The role of fire in dinosaur-dominated ecosystems: examples from the Late Cretaceous of Alberta

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DECLARATION OF AUTHORSHIP

I Sarah Anne Elizabeth Brown hereby declare that this thesis and the work presented in it is entirely my own. Where I have consulted the work of others or incorporated content derived from co-authored publications this is always clearly stated and my role in the latter is made clear.

Signed:

Dated:

‘Oh, for a muse of fire’

William Shakespeare, *Henry V*

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Abstract

Wildfires are a major component of modern ecosystems, however the role of fire in deep time is still being explored. A database of Cretaceous charcoal localities highlights a reduced charcoal record in the Campanian and Maastrichtian compared to that expected given modelled atmospheric oxygen levels. Temporal distribution and relative abundances of charcoal have provided the first detailed information on fire activity spanning c. 11 million years of the Late Cretaceous in Alberta, Canada. A novel approach to charcoal quantification has been developed, allowing relative abundances to be calculated whilst compensating for charcoal fragmentation.

The Campanian Oldman and Dinosaur Park Formations were investigated, (117 lithological units spanning 1.8Ma). Charcoal, dominated by gymnosperm wood, was distributed throughout the sedimentary succession in all lithologies, indicating that the Campanian wildfires were not restricted to specific environmental settings. This represents the first documented charcoal occurrence within the Dinosaur Park Formation. The Maastrichtian Horseshoe Canyon, Battle and Scollard Formations were investigated (60 samples spanning 9.5Ma). Greater charcoal abundances occurred in the lower part of the sedimentary succession but climatic variations exerted little or no control over wildfire occurrence. Samples from recent wildfires contained uncharred and partially charred plant debris addition to charcoal, highlighting a probable bias within the late Cretaceous assemblages.

Elevated charcoal abundances were recorded in four vertebrate deposits within the Dinosaur Park Formation. Water flows and hyperconcentrated flows, responsible for the formation of these vertebrate deposits, may have been enhanced due to rainfall events influencing the burnt landscape, leading to post-fire destabilisation of slopes. Flooding events following wildfires may be the causal mechanism for the formation of other vertebrate assemblages.

Thirteen samples from recent wildfires (Rodeo-Chediski fire -2002, Medano fire -2010 and the Scultz fire -2010) were investigated to further understand the composition of wildfire derived plant debris. Uncharred and partially charred plant debris was recorded in addition to charcoal, highlighting a probable bias within the Late Cretaceous assemblages. Relative abundances of charcoal could not be shown to

be influenced by proximity to burned area, vegetation stands, forest types or the size of channels. Further research into potential controls on charcoal distribution needs to be considered by wildfire researchers.

This research has highlighted the previously unrecorded extent and importance of wildfire activity through the Late Cretaceous and demonstrated the need for greater investigation of sedimentary successions to prevent underestimation of past wildfire occurrence.

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Chapter 1:

Introduction

1.1 SIGNIFICANCE OF FIRE

Wildfire plays a major and integral role in modern ecosystems, influencing both plant communities and sedimentation patterns (Scott, 2000; Bowman et al., 2009; Midgley and Bond, 2013; Ohlson et al., 2013; Scott et al., 2014). 40% of the Earth's present land surface can be considered fire-prone, with several major biomes strongly influenced by the presence of natural fire (Chapin et al., 2002; Belcher et al., 2010b; Bento-Gonçalves et al., 2012; Belcher et al., 2013; Midgley and Bond, 2013). The effect of wildfires on terrestrial ecosystems can be highly destructive through habitat loss and increased erosional rates, however, fire can be necessary in specific biomes for the reproduction and re-growth of certain types of vegetation (Midgley and Bond, 2013; Scott et al., 2014).

Whilst there is intense research on modern wildfire events and their environmental impact, the role wildfires have played in deep time is still being explored (Scott, 2000; Berner et al., 2003; Pausas and Keeley, 2009; Belcher et al., 2010a, b; Glasspool and Scott, 2010; Harrison et al., 2010). The geological record of fire extends from the Silurian (section 1.5) through to the present day, with varying degrees of fire activity. This thesis focusses on developing the knowledge of Late Cretaceous wildfires.

1.2 RECOGNITION OF WILDFIRE PRODUCTS

Wildfires may generate a range of different products, many of which have the potential to be preserved in the fossil record (Brown et al., 2012; Hammes and Abiven, 2013). These include pyrolitic polycyclic aromatic hydrocarbons (referred to as PAHs throughout the thesis), soot and charcoal (Fig. 1.1). PAHs are gaseous compounds, formed under high heat, and released during the burning of plant matter (Finkelstein, 2005; Brown et al., 2012; Glasspool and Scott, 2013; Scott et al., 2014). They typically have characteristics specific to different fuel sources or fire temperatures, and are often produced in large quantities (Simoneit, 2002; Finkelstein, 2005; Brown et al., 2012; Glasspool and Scott, 2013; Scott et al., 2014). These compounds can be washed out of the atmosphere and incorporated into sediments (Scott et al., 2014). PAHs have been used in deep time fire studies, from the Carboniferous (Romero-Sarmiento et al., 2011), with their presence documented at both the Permian-Triassic and Cretaceous-Paleogene boundary sediments (Killops and Massoud, 1992; Finklestein et al., 2005; Belcher, 2009; Belcher et al., 2009; Nabberfeld et al., 2010; Scott et al., 2010).

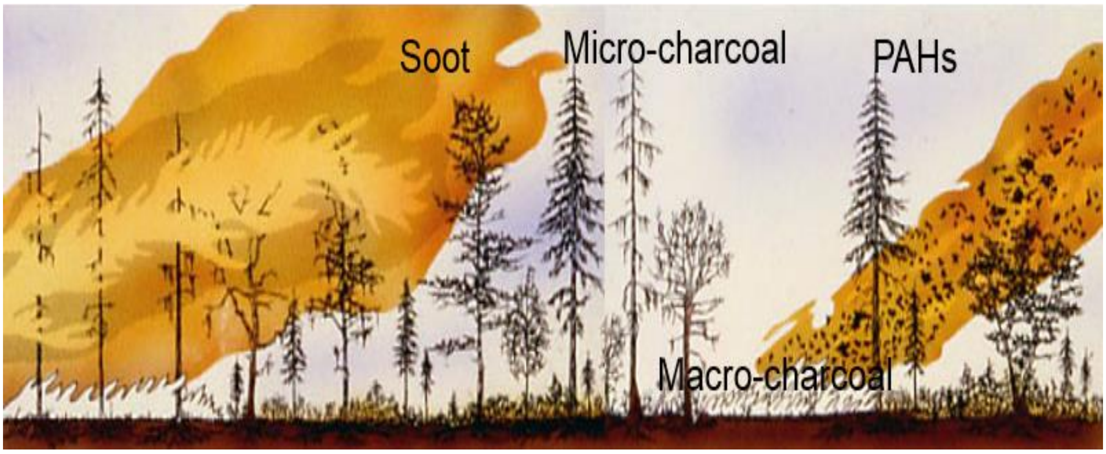


Fig. 1.1 Some of the products created during wildfire activity. Soot, PAHs and micro-charcoal are very fine grained products that are lofted into the atmosphere during wildfire occurrence. These products can be washed out of the atmosphere and incorporated into sedimentary sequences. Macro-charcoal is left on the surface after a fire event, and may be attached to plants (modified after Scott, 2001; Brown et al., 2012).

Soot is a component of smoke, and occurs through the agglomeration of condensed PAHs to form new carbon material (Glasspool and Scott, 2013; Scott et al., 2014). Soot is comprised of almost pure carbon, arranged in clusters or chains, and is morphologically distinctive (Glasspool and Scott, 2013). Soot morphology may be characteristic of different fuel sources (Harvey et al., 2008; Brown et al., 2012; Glasspool and Scott, 2013; Scott et al., 2014). Soot particles are microscopic, typically less than 1µm (Glasspool and Scott, 2013; Scott et al., 2014). Soot has been studied in relation to the Cretaceous-Paleogene boundary as a fire indicator (Belcher et al., 2009). Soot may also be produced through the burning of oil and coal, therefore its presence is not always indicative of wildfire occurrence (Glasspool and Scott, 2013; Scott et al., 2014).

Charcoal is a residue produced as a result of the pyrolysis of plant material, created under conditions of limited oxygen availability (Chaloner, 1989; Scott, 2000; Bird et al., 2008; Scott et al., 2014). Charcoal has a high carbon content (often 60-90%) and has a highly condensed aromatic molecular configuration (Bird et al., 2008; Scott, 2010). Charcoal is not a fully homogeneous substance, with variation in composition based on temperature of formation (Ascough et al., 2011). Charcoal can be characterised by a black, lustrous appearance, with internal anatomy present and a brittle texture that easily splinters (Scott, 2010; Glasspool and Scott, 2014). Charcoal has homogenised cell walls, which are visible under scanning electron microscopy. It is chemically inert and not easily broken down, as charring of wood decreases its susceptibility to decay (Scott, 2000; Scott, 2010; Glasspool and Scott, 2014). These properties allow charcoal to be readily preserved in the fossil record (Scott, 2010; Brown et al., 2012; Glasspool and Scott, 2014; see section 1.5 for geological record of charcoal). Therefore, this thesis investigates relative charcoal abundances as an indicator of Late Cretaceous wildfires (Chapters 4-6).

1.3 CONDITIONS REQUIRED FOR WILDFIRE OCCURRENCE

Specific conditions are required for wildfire occurrence, without which fires would not be possible. Atmospheric oxygen levels, a source of ignition and available fuel are integral factors in determining wildfire occurrence (Fig. 1.2). Other factors are influential in wildfire propagation, including weather and topography; all of which are outlined below.

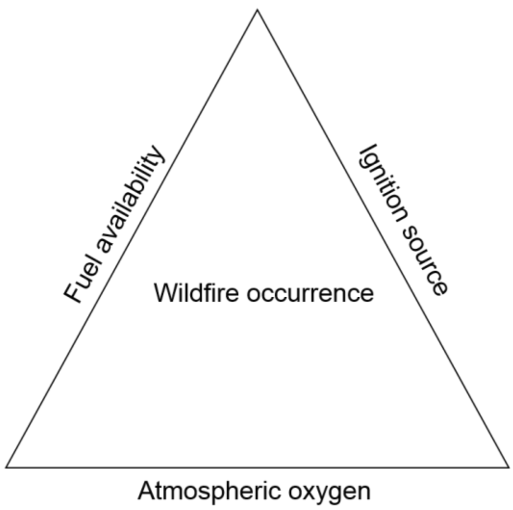


Fig. 1.2 Fire triangle displaying the three key factors controlling wildfire occurrence (Modified after Scott, 1989; Scott et al, 2014).

1.3.1 Atmospheric oxygen

Atmospheric oxygen levels are critical for determining whether combustion can occur. Experimental burning carried out in specifically designed temperature, humidity and atmosphere controlled chambers demonstrated an absence of smouldering or flaming on moss samples below 15% O_2, therefore wildfires would be suppressed below this level (Belcher and McElwain, 2008; Scott et al., 2014).

16-17% is the minimum threshold of atmospheric oxygen required for the sustained combustion of vegetation, with the occurrence of wildfires remaining low until 19% (Lenton, 2013; Scott et al., 2014). With atmospheric oxygen levels between 19-22% there would be enhanced fire occurrence, with high wildfire probabilities above 23% (Belcher et al., 2010b; Lenton, 2013; Scott et al., 2014). A major consequence of high atmospheric oxygen levels is that large quantities of vegetation will combust when subjected to a source of ignition (Watson and Lovelock, 2013; see section 1.3.2 for details of ignition sources).

Atmospheric oxygen levels of 30% are hypothesised to allow extensive burning of wet vegetation, with 35% oxygen leading to inextinguishable fires with fully saturated fuels burning (Scott et al., 2014). This upper limit for fire activity is debated by researchers, with Lenton (2013) stating that wildfires could not be sustained at high (35%) oxygen levels due to high levels of fuel consumption, therefore leading to a reduction in available fuel to burn.

Atmospheric oxygen levels above present day (referred to as PAL throughout the thesis), approximately 21%, have been modelled for the Cretaceous (Chapter 2- Fig. 2.1, section 2.4) indicating a likelihood of enhanced wildfire activity. The Late Cretaceous, in particular, has fewer recorded charcoal occurrences than the rest of the Cretaceous (Chapter 2- Table 2.3, Fig. 2.5, section 2.4), despite relatively high atmospheric oxygen levels. Therefore, this thesis focusses on investigating Late Cretaceous sediments with the aim of documenting the presence or absence of charcoal deposits in a period with modelled high atmospheric oxygen levels.

1.3.2 Ignition source

If suitable atmospheric oxygen conditions are met (section 1.3.1), vegetation can be naturally ignited in four ways; sparks from falling rocks, spontaneous combustion, volcanic activity and lightning strikes, with all four ignition sources present in geological time (Batcheldor, 1967; Scott 2000; Rein, 2013; Scott et al., 2014). Ignitions generated through sparks from falling rocks or the spontaneous combustion of vegetation piles are very rare processes. Spontaneous combustion can occur when a vegetation pile is heated at a greater rate than the heat can be lost to the surroundings, potentially through microbial activity which can raise internal temperatures to 70°C (Pyne et al, 1996). This spontaneous combustion is possible even at ambient temperatures (Drysdale, 2011; Rein, 2013). Porosity through the vegetation, allowing the free flow of oxygen, is required for ignition to occur (Pyne et al, 1996).

Volcanic eruptions and associated pyroclastic density currents can result in wildfires, with a high likelihood of vegetation being ignited by magma or ash during an eruption event (Scott and Jones, 1991a; Scott, 2001; Scott and Glasspool, 2005; Butler, 2008; Scott et al., 2008; Donoghue et al., 2009; Hudspith et al., 2010). Volcanism has been responsible for charcoalification of vegetation both in modern ecosystems and in deep time. The rapid burial associated with volcanic eruptions combined with the inert nature of charcoal (section 1.2) leads to high preservation potential of charcoal within these deposits (Scott and Jones, 1991a; Scott and Jones, 1991b; Scott, 2001; Hudspith et al., 2010).

Eruptions in Montserrat (1997) and in Hawaii (2003) led to the charcoalification of tree trunks and the presence of charcoal in lava (Heliker et al., 2003; Scott, 2010). Pyroclastic flows associated with the Taupo eruption in New Zealand, 1.8ka, led to the charcoalification of vegetation (Hudspith et al., 2010). Carboniferous lavas are also associated with charcoal in Scotland and France (Scott, 2010). Volcanism and lightning are intrinsically linked. Ash produced by volcanism can lead to friction with atmospheric gases resulting in potential lightning discharges (Wilmshurst and McGlone, 1996).

Lightning strikes have been hypothesised to be the main sources of wildfire ignition in deep time (Scott, 2000; Scott et al., 2014). When a fuel is struck by lightning it undergoes rapid high temperature heating, reaching temperatures in excess of 30,000°C, breaking down the cellulose contained within plant tissues (Scott et al., 2014). CO, CO_2, CH_4 and other volatiles are released which subsequently react with atmospheric oxygen, leading to ignitions, and may also result in heat generation which can propagate the wildfire (Pyne et al., 1996; Scott, 2010).

Even with suitable atmospheric oxygen levels, ignition through lightning strikes is not guaranteed. Globally there are approximately 44,000 storms daily, resulting in eight million lightning strikes (Pyne et al., 1996; Scott et al., 2014). The most significant lightning type is that of sky-to-ground lightning, whereby an electrical charge is transferred from a cloud directly to the ground (Scott et al., 2014). Each flash of lightning that is visible to the naked eye contains two or more lightning strokes, with data from Australia indicating an average of one wildfire per 240 lightning stokes (Dowdy and Mills, 2011; Dowdy and Mills, 2012). Ignition is dependent on the nature of the individual lightning stroke, as the degree to which a fuel is heated is related to the current duration within the lightning (Pyne et al., 1996).

The presence or absence of rainfall associated with lightning is crucial, with 'dry' lightning more likely to lead to the ignition and propagation of a wildfire (Dowdy and Mills, 2011; Scott et al., 2014). Atmospherically high thunderstorms, with dry air at lower levels, can lead to the occurrence of dry lightning with rainfall evaporating before it reaches the ground (Dowdy and Mills, 2011). Alternatively fast moving thunderstorms that result in a thin spread of rainfall reaching the ground can also result in 'dry' lightning. The likelihood of a wildfire after a 'dry' lightning event is doubled if there is less than 2mm of rainfall, and quadrupled if there is less than 1mm of rainfall (Dowdy and Mills, 2011).

The occurrence of rainfall associated with lightning is influential in the ignition and propagation of wildfires, and will be strongly influenced by climatic factors. Therefore, the thesis will investigate potential climatic influences on the occurrence and distribution of Late Cretaceous wildfires and associated charcoal deposits (Chapter 6- section 6.4.4).

1.3.3 Fuel

Fuel is an essential component in determining whether a wildfire will occur, and will determine the character of a fire (Pyne et al., 1996; Belcher et al., 2013; Planus and Pastor, 2013). Once suitable atmospheric oxygen levels have been met, the ignition potential and behaviour of wildfires is dependent on fuels above all other factors (Scott et al., 2014). Without suitable biomass amounts a wildfire will not be sustained after ignition, and will therefore extinguish quickly. Fires are considered rare in many modern arid climates due to a scarcity of fuel (Scott et al., 2014). Fuel consumption by wildfires is a function of the fuel itself, not the fire (Davies, 2013). The combustion potential of fuel is influenced by three main factors: fuel chemistry and intrinsic fuel properties, fuel morphology and moisture content (Fig. 1.3).

