid recharge of groundwater following rain, have been frequently found in the Darling Range (Dell et al 1983, Johnston et al 1983, Shearer unpublished).

The root channels apparently result from dissolution of laterite by humic acid produced by roots (Plumb and Gostin 1973). Downwasting of channel material is followed by backfill from topsoil (Gilkes pers. comm.) (Fig.12). Fertile sites, through greater turnover of biomass, could be expected to have greater potential for root channel erosion.

The behaviour of P.cinnamomi at depth within the clay profile, or above a clay horizon below a deep lateritic layer is not known. It is unlikely that aeration would be sufficient for the fungus.

Soils overlying an impeding layer may be too fine-textured to allow transmission of zoospores. Typically the more fertile soils containing a greater clay fraction are least porous (Sochacki 1982).

6.2 Host response

Environmental factors affect both the susceptibility of jarrah, and the activity of P.cinnamomi. The pathogen is able to invade the stem and large roots of jarrah (Shearer et al 1981) and spreads most rapidly through the spongy outer phloem of actively growing trees (Tippett et al 1983). Warm temperatures favour fungal growth, however, for most of the year jarrah is able to resist lesion extension, principally by barrier formation (Tippett et al 1983). But at particular sites jarrah continue to grow through the summer drought, maintaining a higher bark moisture content than trees at other sites. The coincidence of actively growing phloem tissue and warm temperatures enable fungal development to outstrip jarrah resistance mechanisms (Tippett and Hill 1983).

Fig. 10. High grade bauxitic caprock.

Fig. 11. Low grade bauxite with high iron (black) content.

The water relations of trees may differ according to whether they are growing in doleritic or granitic soils.

There is a striking dimorphism in jarrah roots according to whether they are growing in granite- or dolerite-derived soils (Dell et al 1983, Johnston et al 1983). In granitic saprolite jarrah sinker roots are confined to well defined channels that apparently extend to the ground water table. However, in doleritic saprolite jarrah roots are diffuse. Dell et al (1983) attributed the difference to bulk density, the high value of granite clays making them inhospitable. There may be another explanation.

Fig. 12. Root channels through laterite.

The higher maximum water content of doleritic clays provides a greater reserve of water that is more adequately tapped by a diffuse root system. A thick capillary fringe in the doleritic clays would effectively raise the saturated water level. Intense summer rainfall could be detained temporarily in granitic clays upslope from basement ridges of dolerite or of smectite-containing clays which expand when wet (Bettenay et al 1980).

Havel's (1975 a,b) vegetation type P appears to be a high risk disease area (Shearer Tippett unpublished). These sites are characteristically infertile with poor regenerative capacity. Stands thinned by logging and burning would not deplete the soil water reserve as rapidly as more fertile sites.

The ability of the jarrah host to withstand invasion may be affected by its nutrient status. Havel (unpublished manuscript) associated the restricted occurrence of disease at Q and U vegetation types, with their fertility, especially with the high calcium level. The ability of jarrah to resist infection has been linked with calcium availability.

7 Research and Management Options

Properties of soils or soil horizons per se may not adequately explain the response of a site to rainfall. Dunne and Black (1970) and Anderson and Burt (1977) found that concave hillslopes generated greater volumes and more sustained subsurface flow than the other slope elements.

More generally, the effects of individual environmental factors on fungal epidemiology are not readily isolated. Geology, climate, landforms, weathering patterns, soils, hydrology, fertility and vegetation are closely genetically interrelated. However, Havel (1975a,b) has exploited these interactions to establish a predictable relationship between vegetation and landforms and soils. This suggests a diagnostic tool for predicting potential disease impact. Shearer, Tippett and others have been investigating this approach with promising results. They have found that the blanket estimate of diseased area (223,000 Ha of State Forest F.D. 1982) encompasses a range of impact types each potentially requiring different management strategies.

Following ground-level validation of the technique there is potential to use aerial reconnaisance over larger areas. Plumb and Gostin (1973) and Schellman (1975) refer to the distinctive patterns produced by vegetation over bauxite.

However, validation must be based on firm understanding of the processes affecting the interaction between P. cinnamomi, jarrah and the environment.

The relationship between environment and laterite is inferred; it is yet to be tested. Understanding of disease processes must be extended to include the properties of the laterite profile and their distribution throughout the landscape. Extrapolation of disease expression from existing forest stands to disturbed situations is tenuous at least.

The need to understand contemporary lateritisation is especially urgent. There is circumstantial evidence that the difference in growth dynamics between high and low impact jarrah forest has become markedly divergent by the introduction of P.cinnamomi and cultural practices that have favoured both fungal activity and lateritisation. Ironically, both P.cinnamomi and lateritisation are favoured by similar environmental conditions.