1.3.3.1 Fuel chemistry and intrinsic properties

The chemical composition of a fuel; organic polymers, minority complexes (e.g. resins) and mineral composition, have a great influence on the flammability of individual fuels (Van Wilgen et al., 1990; Yang et al., 2007; Davies, 2013; Planas and Pastor, 2013; Weise and Wright, 2014). Minerals within fuels reduce the emission of flammable volatile compounds, therefore fuels low in minerals have a greater flammability (Planas and Pastor, 2013). Additional intrinsic properties of fuel, such as heat capacity, thermal conductivity and particle density, do exhibit controls over fire behaviour, however it is widely considered that extrinsic properties exhibit the greatest control (Planas and Pastor, 2013; Scott et al., 2014).

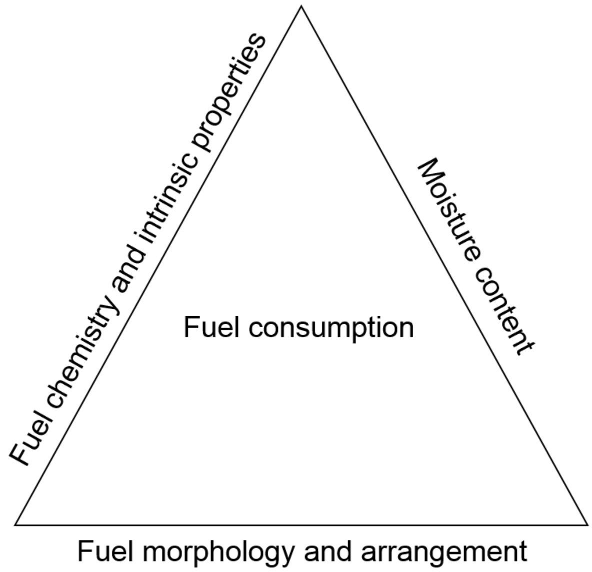


Fig. 1.3 Fuel triangle showing influences of fuel consumption in a wildfire

1.3.3.2 Fuel morphology and arrangement

Fuel morphology and arrangement encompasses the quantity, shape and size, arrangement, continuity and compaction of fuels (Planas and Pastor, 2013; Scott et al., 2014). These extrinsic properties exhibit a significant control of fire propagation. Research into modern wildfires in France shows that neighbouring localities, with similar weather and fuel types, exhibit different wildfire activity due to variations in fuel morphology and arrangement (Curt et al., 2013).

The quantity of available fuel is important for both wildfire sustainability and spread. The amount of fuel available to be consumed by a fire directly affects the fire's energy output, with greater fuel consumption driving further fire propagation (Scott et al., 2014). Expeimental burning has indicated a minimum limit of fuel quantity exists, below which fire spread is not possible (Scott et al., 2014).

The size and shape of fuel is also important for fire propagation and occurrence (Belcher et al., 2013; Curt et al., 2013). These characteristics determine the surface-to-volume ratio, which in turn affects combustion potential (Planas and Pastor, 2013; Scott et al., 2014). Small fuel particles have larger surface-to-volume ratios, which allow faster drying rates, leading to them burning more readily (Belcher et al., 2013; Planas and Pastor, 2013; Scott et al., 2014).

The arrangement of fuels can be influential on the behaviour of wildfires, affecting energy transfer (Weise and Wright., 2014). Fuels can be distributed horizontally, such as dead fuel and litter, or vertically, such as living shrubs and trees (Planas and Pastor, 2013). A continuous horizontal fuel layer will enhance wildfire propagation (Grahem et al., 2004; Planas and Pastor, 2013). Fire activity can be enhanced by the presence of vertical fuels, which can allow flames to pass from the understory to the canopy (Grahem et al., 2004; Planas and Pastor, 2013). Continuity of fuel distribution will determine the spread of a wildfire, with gaps leading to potential fire suppression (Davies, 2013; Planas and Pastor, 2013; Scott et al., 2014).

Fuel compaction is an important factor in determining the fire spread (Pyne et al., 1996; Davies, 2013; Scott et al., 2014). Loosely compacted fuels will result in a faster spreading rate of a fire, due to a greater availability of flowing oxygen compared with compacted fuels (Pyne et al., 1996; Weise and Wright, 2014).

1.3.3.3 Fuel moisture content

The moisture content of fuels influences combustion dynamics (Weise and Wright, 2014). Live fuel moisture is a function of plant physiology, whereas dead fuel moisture varies with environmental conditions (Davies, 2013; Scott et al., 2014; Weise and Wright, 2014). Fuels with a greater water content require more energy to dry out and reach ignition temperatures (Davies, 2013). Ignition of moist fuels requires longer spark durations from lightning strikes (Watson and Lovelock, 2013).

1.3.4. Weather

Whilst the appropriate atmospheric oxygen level, fuel availability and ignition sources are essential in determining wildfire occurrence, weather conditions are also of vital importance in determining wildfire propagation. The relative humidity affects both the ignition and propagation of fires, with air temperature affecting fuel flammability (Planas and Pastor, 2013).

Variations in weather conditions, such as precipitation, will control the moisture content in dead, and to a lesser extent, live vegetation, thus influencing flammability (Davies, 2013). Intense rainfall may also be responsible for extinguishing flames after ignition, preventing wildfire propagation. However wetter fuel has a greater likelihood of igniting and propagating wildfires under higher atmospheric oxygen conditions, particularly if subjected to relatively long lightning spark durations (Watson and Lovelock, 2013; Scott et al., 2014; sections 1.3.1 and 1.3.3.3).

Wind speed has a direct influence on wildfire propagation and intensity (Davies, 2013; Planas and Pastor, 2013). Winds can flatten flames, thus increasing preheating ahead of the fire, leading to faster rates of fire spreading (Davies, 2013). Winds are also influential in the combustion reactions, replenishing the oxygen levels, and affecting heat transfer mechanisms (Planas and Pastor, 2013).

As outlined in section 1.3.3, environments with limited fuel availability have limited fire activity. In environments with abundances of fuel, such as tropical rainforests, wildfire activity is constrained by the occurrence of suitable dry weather conditions (Scott et al., 2014). A combination of suitable weather conditions and abundant fuel availability enhances fire activity. Modern savannahs have a combination of availability of fuel and suitable weather conditions allowing heightened fire occurrence (Scott et al., 2014). Savannahs have hot and wet periods leading to rapid fuel growth, with dry conditions leading to reduced moisture content in dead fuel, thus allowing wildfire ignition and enhanced propagation (Scott et al., 2014).

1.3.5 Topography

The propagation and initial combustion of a wildfire can also be influenced by topographic characteristics; such as slope steepness, aspect and elevation (Davies, 2013; Planas and Pastor, 2013; Scott et al., 2014). These topographical characteristics are linked to fuel properties and meteorological parameters (Planas and Pastor, 2013).

Slope is considered the greatest influencing topographical factor, with steep slopes tilting advancing flames towards unburnt fuels, thus enhancing wildfire propagation in a manner analogous to wind activity (Davies, 2013; Planas and Pastor, 2013; Scott et al., 2014).

Aspect is a controlling factor of the duration and level of solar radiation experienced by a landscape and the relative humidity (Davies, 2013; Scott et al., 2014).

These factors are influential in both the drying out of dead fuels and surface fuel temperatures (Davies, 2013; Scott et al., 2014).

Elevation and meteorological parameters are linked, with lower air temperatures and increased precipitation at higher elevations (Davies, 2013; Scott et al., 2014). Higher elevations are associated with higher fuel moisture contents within dead fuels, and are less likely to ignite (Scott et al., 2014).

1.4 CONSEQUENCES OF WILDFIRES

Wildfires can dramatically alter the geomorphology of landscapes (Shakesby and Doerr, 2006; Doerr and Shakesby, 2013; Scott et al., 2014), along with having considerable effects upon the hydrological cycle of affected watersheds (Cannon et al., 2010). Wildfire activity may result in the burning of both living vegetation and litter layers, which in turn can alter many components of hydrological cycles on a localised scale (Shakesby and Doerr, 2006; Doerr and Shakesby, 2013). Partial or total removal of vegetation and/or litter can lead to a reduction in evapotranspiration, interception and surface storage of rainfall (Shakesby and Doerr, 2006), resulting in greater levels of surface runoff (for further discussion see Chapter 8- section 8.2.1). Increased surface runoff coupled with gravitational forces can enhance a range of erosional processes including the 'detachment, transport and deposition of sediment particles' (Moody et al., 2008). The effect of fire upon soil profiles, vegetation coverage and bedrock all contribute to increasing susceptibility to enhanced erosion and sediment transportation.

Wildfires can result in soils with more friable, less cohesive and more erodible properties (Shakesby and Doerr, 2006; Bento-Gonçalves et al., 2012; Scott et al., 2014). Intense heating of the soil can reduce its intrinsic structural stability, enhancing the chances of erosional processes affecting the soil profile (Shakesby and Doerr, 2006; Doerr and Shakesby, 2013). The soil macropores can also be sealed by ash (a combination of charred organic material and residual mineral matter), produced from the fire event, reducing infiltration levels further (Davies, 2009; Nyman et al., 2010).

Fire events can lead to the combustion of organic matter within soils, volatilising already present aliphatic hydrocarbons (such as waxes and cutin) found within plant material or humic acids (Beatty and Smith, 2010). These subsequently condense onto soil particles as a coating, giving the soil a water repellent (hydrophobic) nature often associated with droughts and wildfires (Shakesby and Dorr, 2006; Finley and Glenn, 2009; Nyman et al., 2010; Doerr and Shakesby, 2013).

Both increased soil hydrophobicity and reduced soil stability result in reduced infiltration levels through the soil, and thus enhance overland flow/surface runoff levels leading to erosion (Bento-Gonçalves et al., 2012; Ebel and Moody, 2013; Moody et al., 2013; Scott et al., 2014). Soil degradation, involving the creation of rills, can be enhanced via increased overland flow due to limited infiltration. It is this surface movement of water that will result in the transportation and deposition of large sediment loads which can occur within and outside of a burnt area (Cannon et al., 2010; Scott et al., 2014). The degree to which a watershed is affected by post-fire erosion is controlled by many factors, including prior sensitivity of affected area to erosion, precipitation and the frequency of wildfire activity (Moody and Martin, 2001).

1.5 GEOLOGICAL HISTORY OF WILDFIRE IN SEDIMENTS

Whilst there is a range of products derived from wildfire activity (section 1.2), the evidence of wildfires in the geological record is predominantly derived from the presence of charcoal (Scott et al., 2014). As outlined in section 1.3.3 fuel is an essential component in determining the occurrence of wildfires. The evolution of land plants in the Late Ordovician/ Early Silurian provided the first occurrence of fuel in deep time (Bateman et al., 1998; Glasspool et al., 2004; Belcher et al., 2013; Scott et al., 2014). Early vascular plants were very small and leafless (Belcher et al., 2013), therefore during the Silurian large accumulations of vegetation were not possible, resulting in a severely limited fuel build up. The earliest evidence of wildfires dates to the Late Silurian from the Welsh Borders (Glasspool et al., 2004), with a single publication thus far.

Plant evolution and diversification occurred during the Devonian. The development of secondary xylem led to taller woody plants, including trees, and the lignin component led to slower decay rates, both of which allowed a greater build-up of fuel loads (Belcher et al., 2013; Scott et al., 2014; Strullu-Derrien et al., 2014). Extensive colonisation of a wider range of environments and habitats took place throughout this Period, with extensive coastal forests by the Late Devonian (Meyer-

Berthand et al., 1999; Scott, 2000; Scott et al., 2014). This diversification of fuel types and colonised environments greatly increased fuel availability and therefore potential fire activity. Charcoal is recorded in increasing quantities through the Late Devonian, with assemblages recorded across Europe and North America, with a range of plant types preserved (Rowe and Jones, 2000; Scott et al., 2014). Global fire activity had become more widespread by the Devonian/Carboniferous boundary (Scott et al., 2014).

Whilst it is evident that fuel availability was a major controlling factor on the origins of wildfires during the Silurian and Early Devonian, by the Devonian/Carboniferous boundary vegetation was well developed on land (Scott et al., 2014). Subsequently atmospheric oxygen levels played a more major role in controlling the occurrence of wildfires from the Carboniferous onwards.

Extensive global charcoal deposits are found throughout the Carboniferous (Scott et al., 2014). Charcoal becomes common by the Mississippian, with charcoal fragments representing a wide variety of plant types (Scott et al., 2014). The Carboniferous can be considered a 'high fire world', with high modelled atmospheric oxygen levels, peaking around 30% (Berner et al., 2003; Berner, 2006; Glasspool and Scott, 2010; Scott et al., 2014). The high modelled atmospheric oxygen levels indicate that wildfires were likely to have been prevalent throughout this Period, and this is supported by an abundance of global charcoal deposits. There is evidence of Carboniferous fires occurring in tropical wetlands (Scott et al., 2014).

The 'high fire world' continues into the Permian, with modelled atmospheric oxygen levels indicating oxygen levels did not fall below 25% and may have reached peaks of between 30%-35% (Berner et al., 2003; Berner, 2006; Glasspool and Scott, 2010; Scott et al., 2014). There are numerous Permian charcoal deposits distributed in both the Northern and Southern Hemispheres (Uhl et al., 2008; Uhl and Jasper, 2011; Kustatscher et al., 2012; Uhl et al., 2012; Scott et al., 2014). However, much of this charcoal record has been documented in the last few years, with a perceived paucity of charcoal in the Permian a decade ago (Scott et al., 2014).

Scott (2010) highlighted that the understanding of Mesozoic fire systems is hampered by a lack of data. With limited research into Mesozoic charcoal occurrence it is difficult to determine whether paucity of charcoal records is representative of a lack of fire activity or simply due to low numbers of charcoal investigations.

The Early Triassic has an absence of identifiable charcoal in lithological samples, which correlates with low, modelled atmospheric oxygen levels, below 15% (Scott, 2000; Uhl et al., 2008; Scott et al., 2014; Uhl et al., 2014; section 1.3.1). These modelled levels of oxygen indicate that fires would not be able to be ignited and propagated, therefore the perceived absence of charcoal during this Period supports the link between fire activity and oxygen. In addition to the low modelled atmospheric oxygen levels, the lack of charcoal may also be related to the slow recovery of terrestrial vegetation after the Permian-Triassic mass extinction, thus greatly reducing fuel availability (Uhl et al., 2008).

There is a paucity of charcoal recorded for the Middle Triassic, with a few charcoal records from South America, Europe and the Middle East (Mancuso and Kelber, 2007; Uhl et al., 2010; Abu Hamad et al., 2013). Atmospheric oxygen levels were still considered low during this part of the Triassic. From the Late Triassic onwards there is an increase in global charcoal records, with oxygen levels at/or above PAL (Abu Hamad et al., 2012, 2014; Byers et al., 2014; Scott et al., 2014).

There is an increase in charcoal records after the Triassic-Jurassic boundary, indicating a sharp rise in fire activity in the Early Jurassic (Scott et al., 2014). There is evidence of fire activity throughout the Jurassic, with charcoal recorded in both the Northern and Southern Hemispheres (Harris, 1957; Harris, 1958; Bojesen-Koefoed et al., 1997; Scott, 2000; Belcher et al., 2010; Marynowski et al., 2011; Scott et al., 2014). Experimental work undertaken by Belcher et al (2010) indicates that narrow-leaf morphologies are more flammable than broad-leaf morphologies, potentially enhancing the fire activity during the Jurassic.

The Cretaceous can be considered a 'high fire world' with modelled atmospheric oxygen levels above PAL and a global distribution of charcoal deposits. A full discussion of charcoal occurrence throughout the Cretaceous is presented in Chapter 2, which represents a new comprehensive database of all published Cretaceous charcoal occurrences. This database highlights a perceived paucity of Late Cretaceous charcoal records.

1.6 INTRODUCTION TO THESIS

As outlined in section 1.5, there are geological periods with low recorded wildfire occurrence. Recent research into Permian charcoal has identified numerous charcoal deposits that had previously been overlooked (section 1.5), thus indicating that perceived paucity in the Late Cretaceous charcoal record may be based upon incorrect assumptions. Therefore Chapter 2 presents a comprehensive new database of Cretaceous charcoal records, drawing attention to the excellent record of Early Cretaceous charcoalified mesofossil assemblages, and highlighting a paucity of charcoal records for the Late Cretaceous.

Chapter 3 outlines the Late Cretaceous localities investigated in this thesis for the presence, distribution and relative abundances of charcoal. Chapter 3 also introduces a new methodology for charcoal quantification in bulk lithological samples, and documents field and laboratory methodology.

Overall, in deep time there is a paucity of investigations into temporal distribution of charcoal within specified time intervals. In the Late Cretaceous this factor is coupled with an apparent paucity of charcoal records overall. Therefore Chapter 4 presents the temporal, spatial and environmental distribution of charcoal in the Campanian of Alberta.

The severe impact wildfires can have on the landscape and associated biota through the removal of vegetation, reduced interception, soil hydrophobicity and enhanced overland flow has been outlined in section 1.4. Dinosaurs were a major presence in the Campanian of Alberta, indicated by large vertebrate assemblages, therefore it is possible that wildfire events may have exhibited a control on their formation. Therefore Chapter 5 presents an investigation into charcoal occurrence within four Campanian vertebrate deposits.

Chapter 6 presents the temporal and environmental distribution of charcoal throughout the Maastrichtian of Alberta, further addressing the perceived paucity of the Late Cretaceous charcoal record. Given that climate is known to have fluctuated in the Maastrichtian of Alberta (based on previous literature) this chapter also investigates links between climate and charcoal relative abundance.

Chapter 7 presents an investigation into three recent wildfires in order to observe the composition of modern wildfire derived plant debris assemblages, particularly with reference to the range of charred, partially charred and uncharred plant debris, along with the range of plant parts and particle shapes present. An understanding of modern wildfire derived plant debris may help to identify any taphonomic biases within the Late Cretaceous samples. In addition, some geomorphic aspects of the burnt areas, such as vegetation stands and size of channels, have been investigated in order to determine whether these exhibit a control over relative abundances of charcoal.

Chapter 8 discusses the methodologies within this thesis, with particular focus on fieldwork methodology, charcoal size fraction selection and the newly developed charcoal quantification technique. Key areas of discussion regarding charcoal transportation, formation of charcoal deposits, charcoal taphonomy and composition of the Late Cretaceous and modern plant debris assemblages have been synthesised within Chapter 8. Many of these aspects are important for all samples within this thesis, and therefore are discussed as a whole.

Chapter 9 presents the major conclusions derived from this thesis, and also indicates key aspects to consider for future research of charcoal deposits in deep time. Charcoal data for Chapters 4-6 is included in Appendix 1. Appendix 2 presents the Brown et al., 2012 paper from which Chapter 2 is adapted. Appendix 3 presents the Brown et al., 2013 paper from which Chapter 5 is adapted.

Chapter 2:

Global record of Cretaceous wildfires

This chapter is an adapted version of Brown et al., 2012. Whilst the paper was collaborative, the Cretaceous locality data tables (Tables 2.1-2.3) and palaeogeographic maps (Fig. 2.3-2.5) were created solely by myself. In addition the introduction and conclusion have been adapted and rewritten for this chapter. Figures 2.1 and 2.2 are from Ian Glasspool, published in Brown et al., 2012. Sections 2.2-2.4 written by A.C Scott, M. E. Collinson and myself, published in Brown et al., 2012, and edited and adapted for this chapter.

2.1 INTRODUCTION

The conditions required for wildfire ignition and propagation have been outlined in Chapter 1, with particular reference to the significance of atmospheric oxygen levels (Chapter 1- section 1.3.1). The Cretaceous is particularly significant in that it represents a period of high (but falling) CO_2 (Hawarth et al., 2005) and a greenhouse climate (Spicer, 2003; Brentnall et al., 2005), with atmospheric oxygen levels modelled to be in excess of present levels. With relatively high levels of atmospheric oxygen, it is likely that the Cretaceous experienced numerous wildfire events.

A series of papers in the 1970s and 1980s on the anatomy of charred Cretaceous plants (Alvin, 1974; Scott and Collinson, 1978; Harris, 1981) alerted palaeobotanists to the distribution and occurrence of fire during the Cretaceous, and drove research towards more intensive taxonomic investigations. However, the discovery of charred flowers (Friis and Skarby, 1981) and other reproductive structures has subsequently driven the search for new Cretaceous charcoal localities. Large numbers of studies on Cretaceous angiosperms have been undertaken over the past 30 years (for a review see Friis et al., 2006; Friis et al., 2011), but the key Early Cretaceous floras containing flowers and reproductive structures contain charcoalified mesofossil assemblages (Friis et al., 2006, 2011). Despite these advances, we still have little information on the global distribution of Cretaceous charcoal and whether fire regimes varied throughout this period.

The climate has been shown to vary through the Cretaceous (for further discussion refer to Chapter 6- section 6.2.2) with intervals of either significant aridity or rainfall (Spicer, 2003). Spatial differences in climate are also documented. Studies using fossils from coastal regions and continental interiors indicate distinct climatic differences between the two (Spicer et al., 2008). Models agree (Fig. 2.1) that during the Early Cretaceous atmospheric oxygen levels rose sharply, subsequently declining gradually (Bergman et al., 2004, Berner, 2009; Glasspool and Scott, 2010). Higher atmospheric oxygen levels may have suppressed the effects of climate on fire activity, with oxygen a controlling factor. The middle to later Cretaceous was also a time of dramatic vegetational change (Niklas et al., 1985; Crane and Lidgard, 1989; Lidgard and Crane, 1990; Lupia et al.,1999) (Fig. 2.1).

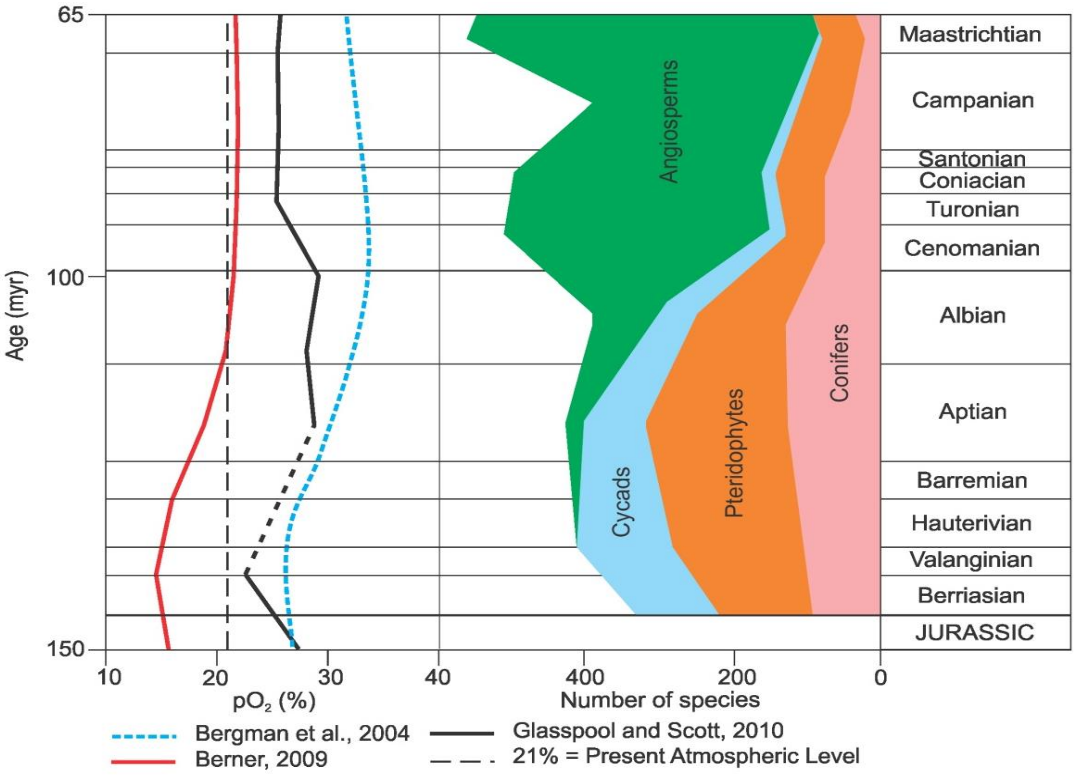


Fig. 2.1 Modelled (Bergman et al.*, 2004; Berner, 2009) and calculated (Glasspool and Scott, 2010) atmospheric oxygen concentrations in the Cretaceous with the global change in vegetational composition (after Niklas* et al.*, 1985; Crane and Lidgard, 1989). Timescale after 2010 ICS/IUGS. Brown et al, 2012.*

This chapter provides a new comprehensive database of all published Cretaceous charcoal localities, and details regarding the composition of each charred assemblage. In addition this chapter presents a background summary of Cretaceous fire activity, discussion regarding geographical distribution of charcoal and identification of potential gaps in the Cretaceous charcoal record.

2.2 OCCURRENCE OF CHARCOAL IN CRETACEOUS SEDIMENTS

Global charcoal records are plotted on three palaeogeographic maps (Figs. 2.3-2.5); subdivided into Early Cretaceous (Berriasian- Albian), Mid Cretaceous (Cenomanian- Santonian) and Late Cretaceous (Campanian- Maastrichtian). The data from which these maps were derived, plus additional assemblage and locality information, is given in Tables 2.1-2.3. These time bins were selected to allow different stages within the Cretaceous to be investigated which would link with terminology used within literature and with palaeogeographic variations. The time bins were also selected to correlate with the plate reconstructions provided by C.R. Scotese.

Pre-Barremian reports of Cretaceous charcoal are dominated by the Wealden facies of Europe (Table 2.1 and references therein, Fig. 2.2), outcropping in Southern England and Belgium. However, there are also reports of charcoal from the Gunpoquan Basin of China, Shubenacadie Basin of Nova Scotia, the Crimean Peninsula of Ukraine, the Algoa Basin of South Africa and Maiya in southwest Madagascar (Table 2.1 and references therein). The record of inertinite (=fossil charcoal (Scott and Glasspool, 2007)) in coal from this interval is rather more spartan, with only the coals of the Valanginian Bickford Formation containing greater than 10% charcoal (Table 2.1).

Despite having a global distribution these earliest Cretaceous fires do not seem to have become abundant until the Valanginian and then occurred throughout the Wealden (Alvin, 1974; Batten 1974, 1998). These fires appear to have burned both fern prairies and large coniferous trees (Harris, 1981; Batten, 1998; Collinson et al., 2000), with the charcoal assemblages either being dominated by fern organs, a plant group less well represented in later assemblages, or by conifer wood (Fig. 2.2).

From the Barremian until the end of the Early Cretaceous the diversity of plants preserved as charcoal, the range of organs preserved and the geographic distribution across which they are reported all increase (Table 2.1). Despite these increases, fires in the polar biome appear to remain rare during this interval (Falcon-Lang et al., 2001)

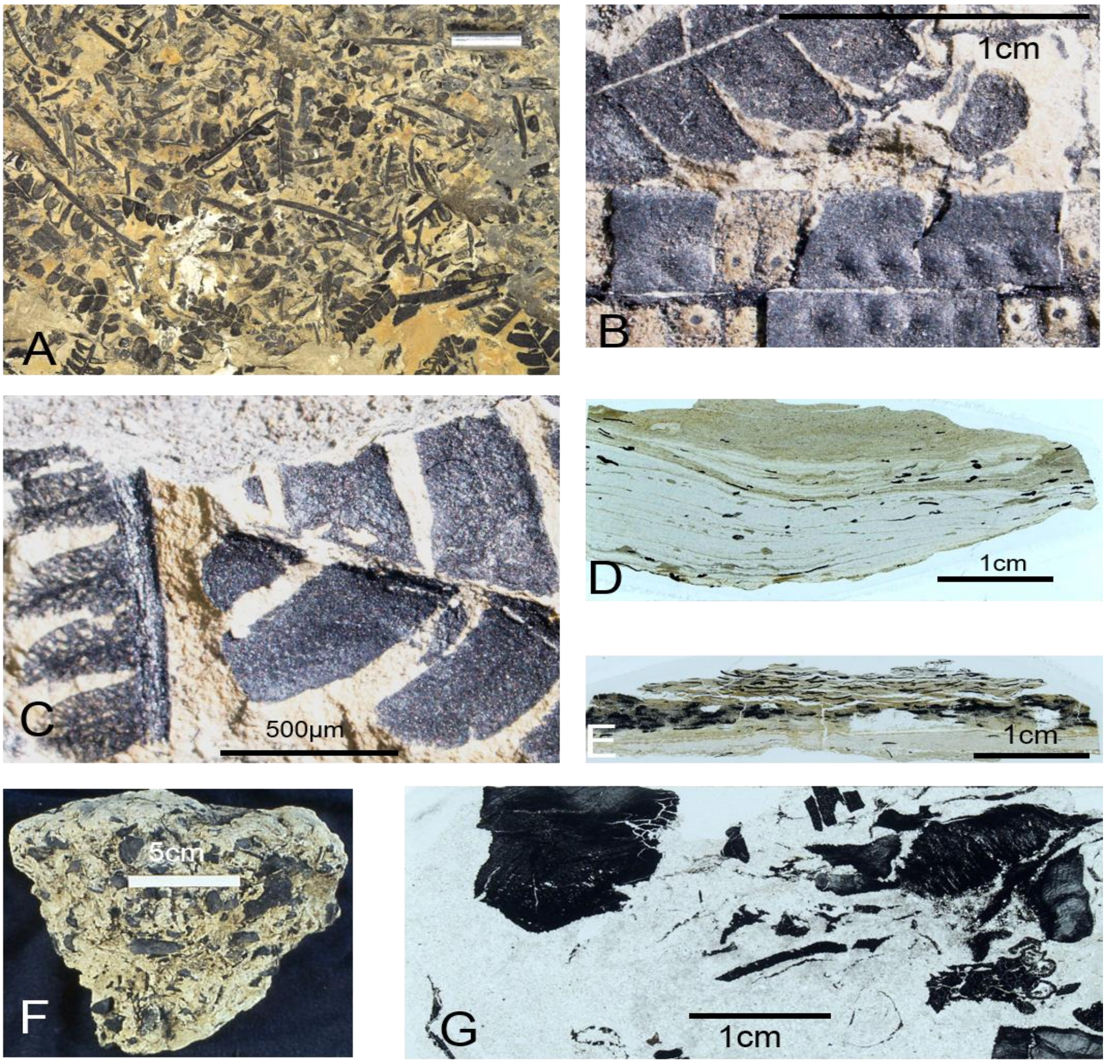


Fig. 2.2 Charred plants from the Wealden of Shepherds Chine, Isle of Wight, England, A- Siltstone with charred ferns, mainly Weichselia pinnules (FMNH PP55329- Field Museum of Natural History, Chicago, U.S.A.), B- Detail of A showing charred fern pinnules of Weichselia and Phlebopteris, C- Detail of A showing charred Weichselia pinnules, D- Thin section of siltstone runnel showing layers with charred fern pinnules (FMNH PP55330), E- Thin section of siltstone with concentrated layers of charred fern pinnules (FMNH PP55331), F- Coarse sandstone with conifer wood charcoal (FMNH PP55332), G- Thin section of F showing conifer wood charcoal (FMNH PP55332) (Brown et al.*, 2012).*

and may have been initiated by volcanic activity. Of particular note are the Portuguese and the North American assemblages of this age, which are of prime taxonomic importance as they preserve many early angiosperm reproductive organs, both as charcoal and lignitic compressions (Friis et al., 2006, 2011, Table 2.1). These charred structures preserve fine anatomical details that have allowed key insights into the evolution and diversification of the flowering plants (Friis et al., 2006, 2011). Also worthy of note is the apparent frequent association of charcoal with deposits of amber (Brasier et al., 2009), fire damage probably having resulted in significant resin generation. However, as Brasier et al. (2009) remark, this association is scarcer in post-Cretaceous deposits. Therefore, this association may in part reflect the prevalence of fire during the Cretaceous.

In the Mid-Late Cretaceous there is evidence of fire on every continent (Tables 2.2-2.3, Figs. 2.4-2.5). However, the majority of data comes from the northern hemisphere, in particular Europe and North America with a paucity of data from the vast bulk of the globe. Inertinite data from coals from the Southern Hemisphere exist (e.g. the Coniacian Agwu and Maastrichtian Mamu formations of Nigeria, and the Campanian-Maastrichtian Pike River Coalfield of New Zealand (Tables 2.2-2.3)) suggesting that fires should have been more common than the current charred mesofossil record indicates, identifying a potential bias in sedimentological investigation. The charcoal assemblages from this interval show a range of taxonomic diversity (Tables 2.2-2.3).

The Mid-Cretaceous charred mesofossil record is particularly important and affords the earliest evidence of several angiosperm clades, however by the Late Cretaceous gymnosperm wood is perhaps the most widely reported charcoalified fossil type (Tables 2.2-2.3) though angiosperm reproductive structures are reported in assemblages right up until the latest Maastrichtian (Table 2.3).

Despite longstanding claims for global fires at the end of the Maastrichtian (K-P boundary) (e.g. Wolbach et al., 1990), a number of studies examining the abundance and distribution of charcoal (Belcher et al., 2003, 2005), the morphology of soot (Harvey et al., 2008) and the nature and distribution of PAHs (Belcher et al., 2009) indicate that the data do not support such a conclusion (Belcher, 2009). New impact models no longer indicate the range of temperatures required to create widespread and intense fires (Goldin and Melosh, 2009). Some recent authors continue to refer to K-P fires (e.g. Kring, 2007), while others follow the change of view (Schulte et al., 2010).

2.3 GEOGRAPHIC DISTRIBUTION OF FIRES

The charcoal data presented in section 2.2 (Tables 2.1- 2.3, Figs. 2.3- 2.5) demonstrate widespread occurrences of fire across many regions in the Cretaceous. A paucity of records in the Southern Hemisphere could reflect a lack of charcoal research and recognition or the predominant occurrence of Cretaceous wildfires in the Northern Hemisphere (Bond and Scott, 2010). Clearly, future research at Southern Hemisphere sites would benefit our understanding of any link between fire occurrence, Cretaceous palaeogeography and climates. Most studies on Cretaceous vegetation and climate (e.g. Horrell, 1991; Spicer and Corfield, 1992; Coiffard et al., 2006, 2007; Sellwood and Valdes, 2006; Sewall et al., 2007; Hay, 2008; Donnadieu et al., 2009; Herman and Spicer, 2010) have not yet incorporated fire as a consideration. This is clearly a relevant factor across many areas (Figs. 2.3-2.5).