Walker et al (1983) introduced a conceptual model that relates vegetation changes to the weathering of soil mantles. Logging, burning, thinning and clearing of forest affect the dieback-laterite connection through their influence on soil fertility, hydrological properties and soil temperature regimes.

Forest management must address that issue.

References

Abbott, I. and Loneragan, O. (1983). Growth rate of jarrah (Eucalyptus marginata) in relation to site quality in cut-over forest, Western Australia. Aust. For.46(2), 91-1Ø2.

Aleva, G.J.J. (1981). Bauxitic and other duricrusts on the Guiana Shields, South America. In 'Lateritisation Processes'. Proc. Int. Sem. on Lateritisation Processes, Trivandrum, India, pp.261-269.

Alexander, L.T. and Cady, J.G. (1962). Genesis and hardening of laterite in soils. Tech. Bull. U.S. Dep. Agric. No. 1282.

Anand, R.R., Gilkes, R.J., Armitage, T.M. and Hillyer, J.W. (1985). Feldspar weathering in lateritic saprolite. Clays Clay Min. 33(1), 31-34.

Anderson, M.G. and Burt, T.P. (1977). Automatic monitoring of soil moisture conditions in a hillslope spur and hollow. J. Hydrol. 33, 27-36.

Baker, G.F.U. (1975). Darling Range bauxite deposits, W.A. In 'Economic Geology of Australia and Papua New Guinea - 1. Metals', (ed. C.L. Knight). Australas. Inst. Min. Metall. Monogr. Ser. 5,pp.98Ø-986.

Bettenay, E., Russell, W.G.R., Hudson, D.R., Gilkes, R.J. and Edmiston, R.J. (198Ø). A description of experimental catchments in the Collie area, Western Australia. CSIRO Aust. Land Manage. Tech. Paper No.7.

Boughton, T.J., Malajczuk, N. and Robson, A.D. (1978). Suppression of the infection of jarrah roots by Phytophthora cinnamomi with application of calcium carbonate. Aust. J. Bot. 26,611-615.

Churchward, H.M. and Gunn, R.H. (1983). Stripping of deep weathered mantles and its significance to soil patterns. In 'Soils : an Australian Viewpoint', Division of Soils, CSIRO, pp. 73-81. (CSIRO : Melbourne / Academic Press : London).

Churchward, H.M. and McArthur, W.M. (198Ø). Landforms and soils of the Darling System Western Australia. In 'Atlas of Natural Resources Darling System Western Australia', Dept. Conserv. West. Aust., pp.25-33.(UWA Press: Nedlands).

Croton, J.T. and Tierney, D.T.A. (1985). A hydrological design model for rehabilitation of bauxite mine pits in the Darling Range, W.A. Draft manuscript.

Davy, R. (1979). A study of lateritic profiles in relation to bedrock in the Darling Range near Perth, W.A. Geol. Survey of W.A., Rep.8.

Dell, B., Bartle, J.R. and Tacey, W.H. (1983). Root occupation and root channels of jarrah forest subsoils. Aust. J. Bot. 31, 615-627.

Dunne, T. and Black, R.D. (197Ø). An experimental investigation of runoff production in permeable soils. Water Resour. Res. 6(2), 478-49Ø.

Forests Department of W.A. (1982). Working Plan No.87, Part 1.

Geidans, L. (1973). Bauxitic laterites of the south western part of Western Australia. In 'Pap. W. Aust. Conf. 1973', Australas Inst. Min. Metall. 173-182.

Grubb, P.L.C. (1970). Mineralogy, geochemistry and genesis of the bauxite deposits on the Gove and Mitchell Plateaux, Northern Australia. Mineral. Deposita 5, 248-272.

Havel, J.J. (1975a). Site vegetation mapping in the northern jarrah forest (Darling Range). I. Definition of site-vegetation types. Bull. For. Dep. W. Aust. 86.

Havel, J.J. (1975b). Site vegetation mapping in the northern jarrah forest (Darling Range). II. Location and mapping of site-vegetation types. Bull. For. Dep. W. Aust. 87.

Johnston, C.D., Hurle, D.H., Hudson, D.R. and Height, M.I. (1983). Water movement through preferred paths in lateritic profiles of the Darling Plateau, Western Australia. CSIRO Groundwater Research Tech. Paper No.1.

Maignien, R. (1966). Review of Research on Laterites. UNESCO Nat. Resour. R. IV. 148pp.

McFarlane, M.J. (1976) Laterite and Landscape. (Academic Press : London). 151pp.

Mulcahy, M.J. (1960). Laterites and lateritic soils in south-western Australia. J. Soil Sci. 11, 206-226.