Though collection bias must be considered, a pattern emerges when charcoal mesofossil data are plotted on time-sliced palaeogeographic maps (Figs. 2.3-2.5). A large number of charred angiosperm reproductive organs occur from the Early and Mid-Cretaceous of western Europe and eastern North America (Tables 2.1-2.2, Figs. 2.3-2.4). However, there are as yet no records from western North America, despite extensive evidence of fire as indicated by charred deposits without angiosperm reproductive organs and inertinite in coal (Figs. 2.3- 2.4). This trend in distribution of charred angiosperm reproductive organs is not as apparent for the Late Cretaceous (Fig. 2.5), with only a single recorded angiosperm reproductive organ in eastern North America. Equally the occurrence of charcoal in some African coals (Wuyep and Obaje, 2010) also indicates that the absence of mesofossil records is not related to an absence of wildfires, and therefore may represent a collection bias.

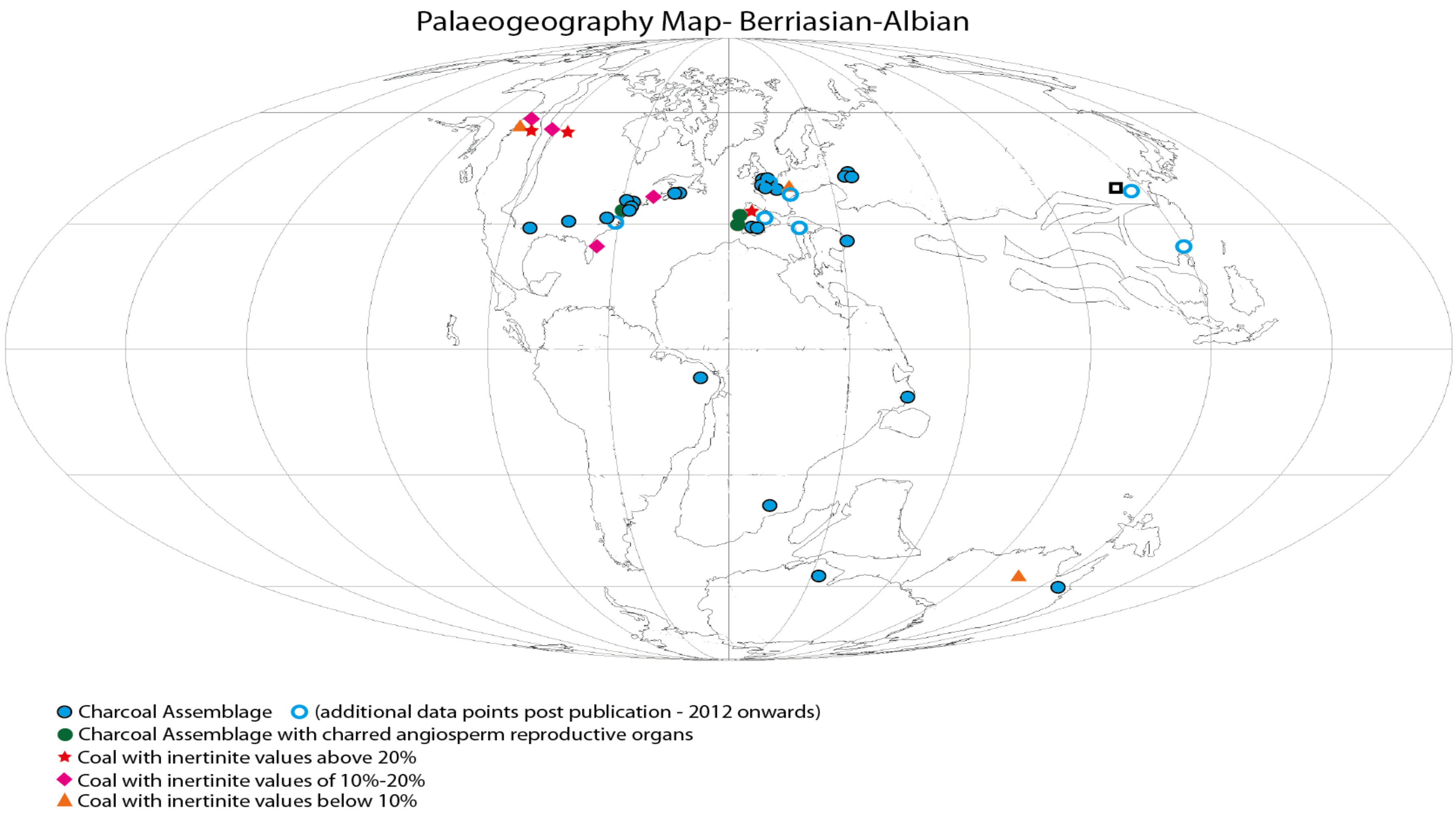


Fig. 2.3 Geographic distribution of charcoal mesofossil assemblages and inertinite for the Berriasian to Albian, plotted on a 120Ma map. Plate reconstructions by C.R. Scotese (Paleomap project), with permission.

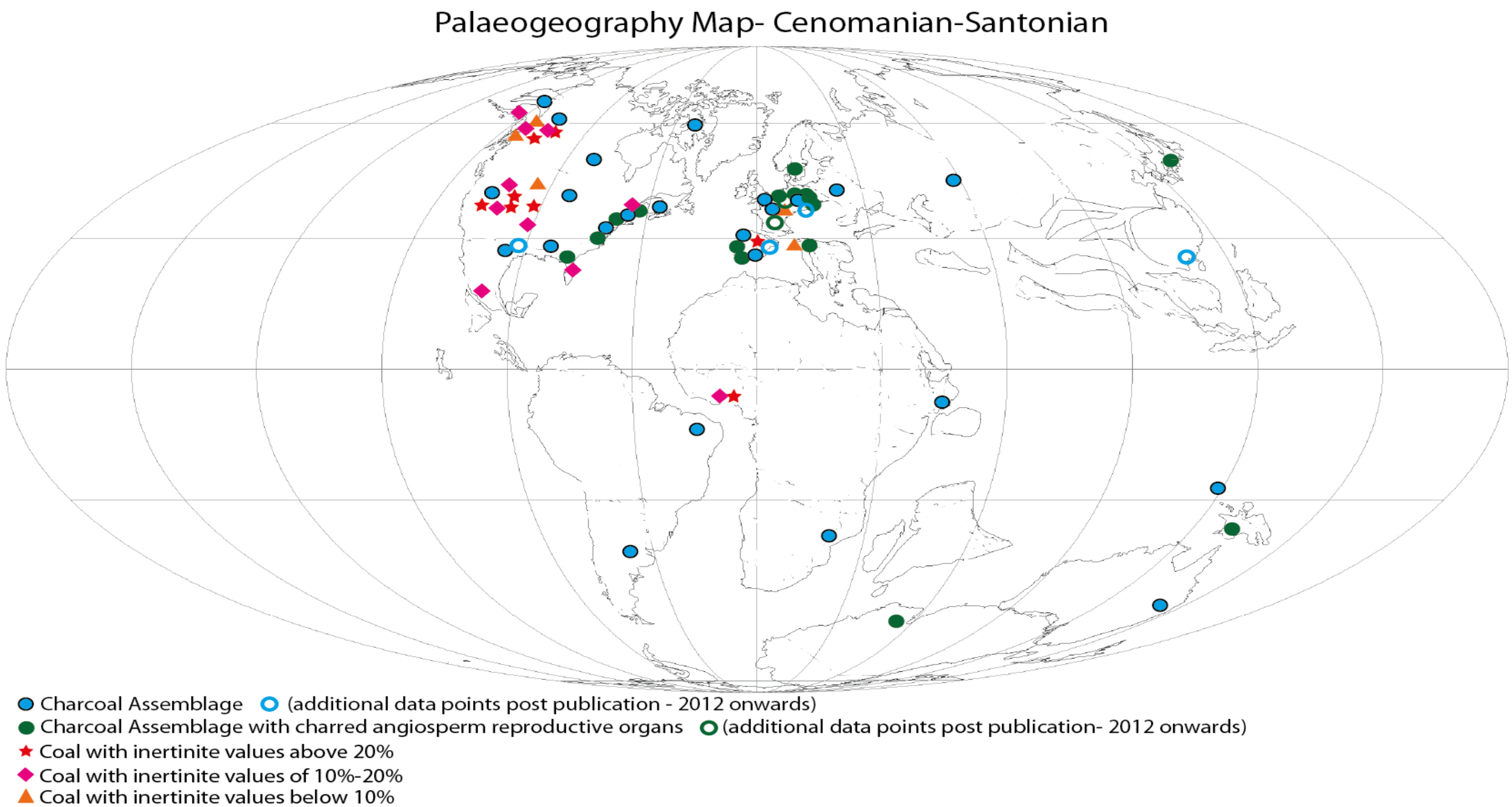


Fig. 2.4 Geographic distribution of charcoal mesofossil assemblages and inertinite for the Cenomanian to Santonian, plotted on a 100Ma map. Plate reconstructions by C.R. Scotese (Paleomap project), with permission.

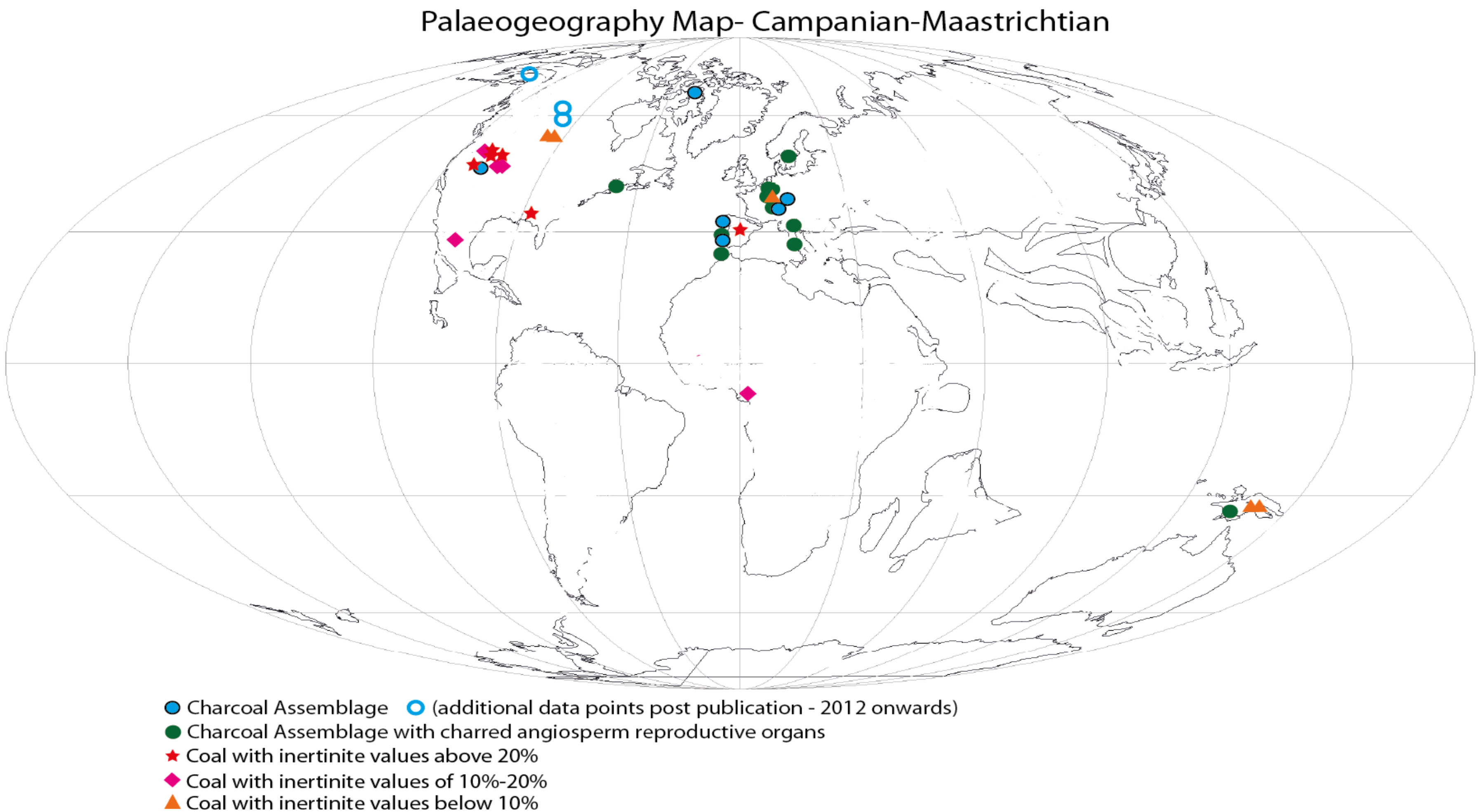


Fig. 2.5 Geographic distribution of charcoal mesofossil assemblages and inertinite for the Campanian to Maastrichtian, plotted on a 80Ma map. Plate reconstructions by C.R. Scotese (Paleomap project), with permission.

Table 2.1. Early Cretaceous (Berriasian-Albian)

Country	Locality	Stratigraphy	Age	Lithology and environment of deposition	Charred vegetation	Uncharred vegetation	Comments	References
England	Portland, Dorset	Lower Purbeck Fm, Great Dirt Bed	Jurassic-Cretaceous boundary	Palaeosol- black carbonaceous marl with limestone pebbles deposited at the edge of a hypersaline lagoon.	Charcoal, type not specified.	Silicified conifer wood and shoots.	Silicified in situ tree stumps occur in the Lower Dirt Bed along with conifer branches. There is no reported charcoal from this bed.	Francis, 1983; Watson & Alvin, 1996; Coram & Jepson, 2012
England	Swanage, Dorset	Lulworth Fm	Berriasian	Purbeck limestone.	Charcoal, type not specified.	Not specified.	Associated with lacewings.	Jepson et al., 2012
Germany	Wealden Basin	Wealden	Berriasian	Coal.			Inertinite (mmf) 6.9%, range: <10%	Average of 11 samples reported in Glasspool & Scott, 2010
China	Gungpoquan Basin, Gansu Province	Lower Laoshuwo Gp	Berriasian-Valanginian	Sandstones & mudstones.	Charcoal, type not specified.	Present, type not specified.	Subsurface (core) deposit only.	Zhang et al., 2014

Table 2.1- Localities of Early Cretaceous (Berriasian-Albian) sediments yielding charcoal, including assemblages with charred angiosperm fertile organs and records of quantitative inertinite data from coals. Localities shown on Fig. 2.3. Data show in red is post publication- 2012 onwards.

Table 2.1. Early Cretaceous (Berriasian-Albian)

Country	Locality	Stratigraphy	Age	Lithology and environment of deposition	Charred vegetation	Uncharred vegetation	Comments	References
England	Hastings	Ashdown Fm	latest Berriasian-early Valanginian	Amber in "charcoal (fusain) lignites".	Only conifer wood.		This amber deposit may owe much to fire as resins "flowed through the carbonized tracheids and into broader fissures" following burning. Charcoal "is also known to be associated with other early amber nodules e.g. the Hauterivian of Lebanon; Barremian of the Isle of Wight; Barremian to Maastrichtian of Spain) although it tends to be scarcer in much younger amber deposits".	Brasier et al., 2009
Ukraine	Crimean Peninsula, Kacha River, Rezanaya Mountain		lower Valanginian	Shallow marine.	Charcoal, type not specified.			Grocke et al 2005
Australia	Surat Basin	Orallo Fm	Valanginian	Coal.			Inertinite (mmf) 1.0%, range: <10%	Data from Glasspool & Scott, 2010
Canada	British Columbia	Bickford Fm	Valanginian	Coal.			Inertinite (mmf) 18.3%, range: 10-20%	Data from Glasspool & Scott, 2010

Table 2.1- Continued

Table 2.1. Early Cretaceous (Berriasian-Albian)

Country	Locality	Stratigraphy	Age	Lithology and environment of deposition	Charred vegetation	Uncharred vegetation	Comments	References
Canada	British Columbia	Minnes Gp, Gorman Creek Fm	Valanginian	Coal.			Inertinite (mmf) 1.0%, range: <10%	Data from Glasspool & Scott, 2010
South Africa	Algoa Basin, Sundays River, Mfuleni farm	Kirkwood Fm	middle-upper Valanginian	Mudstone palaeosoils and coarse fluvial sandstones.	Wood (up to 15 mm long), affinity not specified.	Impressions of bryophytes, ferns, cycads, bennettites, conifers and unassigned gymnosperms. Also conifer and cycadalean leaves in amber.		Gomez et al., 2002
Ukraine	Crimean Peninsula, Kacha River, Rezanaya Mountain		upper Valanginian	Shallow marine.	Not specified, but undifferentiated tracheids illustrated from this interval.			Grocke et al 2005
Canada	Nova Scotia, Shaw Pit, Shubenacadie Basin	Chaswood Fm	Valanginian-Hauterivian	Sands & clays.	Ferns & conifer wood.	Conifer wood, leaves & cones & lycopsid megaspores.	Evidence of post-fire soil erosion (quartz grains in lignite horizons).	Scott & Stea, 2002; Falcon-Lang et al., 2007
Canada	Nova Scotia, Bailey Quarry, Shubenacadie Basin	Chaswood Fm	Valanginian-Hauterivian	Coarse grained, pebbly sandstones & clays.	Gymnosperm wood (~1cm3) -Taxodioxylon (predominates), Cupressinoxylon (present).	Ferns & bennettite cuticle.		Falcon-Lang et al., 2007
Ukraine	Crimean Peninsula, southern slope of Belaya Mountain		lower Hauterivian	Shallow marine.	Charcoal, type not specified.			Grocke et al 2005

Table 2.1- Continued

Table 2.1. Early Cretaceous (Berriasian-Albian)

Country	Locality	Stratigraphy	Age	Lithology and environment of deposition	Charred vegetation	Uncharred vegetation	Comments	References
Madagascar	SW Madagascar, Manja		Hauterivian		Ferns (Gleichenimorpha monostigma, Phlebopteris dunkeri, Weichselia reticulata).	Bennettites (dominant), ferns, spehnopsids, hepatophytes, pteridosperms, conifers, and angiosperm leaves (few).	Despite a diverse flora apparently dominated by benettites, but also including angiosperms, the only charred remains reported are those of ferns.	Appert, 2010
England	Isle of Wight, Hanover Point Assemblage	Wessex Fm	Hauterivian-Barremian	Mudstones deposited along river channel margin.	Charred wood (<1cm3) -Podocarpaceae (predominates), Pseudofrenelopsis (rare).	Silicified Araucarioid wood, leafy conifer shoots & termite coprolites.	Abundant charred mesofossils, but uncharred araucarioid wood is three times as common as charred wood. Assemblage derived from an environment dominated by low diversity conifers, some of which were large trees.	Collinson et al., 2000; Radley & Allen, 2012
England	Isle of Wight, Sheperds Chine Assemblage	Sheperds Chine Mbr, Vectis Fm	Hauterivian-Barremian	Low energy shallow coastal lagoon mudstones, siltstones & sandstones.	Gymnosperm wood (<0.5mm3 ->1mm3) – Aff. Pinaceae, Taxodiaceae or Cupressaceae. Ferns (predominate) – Weichselia & other taxa.	Large uncharred component including wood, plus rarer megaspores, bennettite & cycad cuticles, & arthropod cuticle & fish vertebrae.	Abundant charred mesofossils. The siltstones occur in runnels (Fig. 5D, E), possibly as a result of rapid deposition following post-fire erosion.	Alvin, 1974; Collinson et al., 2000

Table 2.1- Continued

Table 2.1. Early Cretaceous (Berriasian-Albian)

Country	Locality	Stratigraphy	Age	Lithology and environment of deposition	Charred vegetation	Uncharred vegetation	Comments	References
England	Surrey, Clock Pit south of Capel	Lower Weald Clay Fm	Hauterivian	Mudstone.	Wood, fungal hyphae, fern fronds (including Weichselia), gymnosperm seeds, conifer shoots & arthropod remains.	A highly diverse assemblage of seeds & gymnosperm organs.	The charcoal assemblage occurs in facies with dinosaur teeth & bones. The assemblage may reflect post-fire erosion.	Batten, 1998
England	Surrey, Smokejacks Brickworks, Ockly	Upper Weald Clay Fm	Barremian	Mudstone.	Wood, fungal hyphae, fern fronds (including Weichselia), gymnosperm seeds, conifer shoots & arthropod remains.	A highly diverse assemblage of seeds & gymnosperm organs.	The charcoal assemblage occurs in facies with dinosaur teeth & bones. The assemblage may reflect post-fire erosion.	Batten, 1998
England	Isle of Wight, Chilton Chine	Wealden Marls, Wessex Fm	earliest Barremian	Amber in lignite formed as a channel-lag deposit.	Unidentified wood, affinity not specified.	Conifers (abundant) probably Brachyphyllum, and 21 miospore species.		Nicholas et al., 1993
England	Surrey, Beare Green Brick Pit, Holmwood	Upper Weald Clay Fm	Barremian	Broad river channel facies.	Only ferns: Weichselia (abundant), Gleichenites & Phlebopteris dunkeri (less common).	None reported.		Harris, 1981
Belgium	Mons Basin, Danube-Bouchon Quarry	Hautrage Fm	Barremian	Floodplain clays, silts & sands.	Wood, coniferous twigs & seeds, unidentified reproductive structures, ferns & fern litter.	Ginkgoalean fruit cuticle, conifer twigs, leaves, seeds, cones & scales & scales & cones of unknown affinity.	Plant composition varies within each of the seven beds reported at this locality. Some of the channel sands contain rip-up clasts of charred litter dominated by ferns.	Gomez et al., 2008

Table 2.1- Continued

Table 2.1. Early Cretaceous (Berriasian-Albian)

Country	Locality	Stratigraphy	Age	Lithology and environment of deposition	Charred vegetation	Uncharred vegetation	Comments	References
U.S.A	Virginia, Drewry's Bluff, southeast of Richmond	Potomac Gp	Barremian-Aptian	Clay balls embedded in a sand and gravel bed. Leaf bed is contained within a thin clay bed higher in the section than the clay balls.	Charcoal, type not specified.		Charcoal is present at this locality along with lignitised compressions. It is unclear which flora has been charred. Flora is contained within clay balls and a leaf beds. The clay balls contain fern fragments, gymnospermous leaves, twigs and seeds. The leaf bed contains angiosperm leaves, fern fronds, conifer shoots and cycad leaves.	Pedersen et al., 1993; Crane & Herendeen, 1996
U.S.A	Virginia, Dutch Gap, southeast of Richmond	Patuxent Formation, Potomac Gp	Barremian-Aptian	Fluviatile / deltaic crossbedded sands, laminated clays and silt, gravel beds.	Charcoal, type not specified.		Charcoal is present at this locality along with lignitised compressions. It is unclear which flora has been charred. Vegetation includes 12 angiosperm leaf types (magnoliid affinity). Conifers, bennettitalean leaves, ginkgoalean leaves and fern fragments are all present.	Pedersen et al., 1993; Crane & Herendeen, 1996

Table 2.1- Continued

Table 2.1. Early Cretaceous (Berriasian-Albian)

Country	Locality	Stratigraphy	Age	Lithology and environment of deposition	Charred vegetation	Uncharred vegetation	Comments	References
Portugal	Torres Vedras, Lusitanian Basin	Base of Almargen Fm	late Barremian-early Aptian	Sandy lignite.	Angiosperm flowers, fruits & seeds. Unidentified fragments.	Megaspores & pollen within coprolites (small component).	Charred angiosperm flora less diverse than other early Cretaceous Portuguese localities.	Friis et al., 2004
Portugal	Catefica, western margin of Runa Basin		late Barremian-Aptian	Fluviatile cross-bedded sands with organic horizons & clay beds.	Angiosperm flowers, fruits & seeds, ferns, liverworts & conifer twigs.	Rare lignitic compressions.		Friis et al., 1999
Canada	Alberta & British Columbia	Gething Fm	Aptian	Coal.			Inertinite (mmf) 19.1%, range: 10-20%	Average of 68 samples reported in Glasspool & Scott, 2010
Portugal	Famalicão, western Portuguese Basin		late Aptian	Organic rich clay.	Angiosperm fruits, seeds & flowers, Cheirolepidiaceous conifers (rare).	Lignitised angiosperms.	Most diverse floral assemblage from the early Cretaceous of Portugal.	Friis et al., 1994., 1999., 2000; Eriksson et al., 2000; Frris et al., 2014
Italy	Cusano Mutri, Campania Region		late Aptian	Marls.	Conifer wood.	Impressions and compressions of conifers and angiosperm leaves.		Bartiromo et al., 2012
Portugal	Vila Verde, ENE of Figueria de Foz area	"Arenitos de Carrascal" complex	late Aptian-early Albian	Alternating clay & silt layers.	Angiosperm flowers, leaves & seeds, unspecified wood.	Impressions of conifer twigs, ferns & angiosperm leaves (rare).		Friis et al., 1996., 2006., 2010
Portugal	Vale de Agua, Lusitanian Basin	Famalicão Mbr of Figueria de Foz Fm	late Aptian-early Albian	Clay.	Angiosperm fruits & seeds, Magnoliid & Ranunculalean flowers. Charred conifer cones and twigs.	Lignitised flowers & pollen organs.		von Balthazar et al., 2005; Friis et al., 1997., 1999., 2006; Pedersen et al., 2007; Mendes et al., 2010

Table 2.1- Continued

Table 2.1. Early Cretaceous (Berriasian-Albian)

Country	Locality	Stratigraphy	Age	Lithology and environment of deposition	Charred vegetation	Uncharred vegetation	Comments	References
Portugal	Buarcos, Beira Litoral region	"Arenitos de Carrascal" complex	late Aptian-early Albian	Cross bedded coarse sandstone with fluviatile or lacustrine intercalated layers of clay & silt.	Angiosperm flowers & fruits (Chloranthaceae).	None reported.	Gymnosperm twigs of Cheirolepidiaceae affinity - not clear if these are charred.	Friis et al., 1997., 1999., 2000
U.S.A.	Texas, Hood County	Twin Mountains Fm	Aptian-Albian	Fluvially derived well cemented sandstones.	Wood (Cheirolepidiaceae).	Silicified logs (Cheirolepidiaceae), gymnospermous shoots, cones.	Extends geographical extent of Frenelopsis ramosissima by 2100km within the U.S.A. Dinosaurs found within this formation. Charcoal contained within channel fills.	Axsmith & Jacobs, 2005; Adams, 2013
U.S.A.	Arkansas, north of Nashville	Holly Creek Fm	Aptian-Albian	Clay bed.	Wood, affinity not specified.	Uncharred wood and twigs, silicified wood.		Axsmith, 2006
Brazil	Araripe Basin, Caatinga	Romualdo Mbr, Santana Fm	Early Albian	Lacustrine silty shales with carbonate concretions.	Woody gymnospermous fragments.	Calcitized plant debris including cones from cycads and Equistetales stems. Rare calcitized logs are present.	Charcoal is contained within the carbonate concretions. 3D fish and rare pterosaurs have also been observed within the concretions.	Martill et al., 2012

Table 2.1- Continued

Table 2.1. Early Cretaceous (Berriasian-Albian)

Country	Locality	Stratigraphy	Age	Lithology and environment of deposition	Charred vegetation	Uncharred vegetation	Comments	References
England	Bedfordshire, Munday's Hill Quarry near Leighton Buzzard	3m Below the Gault Fm	early Albian	Tidal flat, organic rich clays & silts from near an estuary mouth.	Gymnosperm wood (abundant), fern pinnules & rachis (Gleichenia).	None reported.		Herendeen & Skog, 1998
Spain	Cantabria	Las Penosas Fm	early Albian	Amber within carbonaceous shales, siltstones, and wavy/ lenticular sandstone layers. Interpreted to have been deposited in an estuarine bay system with small bayhead deltas.	Wood, affinity not specified.	Alvinia cones and Frenelopsis branching shoots.	A few amber pieces contain charcoalified plant fibres. Charred Weichselia occurs in adjacent beds to those containing amber.	Najarro et al., 2010
Antarctica	Kerguelen Plateau, Site 750, Raggatt Basin	Lith. Unit IV	early Albian	Clay/ siltstone with volcaniclastics and coal.	Only wood (Podocarpoxylon).		Fires may have been initiated by volcanism.	Francis & Coffin, 1992
U.S.A.	Virginia, Puddledock in Prince County	Potomac Gp	early-middle Albian	Clay & silt.	Angiosperm fruits, wood & flowers (Aff. Magnolialean or Lauralean).	Compressed lignitic flowers & fruits.	Most diverse mesofossil flora from the Early Cretaceous of North America.	Herendeen, 1991a,b; Srinivasan, 1992; Crane et al., 1993, Friis et al., 1994; von Balthazar et al., 2007; Friis et al., 2014

Table 2.1- Continued

Table 2.1. Early Cretaceous (Berriasian-Albian)

Country	Locality	Stratigraphy	Age	Lithology and environment of deposition	Charred vegetation	Uncharred vegetation	Comments	References
U.S.A.	Virginia, Bank near Brooke	Potomac Gp	early-middle Albian	Sandstones with intercalated claystones and siltstones.	Charcoal, type not specified.	Lignitised compressions, type not specified.	It is unclear which flora has been charred. Angiosperm leaves, conifer shoots and leaves and fragmentary ferns are present.	Crane et al., 1993; Crane & Herendeen, 1996
U.S.A.	Virginia, Quantico	Potomac Gp	early-middle Albian		Charcoal, type not specified.	Lignitised compressions, type not specified.	It is unclear which flora has been charred. Vegetation includes gymnospermous leaves and shoots, conifers, cycadophyte, pteridophyte; along with angiosperm leaves.	Crane & Herendeen, 1996
U.S.A.	Maryland, Rocky Point	Potomac Gp	early-middle Albian	Sandstones.	Charcoal, type not specified.			Belcher et al., 2013
Spain	Valle del Rio Martin	Esucha Fm, La Orden Mbr	Albian	Floodplain near channel levee; clay-rich, fine-grained sandstone.	Gymnosperm wood and fragments of ferns- Weichselia reticulate & Phlebopteris dunkeri.	Impressions & compressions of Brachyphyllum with cones (abundant), ferns (Cladophlebis & Weichselia reticulata), Zamites, Cycadales.		Sender et al., 2005; Sender et al., 2014
Spain	Cantabria	Esucha Fm	Albian	Coastal plain sediments.	Charcoalified plant fibres, type not specified		Charcoal and insect wings found within amber.	Pérez-de la Fuente et al., 2012
Korea	Gyeongsang Basin, Southeast Korea	Hasandong Fm	Albian		Charcoal, type not specified.			Hong & Lee, 2012

Table 2.1- Continued

Table 2.1. Early Cretaceous (Berriasian-Albian)

Country	Locality	Stratigraphy	Age	Lithology and environment of deposition	Charred vegetation	Uncharred vegetation	Comments	References
Australia		Burgowan Coal	Albian	Coal.			Inertinite (mmf) 9.0%, range: <10%	Data from Glasspool & Scott, 2010
Canada	Alberta & British Columbia	Gates Fm	Albian	Coal.			Inertinite (mmf) 29.9%, range: >20%	Average of 19 samples reported in Glasspool & Scott, 2010
Canada	British Columbia, Peace River	Boulder Creek Fm	Albian	Coal.			Inertinite (mmf) 45.9%, range: >20%	Data from Glasspool & Scott, 2010
Canada		Mannvile Gp	Albian	Coal.			Inertinite (mmf) 23.4%, range: >20%	Average of 19 samples reported in Glasspool & Scott, 2010
Spain			Albian	Coal.			Inertinite (mmf) 22.3%, range: >20%	Average of 14 samples reported in Glasspool & Scott, 2010
U.S.A.	Atlantic Continental Slope, New Jersey	Sample 8030	Albian	Coal.			Inertinite (mmf) 17.8%, range: 10-20%	Data from Glasspool & Scott, 2010
Antarctica	Alexander Island	Triton Point Fm	late Albian	Water-lain tuffs within meander-belt association.	Conifer wood (dominant) Araucariopitysm & Podocarpoxylon, podocarp twigs, scale leaves (cf. Brachyphyllum, Pagiophyllum) and seed-coats.		Fires considered rare in the polar biome and may have been initiated by volcanism.	Falcon-Lang et al 2001

Table 2.1- Continued

Table 2.1. Early Cretaceous (Berriasian-Albian)

Country	Locality	Stratigraphy	Age	Lithology and environment of deposition	Charred vegetation	Uncharred vegetation	Comments	References
U.S.A.	Maryland, West Brothers, Prince Georges County	Patapsco Fm	latest Albian	Abandoned channel silts, clays & cross bedded sands.	Angiosperm flowers, affinity not specified.	Lignitic and compressed flowers, affinity not specified.	First evidence of the buxaceous lineage. Angiosperm & gymnosperm wood, conifer cones, shoots & seeds are also present. It is unclear whether these are charred or lignitised.	Crane & Upchurch, 1987; Friis et al., 1988; Drinnan et al., 1991
China	Inner Mongolia, Erlian Basin, Shengli coalified		Early Cretaceous (age not specified)	Coarse sandstones with fine sandstones and muds.	Charcoal, type not specified.			Dai et al., 2012; Hower et al., 2013b

Table 2.1- Continued

Table 2.2. Mid-Cretaceous (Cenomanian-Santonian)

Country	Locality	Stratigraphy	Age	Lithology and environment of deposition	Charred vegetation	Uncharred vegetation	Comments	References
U.S.A.	Kansas, Ellsworth and Cloud counties	Dakota Fm	Albian-Cenomanian	Fine sands, shales and clays.	Undifferentiated wood (dominant).		Charcoal accounts for between ~1-11% by weight of the sediments studied. 4899 mesofossils (267 morphotypes) including angiosperm flowers, fruits & seeds, conifers & pteridophytes. Fossils lignitic or charred. Assemblages dominated by gymnosperms, but angiosperms were common & diverse.	Wang, 2004
U.S.A.	Alaska, Kukpowruk River	Kukpowruk Fm	Albian-Cenomanian	Siltstones and mudstones interpreted as representing woody mires.	Charcoalified wood fragments.	Ironstone preserved twigs.		Spicer & Herman, 2001
Spain	Iberian desert		Albian-Cenomanian	Mudstones & siltstones with interbedded sandy laminae.	Abundant charcoal fragments, type not specified.			Rodríguez-Lopéz et al., 2012
Australia	Queensland, Eromanga Basin	Winton, Mackunda, & Allaru Fms	late Albian-Cenomanian		Unspecified, probably wood in association with *Ptilophyllum*.		Bennettitales, Cycadales and ginkgophytes.	Pole & Douglas, 1999; Lamont & He, 2012

Table 2.2- Localities of Mid-Cretaceous (Cenomanian-Santonian) sediments yielding charcoal, including assemblages with charred angiosperm fertile organs and records of quantitative inertinite data from coals. Localities shown on Fig. 2.4. Data shown in red is post publication- 2012 onwards.