Murray, A.M. (1979). Bauxite. In 'Mining in Western Australia', (ed. R. Prider). pp.101-110.

Petersen, U. (1971). Lateritic and bauxite formation. Econ. Geol. 66, 1070-1082.

Plumb, K.A. and Gostin, V.A. (1973). Origin of Australian bauxite deposits. Bureau of Mineral Resources, Geology and Geophysics. Aust. Dept. Minerals and Energy. Record 1973/156.

Podger, F.D. (1972). Phytophthora cinnamomi, a cause of lethal disease in indigenous plant communities in Western Australia. Phytopathology. 62, 972-981.

Prescott, J.A. and Pendleton, R.L. (1952). Laterite and Lateritic Soils. Commonw. Bur. Soil Sci. Tech. Commun. No.47.

Sadleir, S.B. and Gilkes, R.J. (1976). Development of bauxite in relation to parent material near Jarrahdale, Western Australia. Geol. Soc. Aust. Jour. 24(4), 333-344

Schellman, W. (1975). Formation of and prospecting for tropical bauxite above silicate rocks. Mining Magazine, July, 1975, 33-39.

Schellman, W. (1981). Considerations on the definition and classification of laterites. In 'Lateritisation Processes'. Proc. Int. Sem. on Lateritisation Processes, Trivandrum, India, pp.1-14.

Shea, S.R. (1975). Environmental factors of the northern jarrah forest in relation to pathogenicity and survival of Phytophthora cinnamomi. West. Aust. For. Dep. Bull. 85. 83pp.

Shea, S.R., Gillen, K.J. and Leppard, W.L. (1980). Seasonal variation in population levels of Phytophthora cinnamomi Rands in soil in diseased, freely-drained Eucalyptus marginata Sm sites in the northern jarrah forest of south-western Australia. Prot. Ecol. 2, 135-156.

Shea, S.R., Shearer, B.L. and Tippett, J.T. (1981). Recovery of Phytophthora cinnamomi Rands from vertical roots of jarrah (Eucalyptus marginata Sm).Australas. Plant Pathol. 11, 25-28.

Shea, S.R., Shearer, B.L., Tippett, J.T. and Deegan, P.M. (1983). Distribution, reproduction, and movement of Phytophthora cinnamomi on sites highly conducive to jarrah dieback in south Western Australia. Plant Disease 67, 970-973.

Shearer, B.L., Shea, S.R. and Fairman, R.G. (1981). Infection of stem and large roots of Eucalyptus marginata by Phytophthora cinnamomi. Australas. Plant Pathol. 10, 2-3.

Sivarajasingham, S., Alexander, L.T., Cady, J.G. and Cline, M.G. (1962). Laterite. Advan. Agron. 14, 1-60.

Smurthwaite, A.J. and Shearer, B.L. (1983). Laterite geology and jarrah dieback mapping methods and preliminary findings. Geol. Survey of W.A., Environ. Geology Rep. EV22.

Sochacki, S.J. (1982). A comparative study of four northern jarrah forest soil types in relation to Phytophthora cinnamomi Rands. Hons. thesis, Murd. Univ.

Stephens, C.G. (1946). Pedogenesis following the dissection of lateritic regions in southern Australia. CSIRO Aust. Bulletin No. 206.

Taylor, R.M., McKenzie, R.M., Fordham, A.W. and Gillman, G.P. (1983). Oxide minerals. In 'Soils : an Australian viewpoint', Division of Soils, CSIRO, pp.309-334 (CSIRO : Melbourne / Academic Press : London).

Throssell, J.S. (1984). The role of duricrust in the perching of groundwater in the Darling Range. Hons. thesis, Univ. W. Aust.

Tippett, J.T. and Hill, T.C. (1983). The relationship between bark moisture and invasion of Eucalyptus marginata by Phytophthora cinnamomi. Australas. Plant Pathol. 12(3), 40-4

Tippett, J.T., Shea, S.R., Hill, T.C. and Shearer, B.L. (1983). Development of lesions caused by Phytophthora cinnamomi in the secondary phloem of Eucalyptus marginata. Aust. J. Bot. 31,197-210.

Turton, A.G., Marsh, N.L., McKenzie, R.M. and Mulcahy, M.J. (1962). The chemistry and minerology of lateritic soils in the south - west of Western Australia. CSIRO Aust. Soils Publ. No. 20.

Walker, J., Thompson, C.H. and Jehne, W. (1983). Soil weathering stage, vegetation succession and canopy dieback. Pacific Science 37(4), 471-481.

Wild, A. (1950). The retention of phosphate by soil. A review. J. Soil Sci. 1(2), 221-238.

Woolnough, W.G. (1927). The chemical criteria of peneplation. J. Roy. Soc. N.S.W. 61, 1-53.