Table 2.2. Mid-Cretaceous (Cenomanian-Santonian)

Country	Locality	Stratigraphy	Age	Lithology and environment of deposition	Charred vegetation	Uncharred vegetation	Comments	References
Argentina	Bajo Comision, Santa Cruz Province	Kachaike Fm	late Albian-Cenomanian	Near-shore marine facies grading to deltaic and fluvial facies.	Wood (unidentified).	Angiosperm leaves, fern fronds & branches with *Brachyphyllum.*	Rare fires.	Passalia, 2007
U.S.A.	South Central Minnesota	Dakota Fm	Late Albian-Cenomanian	Grey clays.	Fern sporangia & synangia (Aff. Marattiaceae).		Provides evidence for Marattiaceaen ferns post-Jurassic within North America.	Hu et al., 2006
Germany	Prangenhaus Quarry, Wülfrath		Late Albian-Cenomanian	Clays.	*Chloranthistemon* flowers.		Evidence of direct arthropod feeding on flower surfaces. Charcoalified flowers washed into Devonian cave system after wildfires.	Harthopf-Fröder et al., 2012
U.S.A.	North Maryland, Bull Mtn		Latest Albian-Cenomanian		Charcoal present, type not specified.		Platanoid leaves, wood and reproductive structures are present at this locality however it is not specified if these are charred.	Crane & Herendeen, 1996
U.S.A.	Maryland, Maudlin Mountain, Elk Neck Peninsular	Potomac Gp, Elk Neck Beds	Early Cenomanian	Clays.	Angiosperm wood & flowers (Aff. Lauraceae).	Lignitized flowers (Aff. Lauraceae).		Drinnan et al., 1990; Herendeen 1991a, 1991b

Table 2.2- Continued

Table 2.2. Mid-Cretaceous (Cenomanian-Santonian)

Country	Locality	Stratigraphy	Age	Lithology and environment of deposition	Charred vegetation	Uncharred vegetation	Comments	References
Czech Republic	Brník, Bohemian Cretaceous Basin, east of Prague	Peruc-Korycany Fm	Cenomanian	Fluviatile / Meandering river, sandy mudstone.	Abundant angiosperms.	Impressions & compressions - fossil type unknown.		Kvaček & Friis, 2010
Czech Republic	Hloubětín-Hutě, Prague	Peruc Mbr, Peruc-Korycany Fm	Cenomanian		Charcoal present, type not specified.	Compressions and lignitized flora, type not specified.	Angiosperms are present, however it is not clear whether these are charred.	Eklund & Kvaček, 1998; Kvaček & Eklund, 2003
Czech Republic	Moravia	Peruc Mbr	Cenomanian		Angiosperm fruits and seeds, including those with Platanaceae affinities.			Knobloch & Mai, 1991
U.S.A.	North central Texas	Woodbine Fm	Cenomanian	Palaeosol.	Charcoal, type not specified.		Charcoal above horizon containing Ornithopod dinosaur.	Noto et al., 2012
U.S.A.	Colorado, San Juan River Coalfield	Dakota Coal	Cenomanian	Coal.			Inertinite (mmf) 42.8%, >20%	Data from Glasspool & Scott, 2010
France	Languedoc Roussillon region	Pauletian facies	Middle Cenomanian	Sandstones.	Charcoalified flowers, affinity not specified.	Lignitized flowers, affinity not specified.		Moreau et al., 2014
Czech Republic	Pecínov Quarry, Bohemian Cretaceous Basin , NW Prague	Peruc-Korycany Fm	Mid-late Cenomanian	Braided river to estuary mouth sediments.	Angiosperm flowers & wood, conifer wood & twigs, ginkgo branches, ferns & lycopsids.	Angiosperm & cycad leaves, conifer cones, foliage & twigs, lycopsids, ferns & bennettites (rare).	Varied fossil assemblages within the six environmental settings represented in this quarry.	Eklund & Kvaček, 1998; Falcon-Lang et al., 2001, 2004; Kvaček & Eklund, 2003; Uličný et al., 1997

Table 2.2- Continued

Table 2.2. Mid-Cretaceous (Cenomanian-Santonian)

Country	Locality	Stratigraphy	Age	Lithology and environment of deposition	Charred vegetation	Uncharred vegetation	Comments	References
USA.	Utah, Southwestern Utah Coalfield	King Cannel Coal	Cenomanian-Turonian boundary	Coal.			Inertinite (mmf) 8.2%, <10%	Data from Glasspool & Scott, 2010
Kazakhstan	Rudnyy, Kustanay Region	Shet-Irgiz Suite Novokozyrevsk suite	Cenomanian-early Turonian	Lacustrine / alluvial sands and clays. Lagoonal kaolinitic clays and silts.	Rare charcoalifications-type not specified.	3D lignitized angiosperm flowers, fruits, seeds, cone scales, cones, needles, twigs and fern sporangia.		Frumin & Friis 1996
Canada	British Columbia, Bullmoose Creek	Kaskapau Fm	late Cenomanian to middle Turonian	Coal.			Inertinite (mmf) 1.0%, <10%	Data from Glasspool & Scott, 2010
New Zealand	Pitt Island	Tupuangi Fm	Turonian	Mudstone.	Conifer leaves, wood (*Taxodioxylon*) & ginkgoleans (rare).		Abundant charred conifers indicate fire was important in this ecosystem.	Pole & Philippe, 2010; Lamont & He, 2012
U.S.A.	New Jersey-Sayreville	Raritan Fm	Turonian	Levee/back levee/swamp fluvial silts & clays.	Angiosperm, fruits, seeds & flowers (Aff. Lauraceae, Triuidaceae, Chloranthaceae, Capparales, & platanoids), (predominate), ferns (present).		Oldest known record of Capparales. Fossil Triuridaceae flowers represent the 'oldest unequivocal fossil monocots'.	Crepet et al., 1992; Gandolfo et al., 1998, 2002; Herendeen et al., 1993; Nixon & Crepet, 1993
U.S.A.	New York, Staten Island, Charleston (Kreishcherville)	Raritan Fm	Turonian	Lignite in sands.	Wood, affinity not specified.	Conifer cones, cone scales, leafy twigs & wood, & *Czekanowskia*.	In situ combustion of the lignite.	Hollick, 1906; Hollick and Jeffrey, 1909

Table 2.2- Continued

Table 2.2. Mid-Cretaceous (Cenomanian-Santonian)

Country	Locality	Stratigraphy	Age	Lithology and environment of deposition	Charred vegetation	Uncharred vegetation	Comments	References
U.S.A.	Maryland, Cape Sable	Raritan Fm	Turonian	Lignite in clay.	Wood, affinity not specified.		Charcoal in association with amber.	Troost, 1821
U.S.A.	New Jersey, Crossman	South Amboy Fire Clay Mbr, Raritan Fm	Middle-late Turonian	Clay.	Charcoal is present, type not specified.	Not specified.	Angiosperm flowers and fruits with magnoliid and lauraceae affinity are present; however it is not clear whether these are charred.	Crane & Herendeen, 1996
Czech Republic	Slezské Pavlovice Borehole, Silesia		Upper Turonian-Lower Coniacian		Low abundance angiosperm fruits and seeds.	Not specified.		Knobloch & Mai, 1991
U.S.A.	Utah, Emery Coalfield	Mancos Shale, Ferron Sandstone Mbr	Turonian to Coniacian	Coal.			Inertinite (mmf) 16.5%, 10-20%	Data from Glasspool & Scott, 2010
Nigeria	Middle Benue Trough	Agwu Fm	Coniacian	Coal.			Inertinite (mmf) 27.5%, >20%	Data from Glasspool & Scott, 2010
Czech Republic	Klikov	Klikov Fm	Turonian-Santonian	Fluvial & lacustrine sandstones & mudstones.	Angiosperm fruits & seeds belonging to 92 genera including Aff. *Liriodendron*, *Saurauia* & *Sabia*.	Leaf impressions & compressions representing 23 species.	Potential charred insect eggs, however these may be seeds.	Váchová & Kvaček, 2009; Heřmanová & Kvaček, 2010
Korea	Gyeongsang Basin, Southeastern Korea	Geoncheonri Fm	Turonian-Santonian	Mudstones.	Woody charcoal, affinity unknown.	Phytoclasts and palynomorphs.		Hong et al., 2012

Table 2.2- Continued

Table 2.2. Mid-Cretaceous (Cenomanian-Santonian)

Country	Locality	Stratigraphy	Age	Lithology and environment of deposition	Charred vegetation	Uncharred vegetation	Comments	References
U.S.A.	New San Juan River Coalfield	Green Coal	Turonian-Santonian	Coal.			Inertinite (mmf) 11.0%, 10-20%	Data from Glasspool & Scott, 2010
U.S.A.	New San Juan River Coalfield	Mesaverde Gp, Crevasse Canyon Fm	Turonian-Santonian	Coal.			Inertinite (mmf) 14.5%, 10-20%	Data from Glasspool & Scott, 2010
Canada	Vancouver Island	Comox Fm	Turonian to Santonian	Coal.			Inertinite (mmf) 18.8%, 10-20%	Average of 2 samples reported in Glasspool & Scott, 2010
U.S.A.	Utah, Kaiparowits Plateau Coalfield	Christensen Coal Zone	Coniacian to Santonian	Coal.			Inertinite (mmf) 13.0%, 10-20%	Data from Glasspool & Scott, 2010
Japan	North-eastern Honshu, Kamikitaba	Futaba Gp, Asamigawa Mbr, Ashizawa Fm	early Santonian	Alluvial fan, poorly sorted, sandy siltstone.	Angiosperm flowers (*Archaefagaceae futabensis*), fruits (Cornalean), seeds, leaf fragments & wood. Conifer shoots, pollen cones, cone scales, seeds & fern rachides.	Lycopsid megaspores & fern leaves.	Cornalean fruits indicate 'minimum age for the early divergence of the asteroid clade'.	Takahasi et al., 1999a, 1999b, 2008; Friis et al., 2010b
U.S.A.	Georgia, Upatoi Creek	Eutaw Fm	Santonian	Unconsolidated carbonaceous clays & silts.	Seven types of charred angiosperm wood-including twigs.		Two new affinities of angiosperm wood identified.	Crane & Herendeen, 1996; Falcon-Lang et al., 2012
Hungary	Iharhút	Csehbánya Fm	Santonian,	Sandstone channel	Charcoal present, type not specified.		Charcoal horizon above lizard bone bed.	Makádi, 2013a; Makádi, 2013b

Table 2.2- Continued

Table 2.2. Mid-Cretaceous (Cenomanian-Santonian)

Country	Locality	Stratigraphy	Age	Lithology and environment of deposition	Charred vegetation	Uncharred vegetation	Comments	References
Antarctica	Eastern side of Antarctic Peninsular	Table Nunatak Fm	late Santonian	Marine or extremely distal deltaic distributary / estuarine mouth very fine sandstones and siltstones.	Angiosperm flowers, fruits, seeds & leaves (Aff. magnoliid, eudicot), ferns, conifer shoots, leaves, pollen cones, wood & seeds (abundant).	Megaspores.		Eklund, 2003; Eklund et al., 2004
U.S.A.	Georgia, Allon	Gaillard Fm, Buffalo Creek Mbr	late Santonian	Lower floodplain pond, microlaminated carbonaceous clay lens.	Angiosperm flowers, fruits, leaves & seeds, conifer leaves, cones, leafy shoots & mosses. Charred *Gleicheniaceae* ferns	Lignitised angiosperm flowers & leaves, conifers, ferns & lycopsids.	Similar organ assemblage composition to that observed in a modern heathland fire observed in Surrey. Assemblage likely to represent a surface fire.	Herendeen et al., 1999; Sims et al., 1998, 1999; Scott et al., 2000; Scott, 2010; Lupia, 2011; Schönenberger et al., 2012
Sweden	Åsen, Kristianstad Basin, north-east Scania, Southern Sweden		Late Santonian	Lacustrine finely laminated clays, silts and sands.	Angiosperm flowers (*Actinocalyx bohrii*), fruits and seeds. Taxodiaceaous conifers and charred ferns.	Lignitic compressions of flowers, conifer twigs, cone and ferns.	Evidence of adaptation to insect pollination prior to end Cretaceous (*Actinocalyx bohrii*). This locality also contains early Campanian charcoal (see Table 2.3).	Crane et al., 1989; Friis 1983, 1984, 1985; Endress & Friis, 1991; Herendeen, 1991b; Leng et al., 2005; Friis et al 2011; Friis et al 2013a,
U.S.A.	North Carolina, Neuse River cut-off, Goldsboro.	Black Creek Formtion	Latest Santonian-early Campanian	Fluviatile sands, silts and clays.	Charcoal, type not specified.	Lignitized flora, type not specified.	Angiosperm reproductive organs, leaves and wood are present along with conifer twigs- preservation type not specified.	Crane & Herendeen, 1996; Friis et al., 1988; Frumin & Friis, 1996

Table 2.2- Continued

Table 2.2. Mid-Cretaceous (Cenomanian-Santonian)								
Country	**Locality**	**Stratigraphy**	**Age**	**Lithology and environment of deposition**	**Charred vegetation**	**Uncharred vegetation**	**Comments**	**References**
Hungary	Bakony Mtns	Ajka Fm	Upper Santonian-lower Campanian		Charred angiosperm fruits and seeds with abundant specimens with Magnoliaceae affinities.			Knobloch & Mai, 1991
Germany	Aachen	Aachen Fm	Upper Santonian-lower Campanian		Charred angiosperm fruits and seeds. Highly diverse assemblage with a high abundance (over 100 specimens). Menispermaceae, Clethraceae and Cyrillaceae dominate.			Knobloch & Mai, 1991
Holland	South-Limburg	Aachen Fm	Upper Santonian-lower Campanian		Charred angiosperm fruits and seeds. Highly diverse assemblage with a high abundance (over 100 specimens). Menispermaceae, Clethraceaeand Cyrillaceae dominate.			Knobloch & Mai, 1991

Table 2.2- Continued

Table 2.3. Late Cretaceous (Campanian-Maastrictian)

Country	Locality	Stratigraphy	Age	Lithology and environment of deposition	Charred vegetation	Uncharred vegetation	Comments	References
Sweden	Åsen, Kristianstad Basin, north-east Scania, Southern Sweden		early Campanian	Fluviatile cross bedded & laminated sands, silts & clays.	Angiosperm flowers (Aff. Saxifragales & Chloranthaceae), fruits & seeds. Angiosperm wood - unclear which horizon this belongs to.	Rare compressions.	Charred angiosperms dominate with 100 different taxa & 20 flower types identified. This locality also contains late Santonian charcoal (see Table 2).	Endress & Friis, 1991; Friis, 1983, 1984, 1985; Friis & Pederson, 1990; Friis et al., 1986., 2011; Friis & Skarby, 1981., 1982; Herendeen, 1991b; Leng et al., 2005; Schönenberger et al., 2001
U.S.A.	SE Arizona	Fort Crtittenden Fm	Santonian/ Campanian	Aluvial fan and braided river shales.	Charcoal present, type not specified.		PAH data from this locality indicates variations in intensities of the wildfire. Reflectance data from the charcoal indicates combustion temperatures between 470-550°C.	Finklestein et al., 2005
U.S.A.	Wyoming, Hams Fork	Adaville Fm	Santonian to early Campanian	Coal.			Inertinite (mmf) 4.9%, <10%	Average of 7 samples reported in Glasspool & Scott, 2010
Portugal	Esgueira, north-east Aveiro, Beira Litoral region	“Arenitos e argilas de Aveiro”	Conacian-Maastrictian	Alternating sands, silts & clays.	Gymnosperm & angiosperm wood.	Abundant lignitized compressions of flowers. Leaf impressions & conifer leaf mats.	Uncharred component dominates the assemblage.	Friis et al, 1992, 2003; Herendeen 1991b
U.S.A.	Massachusetts, Matha’s Vineyard	Magothy Fm	Campanian	Lignitic clay	Diverse assemblage of gymnosperms & charred fruits & seeds.	3D compactions of gymnospermous wood, cones & leaves, angiosperm flowers, fruits & seeds.		Tiffney, 1977

Table 2.3- Localities of Late Cretaceous (Campanian-Maastrichtian) sediments yielding charcoal, including assemblages with charred angiosperm fertile organs and records of quantitative inertinite data from coals. Localities shown on Fig. 2.5.

Table 2.3. Late Cretaceous (Campanian-Maastrictian)

Country	Locality	Stratigraphy	Age	Lithology and environment of deposition	Charred vegetation	Uncharred vegetation	Comments	References
U.S.A	Alaska	MacColl Ridge Fm	Campanian	Fine-medium sandstone & shale	Charcoal, type not specified.	Gymnosperm trunks, two types of conifer, horsetail and fern impressions.		Fiorillo et al., 2012
Canada	Alberta, Dinosaur Provincial Park	Oldman Fm	Campanian	Fine grained sandstones, mudstones & shales.	Refer to Chapter 4			Brown et al., 2012; Thesis- Chapter 4
Canada	Alberta, Dinosaur Provincial Park	Dinosaur Park Fm	Campanian	Fine grained sandstones, mudstones & shales.	Refer to Chapters 4-5			Brown et al., 2012; Brown et al., 2013; Thesis- Chapters 4-5
U.S.A.	Utah, Sego Coalfield	Nelson Fm	Campanian	Coal.			Inertinite (mmf) 18.7%, 10-20%	Data from Glasspool & Scott, 2010
U.S.A.	New Mexico, San Juan Basin, Cerrillos coalfield	Menefee Fm	Campanian	Coal.			Inertinite (mmf) 14.0%, 10-20%	Data from Glasspool & Scott, 2010; Hower et al., 2013a
Austria		Gosau Fm	Campanian	Coal.			Inertinite (mmf) 6.1%, <10%	Average of 24 samples reported in Glasspool & Scott, 2010
U.S.A.	Wyoming, Green River Coalfield	Rock Springs Fm	Campanian	Coal.			Inertinite (mmf) 6.3%, <10%	Data from Glasspool & Scott, 2010

Table 2.3- Continued, data shown in red is post publication- 2012 onwards. Data shown in blue is from this thesis.

Table 2.3. Late Cretaceous (Campanian-Maastrictian)

Country	Locality	Stratigraphy	Age	Lithology and environment of deposition	Charred vegetation	Uncharred vegetation	Comments	References
U.S.A.	New Mexico, San Juan Basin	Fruitland Fm	Campanian	Coal.			Inertinite (mmf) 16.1%, 10-20%	Data from Glasspool & Scott, 2010
U.S.A.	Utah, Uinta Coalfield	Rock Canyon Coal	Campanian	Coal.			Inertinite (mmf) 22.4%, >20%	Data from Glasspool & Scott, 2010
U.S.A.	Utah	Blackhawk Fm	Campanian	Coal.			Inertinite (mmf) 12.2%, 10-20%	Average of 76 samples reported in Glasspool & Scott, 2010
Portugal	Mira, south of Aviero, Beira Litoral region	“Agilas de Vagos” & “Conglomerado de Mira”	Campanian to Maastrichtian	Clay & silt.	Angiosperm flowers (Aff. Myrtales & Fagales), fruits (abundant), wood & gymnosperm wood.	Lignitized flower & leaf fragments.	Angiosperm flowering structures give evidence of wind pollination.	Friis et al., 1992, 2003; Schönenberger et al., 2001
Canada	NW Ellesmere Island, unnamed peninsular between Emma Fiord & Audhild Bay.	Hasen Point Volcanic Unit	Campanian to Maastrichtian	Coastal plain/peat mire horizon.	Only conifer wood (2cm).		Uncharred angiosperm foliage, ginkgoleans, conifer shoots & wood (silicified) occur two horizons above. Silicified wood exhibits evidence of disturbance.	Falcon-Lang et al, 2004
New Zealand	Pike River Coalfield	Members 3 & 4	Campanian to Maastrichtian	Coal.			Inertinite (mmf) 7.9%, <10%	Average of 2 samples reported in Glasspool & Scott, 2010
New Zealand	Pike River Coalfield	Rewanui Coal Measures	Campanian to Maastrichtian	Coal.			Inertinite (mmf) 7.2%, <10%	Average of 48 samples reported in Glasspool & Scott, 2010

Table 2.3- Continued

Table 2.3. Late Cretaceous (Campanian-Maastrictian)

Country	Locality	Stratigraphy	Age	Lithology and environment of deposition	Charred vegetation	Uncharred vegetation	Comments	References
Austria	Vienna Flysch	Sievering Fm	Campanian to Maastrichtian	Siliciclastic sediments.	Low diversity and abundance of angiosperm fruits and seeds.			Knobloch & Mai, 1991; Heřmanová et al., 2013
Czech Rupublic	Flysch, Moravian-Silesian Bezkydy Mts		Campanian to Maastrichtian		Low diversity and abundance of angiosperm fruits and seeds.			Knobloch & Mai, 1991
Canada	Drumheller	Horseshoe Canyon Fm	Maastrichtian	Sandstones, mudstones & shales.	Refer to Chapter 6.			Thesis- Chapter 6
Canada	Drumheller	Scollard Fm	Maastrichtian	Sandstones, mudstones & shales.	Refer to Chapter 6.			Thesis- Chapter 6
Canada	Southern Saskatchewan	Frenchman Fm	Maastrichtian	Siltstone.	Charcoal, type not specified.	53 angiosperm leaves.	Charcoal pieces all >1mm.	Bamforth et al., 2014
New Zealand	South of Dunedin, Kaitangata Coalfield	Taratu Fm	latest Maastrichtian	Fluvial plane mudstones.	Angiosperm fruits, seeds & flowers (Aff. Lauraceae).	Lignitised angiosperms, conifer leaves, shoots, scales & seeds.		Cantrill et al., 2011
U.S.A.	North Dakota	Hell Creek Fm	Maastrichtian	Coastal plain sandstone.	Charcoal, type not specified.	Uncharred woood, phytoclasts, spores, pollen and cuticle.	Charcoal associated with an exceptionally preserved Hadrosauridae. Charcoal represents 9% of the overall plant debris assemblage. Wildfires reported to be common within this ecosystem.	Vajda et al., 2013

Table 2.3- Continued

Table 2.3. Late Cretaceous (Campanian-Maastrictian)								
Country	**Locality**	**Stratigraphy**	**Age**	**Lithology and environment of deposition**	**Charred vegetation**	**Uncharred vegetation**	**Comments**	**References**
Germany	Walbeck		Maastrichtian		High abundance of angiosperm fruits and seeds. Low diversity of species including Theaeceae and Cyrillaceae.			Knobloch & Mai, 1991
Germany	Eisleben		Maastrichtian		High abundance of angiosperm fruits and seeds. Low diversity of species including Theaeceae and Cyrillaceae.			Knobloch & Mai, 1991
Austria	Kossen Niedendorf	Gosau Fm	Maastrichtian		High abundance of angiosperm fruits and seeds including Cyrillaceae affinities.			Knobloch & Mai, 1991
Nigeria		Mamu Fm	Maastrichtian	Coal.			Inertinite (mmf) 17.5%, 10-20%	Average of 4 samples reported in Glasspool & Scott, 2010
U.S.A.	Colorado, Denver Coalfield	Laramie Fm	Maastrichtian	Coal.			Inertinite (mmf) 20.7%, >20%	Data from Glasspool & Scott, 2010
U.S.A.	Alabama	McNairy Fm	Maastrichtian	Coal.			Inertinite (mmf) 24.8%, >20%	Data from Glasspool & Scott, 2010
Spain	Pedraforca, Saldes Basin		Maastrichtian	Coal.			Inertinite (mmf) 39.2%, >20%	Data from Glasspool & Scott, 2010

Table 2.3- Continued

Table 2.3. Late Cretaceous (Campanian-Maastrictian)

Country	Locality	Stratigraphy	Age	Lithology and environment of deposition	Charred vegetation	Uncharred vegetation	Comments	References
Mexico	Fuentes - Rio Escondido Basin		Maastrichtian	Coal.			Inertinite (mmf) 19.1%, 10-20%	Data from Glasspool & Scott, 2010
U.S.A.	New Mexico	Sugarite Coal	K-T boundary	Coal.			Inertinite (mmf) 27.9%, >20%	Data from Glasspool & Scott, 2010
Mexico	Arroyo el Mimbral		K-T boundary	Coarse grained, laminated calcarenite.	Charcoal, type not specified.		Partially charred plant debris, type not specified	Kruge et al. 1994

Table 2.3- Continued

There are fewer recorded charcoal localities (both for charcoal deposits and charred angiosperm reproductive organs) in the Late Cretaceous compared with the Early and mid-Cretaceous. This variation in charcoal localities may be due to changes in fire activity or lack of sufficient investigator effort (as outlined above). However, other factors may be influential such as the nature of the rock record or the time bin partitioning of charcoal data within the Cretaceous charcoal database.

The partitioning of charcoal data into unequal time bins could give a false impression of variation in charcoal occurrence. The Early Cretaceous (Berriasian-Albian, 45.5 million years) and the mid to Late Cretaceous (Cenomanian-Maastrichtian, 34.5 million years -International chronostratigraphic chart, 2014) span similar intervals of time and have similar numbers of charcoal localities. However, the Cenomanian- Santonian (mid Cretaceous) encompasses 13.9 million years (International chronostratigraphic chart, 2014), yet contains a greater number of recorded charcoal localities than the Campanian and Maastrichtian (Late Cretaceous) spanning 17.6 million years. Therefore, unequal time bins are not responsible for the reduced number of Late Cretaceous charcoal localities.

The amount of available sediment outcrops and the range of environments of deposition these encompass are highly variable across deep time, and within individual time periods (Smith and McGowan, 2007). Fluctuations in global sea-levels throughout deep time, caused by a pattern of growth and decay of continental ice sheets, have been influential in determining the ratio of terrestrial to marine sediments along with their distribution (Miller et al., 2005; Smith and McGowan, 2007). Therefore, a comparison of charcoal occurrences needs to consider whether the same amount of terrestrial outcrop is present for each time bin within the Cretaceous. Global sea-level change across the Cretaceous has resulted in fewer Late Cretaceous terrestrial rock sequences (Smith and McGowan, 2007). The limited number of Late Cretaceous charcoal localities could be a consequence of a reduced terrestrial rock record.

Within North America, in time bins of very similar duration, there are fewer recorded Late Cretaceous (Campanian and Maastrichtian) charcoal localities compared with the mid-Cretaceous (Cenomanian to Santonian). North America was predominantly terrestrial throughout the Cretaceous, with the exception of the incursion of the Western Interior Seaway (Lillegraven and Ostresh, 1990; Eberth, 2005). Therefore, if fewer charcoal localities in the Late Cretaceous was solely due to a lack of continental sediment a reduction in charcoal records in this region would not be expected. The availability of terrestrial outcrop is likely to have played a role in global Cretaceous charcoal distribution, however it is unlikely to solely explain the reduction in Campanian and Maastrichtian charcoal localities. Therefore it is necessary to investigate known Late Cretaceous terrestrial sediments in order to ascertain the presence or absence of charcoal.

2.4 ATMOSPHERIC OXYGEN CONTENT AND A CRETACEOUS 'HIGH FIRE' WORLD

There has been much debate over the atmospheric O_2 levels required to allow combustion (refer to Chapter 1- section 1.4 for further discussion). However, from the most recent experimentation (Belcher et al., 2010b; Chapter 1- section 1.4) it appears that for large wildfires to occur atmospheric oxygen must exceed 17%.

Models have varied in their predictions of Cretaceous atmospheric oxygen concentration (Berner et al., 2003; Bergman et al. 2004, Berner, 2006, 2009; Glasspool and Scott, 2010) (Fig. 2.1). Berner (2009) predicted levels below present until the Albian, rising just above 21% thereafter. Bergman et al. (2004) predicted levels significantly above present throughout the Cretaceous but reaching their highest during the Cenomanian. Similarly, Glasspool and Scott (2010) predicted levels above present throughout the Cretaceous but more moderately so and peaking at about the Albian-Cenomanian transition. Despite differences of degree, all three models predict a roughly similar pattern for Cretaceous atmospheric oxygen levels: falling initially from the Jurassic through the Berriasian then rising to a peak above present day levels by the Cenomanian before gradually declining (Fig. 2.1).

Under high oxygen conditions precipitation will be less of a control on fire occurrence and fire will be less of a marker of aridity (Finkelstein et al., 2005). Higher oxygen would allow much wetter vegetation to burn than at the present day. The Cretaceous charcoal database (Tables 2.1-2.3, Figs. 2.3-2.4) documents a large number of charcoalified plant mesofossil assemblages from the Valanginian to the Santonian. However there are fewer recorded Campanian and Maastrichtian charcoalified plant mesofossils (Fig. 2.5), despite atmospheric oxygen levels modelled to be in excess of present day values. This may be due to a change in Cretaceous fire activity, or due to a lack of investigation into these sediments. Greater research into Late Cretaceous sediments could help indicate whether the data shown on Fig. 2.5 is a representation of a change in Cretaceous fire activity or due to a lack of research into this age of sediments.

2.5 LIMITATIONS OF THE CRETACEOUS CHARCOAL DATABASE

The content of the new charcoal database outlined within this chapter was derived from the literature in addition to the novel research presented within this thesis. The literature was derived through several methods; journals and reprints with global coverage from the personal collections of A.C. Scott and M.E. Collinson, previous global data compilations in publications authored or co-authored by A.C. Scott, personal communication with charcoal researchers and through online scientific journal searches. Personal communication with authors was a minor component of the compilation of the database. This method was used mostly to obtain Japanese literature, which was not easily accessibly online. Personal communication led to additional journal articles being obtained (used primarily for Takahashi et al 1999a, 1999b, 2008). The majority of the data that forms the Cretaceous charcoal database was obtained through online searches, predominantly through Web of Science or through advanced Google Scholar search engines.

This methodology proved effective for compiling a geographically widespread database of Cretaceous charcoal localities, however there are some limitations with the techniques used. The web searches were carried out in English so literature in other languages may have been missed. Although there were no scientific journals that were identified as being inaccessible due to language no Russian literature is present within this database. Therefore, it is possible that Russian journals were not identified through the compilation techniques used for the development of this Chapter. However, some Russian and Chinese journals exist with English translations and no Cretaceous charcoalified plants appear to have been described. The largest problem is that many authors (and particularly in Russia and China) do not indicate the preservation state of the plants which they record or describe so it is possible that some charcoal occurrences were missed. The data compilation method may have led to some underrepresentation of charcoal localities in some geographical regions. However, this is unlikely to have affected the overall interpretation of fewer Late Cretaceous charcoal occurrences. No occurrences have been brought to the author's attention from these regions since the paper was published online in March 2012.

2.6 CONCLUSIONS

The comprehensive compilation of charcoal data from throughout the Cretaceous shows that charcoal is widely distributed, indicating the extensive occurrence of wildfires. Records are concentrated in the Northern Hemisphere, but this is most likely due to a lack of exposed Cretaceous sedimentary successions or due to limited research focused on charcoals within the Southern Hemisphere.

In modern environments wildfires are controlled in part by fuel moisture (Chapter 1- section 1.3) but this may be partly overridden in the Cretaceous where it is suggested that the atmospheric oxygen concentration was greater than present, potentially over 25% (Fig. 2.1). Higher atmospheric oxygen levels would enable wetter vegetation to burn and allow greater occurrences and more widespread wildfires. Fires may have played a particularly significant role in the mid-Cretaceous as oxygen levels were at their highest and angiosperms began to diversify.

Atmospheric oxygen levels are modelled to be higher than present during the Late Cretaceous, however there are fewer recorded charcoal localities for the Campanian-Maastrichtian than for the rest of the Cretaceous. A greater number of charcoal bearing localities would be expected given the modelled atmospheric oxygen. Therefore the Late Cretaceous was selected for further investigation (Chapters 4-6) to determine whether the reduced record of charcoal localities are a function of decreased Late Cretaceous fire activity or due to a lack of investigation into these sediments.

With the evidence of extensive wildfires throughout the Cretaceous, post-fire erosion and transportation (Chapter 1- section 1.4) is likely to have played a major role in terrestrial environments. Extensive dinosaur deposits are recorded throughout the Cretaceous, however the role fire may have played in their formation has never been investigated. Therefore the role post-fire induced flooding events may have played during the Late Cretaceous is investigated in Chapter 5.

Chapter 3:

Localities, fieldwork and laboratory methodology

The compilation of an extensive Cretaceous charcoal database (Chapter 2) highlighted a paucity of Late Cretaceous charcoal localities, in comparison with both the Early and Mid-Cretaceous. Sufficient atmospheric oxygen levels, modelled in excess of 17% (Chapter 1- section 1.3, Chapter 2- Fig. 2.1), with levels similar to the later stages of the Mid-Cretaceous indicate that wildfires would have been able to ignite and propagate, therefore greater charcoal records would be expected in Late Cretaceous sediments. Late Cretaceous sediments were selected for investigation to determine charcoal occurrence, and to address whether the reduced number of data points on Fig. 2.5 is a function of a lack of charcoal research in this age of sediments.

In order to document charcoal occurrence and distribution within Late Cretaceous sedimentary successions, specifically through the Campanian and Maastrichtian, fieldwork was carried out within two areas, Dinosaur Provincial Park and Drumheller, both in Alberta, Canada focussing on continental sediments. The locations were selected due to the large continuous expanse of Late Cretaceous sediments exposed within the badland terrain across southern Alberta.

Sampling strategies for the Late Cretaceous localities are outlined below. A novel approach to charcoal quantification has been developed to determine variation in relative charcoal abundances throughout the Late Cretaceous (Chapters 4-6), and within modern wildfire derived plant debris assemblages (Chapter 7). For details regarding localities and the sampling strategy adopted for modern wildfire derived sediments refer to Chapter 7 (section 7.2.2).

3.1 LOCALITIES

3.1.1 Geographic and stratigraphic context of Late Cretaceous successions

Late Cretaceous sediments are exposed across Alberta, Canada, with badland terrain resulting in large exposures within southern Alberta in particular. These sediments extend into neighbouring Saskatchewan and also into Montana, USA (Eberth and Hamblin, 1992). The accessibility of sediments and the extent of the sedimentological record were instrumental in choosing field localities. Southern Alberta was selected due to a sedimentary succession that extended from the Campanian into the Paleocene. Field work focussed on two areas: Dinosaur Provincial Park, which has a sedimentary succession throughout the Campanian, and Drumheller, which has a sedimentary succession spanning the whole of the Maastrichtian (Fig. 3.1).

The three Formations comprising the Campanian Judith River Group outcrop throughout Alberta, Saskatchewan and Montana (Figs. 3.2-3.3). Whilst this group is laterally extensive there are limited surface exposures of these Formations in both Saskatchewan and central Alberta, with the majority of Formations occurring as subsurface deposits (Eberth and Hamblin, 1992). Southern Alberta provided both the most extensive stratigraphic succession of exposed sediments and the most accessible localities, therefore this location was selected for the investigation of Late Cretaceous charcoal.

The Late Cretaceous sediments exposed in southern Alberta are divided into eight Formations that span from 79.1Ma-65.5Ma (Eberth, 2005) (Fig. 3.3). Two Formations (Oldman and Dinosaur Park) were selected to investigate Campanian charcoal deposits, and three Formations (Horseshoe Canyon, Battle and Scollard) were selected to investigate Maastrichtian charcoal deposits. There is limited exposure of the Campanian Foremost Formation in southern Alberta, with no outcrops present at either of the selected localities. Therefore this Formation is not included within this thesis. Whilst the Bearpaw Formation outcrops at both localities, a continuous succession cannot be correlated between the two localities. In addition the Bearpaw Formation is fully marine, deposited during an incursion of the Western Interior Seaway. This thesis focusses on investigating the continental record of charcoal throughout the Late Cretaceous of southern Alberta, therefore the Bearpaw Formation is not included within this study.

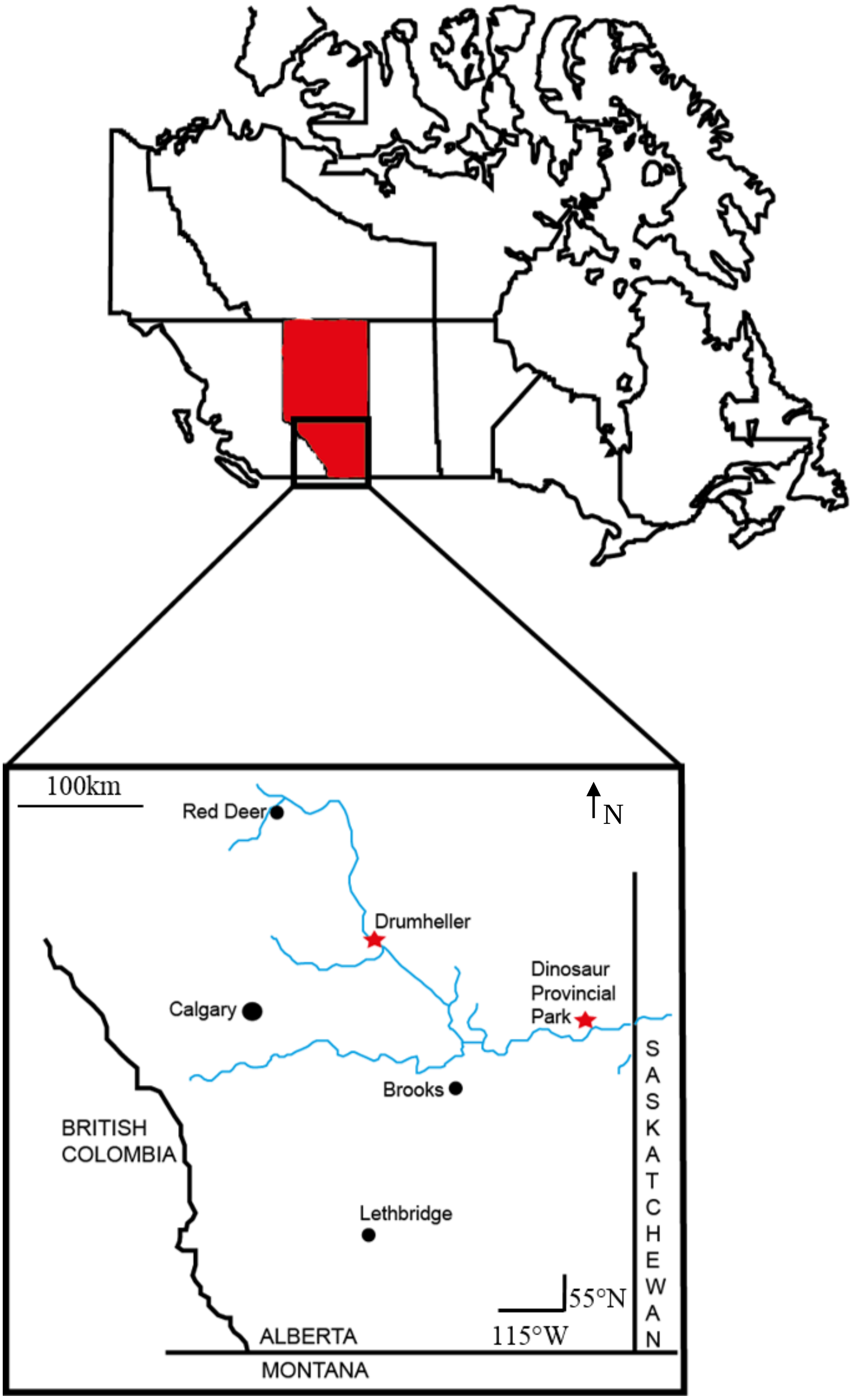


Fig. 3.1 Location map of Canada highlighting Alberta, with an enlarged locality map of southern Alberta below. The locations of the two field areas are shown by red stars.

Fig. 3.2 Geographical distribution of surface outcrops of the Judith River Group across Alberta, Saskatchewan and Montana. Dinosaur Provincial Park is indicated by a red star (modified from Eberth and Hamblin, 1992).

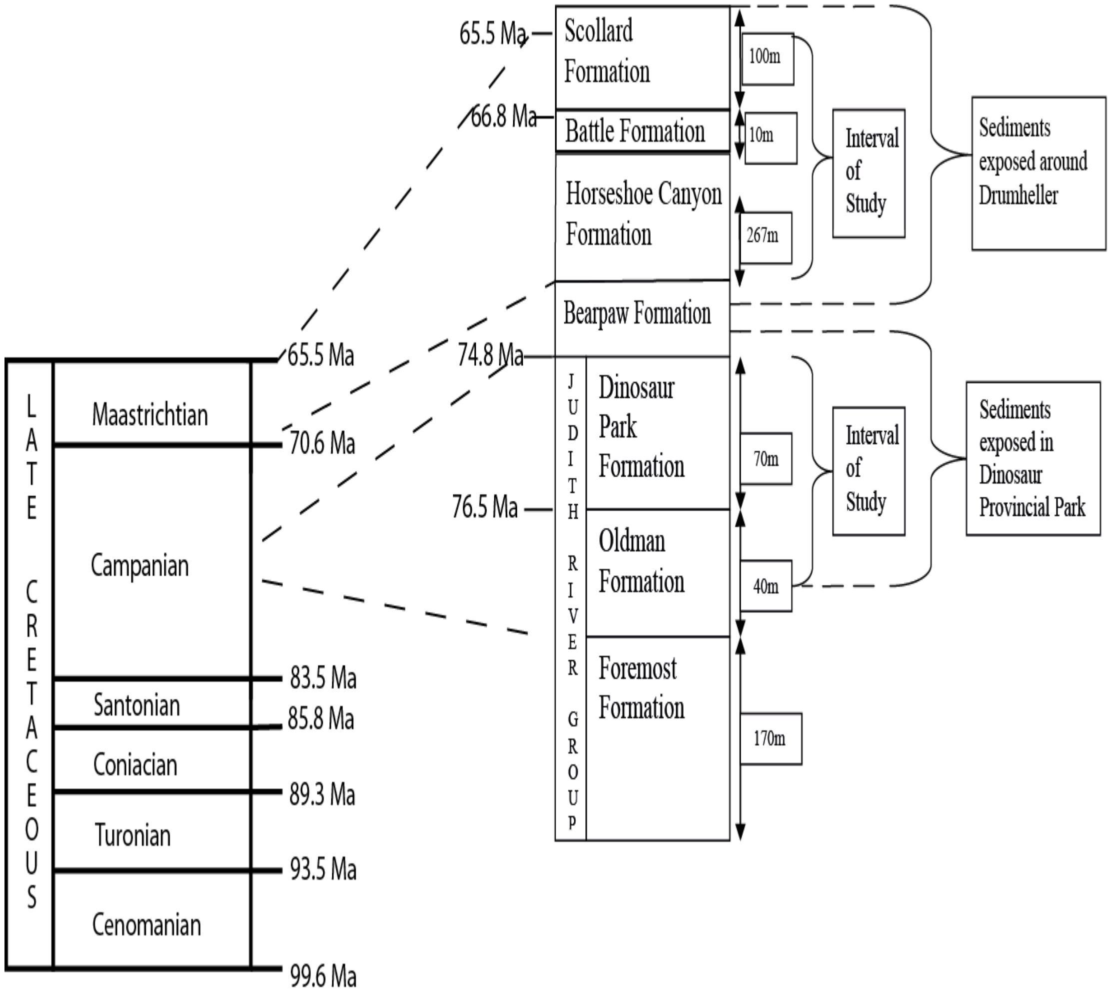


Fig. 3.3 The eight Late Cretaceous Formations exposed within southern Alberta with their ages and location of exposures. Only continental sediments are within the scope of this thesis, with the studied Formations indicated (after Eberth, 2005).

The dates shown on Fig. 3.3 have been derived from single crystal laser fusion of $^{40}Ar/^{39}Ar$ of outcropping bentonites (Eberth, 2005). Bentonite units were dated 4m below the Oldman/ Dinosaur Park Formation disconformity, at the top of the Oldman Formation, within the Dinosaur Park Formation, 44m above the disconformity, and at the base of the Bearpaw Formation in order to constrain the age of deposition (Eberth and Hamblin, 1992; Eberth, 2005). The lower part of the Bearpaw Formation has also been biostratigraphically dated through the presence of Campanian *Baculites compressus* ammonite fragments (Catuneanu et al., 2000; Eberth, 2005).

3.2 FIELDWORK STRATEGY FOR CRETACEOUS SUCCESSIONS

3.2.1 Sampling locations

Fieldwork within both Dinosaur Provincial Park and Drumheller was carried out with permission from the Albertan Government and the Alberta Parks Authority. Dinosaur Provincial Park is a UNESCO world heritage site, and as such there were limitations on the duration of the fieldwork within the Park. In addition, the badland terrain of both sampling localities meant that an experienced field guide (Dr D. Braman) was necessary to facilitate access to suitable exposures of Cretaceous sediment. Therefore, fieldwork duration and timing was also limited due to the availability of Dr Braman and permission for his absence from the Royal Tyrell Museum, Alberta. As such, fieldwork and sediment collection focussed on documenting charcoal occurrence throughout the Late Cretaceous, in addition to investigating the presence of charcoal within vertebrate deposits (for further discussion of the limitations of fieldwork refer to Chapter 8).

3.2.1.1 Dinosaur Provincial Park

Sampling was undertaken from the 16th-21st of July 2010 within Dinosaur Provincial Park, Alberta, in order to investigate charcoal occurrence in Campanian sediments. The uppermost 20m of the Oldman Formation and lowermost 50m of the Dinosaur Park Formation were sampled with the aim of documenting the presence or absence of charcoal. Relative abundances of charcoal throughout a 1.8Ma continuous sedimentary succession were investigated.

Sampling locations were selected in order to encompass the full 1.8Ma succession, and were based on multiple factors. The continuous exposure of the Oldman and Dinosaur Park Formations, accessibility of sedimentary successions, and the ability to correlate the successions were influential in locality selection. In order to investigate the area influenced by Cretaceous wildfires the eastern edge of Dinosaur Provincial Park was sampled; thus allowing charcoal distribution and relative abundances to be compared across 7km (Fig. 3.4). This data may allow a determination of whether fire activity was localised or regional. However, the

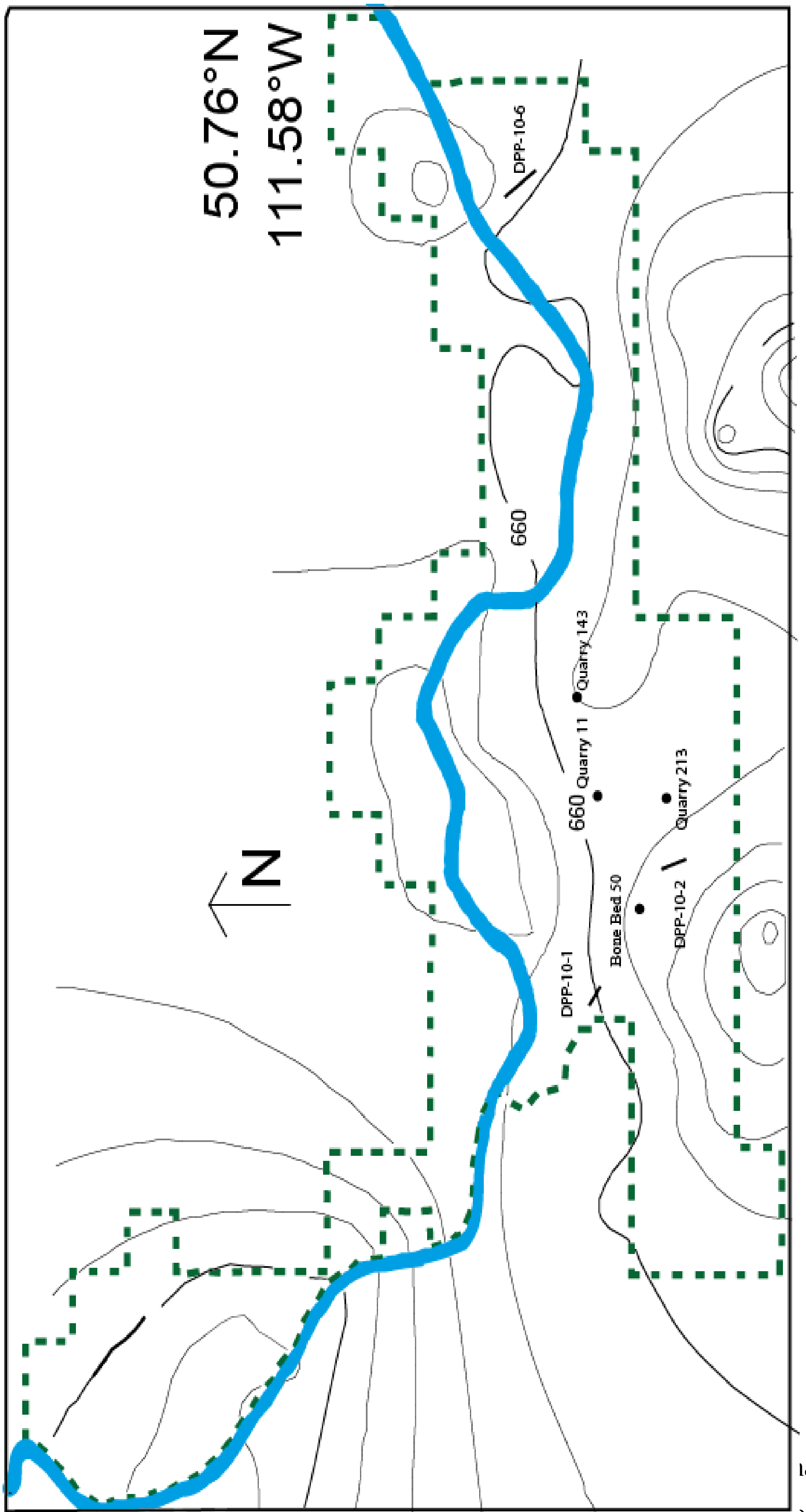


Fig. 3.4 Map showing the outline of Dinosaur Provincial Park and the sedimentary successions and vertebrate deposits sampled.

inaccessible due to cliffs, and the lateral tracing of lithological units was rarely possible for more than a few metres. GPS (WG584) measurements were recorded at the base and top of each sampled sedimentary succession.

3.2.1.2 Drumheller

Fieldwork was undertaken from the 4th-7th of July 2011 in five localities across Drumheller in order to sample approximately 400m of sedimentary succession spanning 9.5Ma. Sampling was undertaken for the Maastrichtian Horseshoe Canyon, Battle and Scollard Formations. Sampling localities were selected in order to encompass 9.5Ma of succession, with the completeness of the three exposed Formations, landowner permission and accessibility key parameters in selection. GPS (WG584) measurements were recorded at the base and top of each sampled sedimentary succession. The ability to correlate the sedimentary successions through the presence of industry numbered coal seams was also a necessity in locality selection (Chapter 6- section 6.2.1).

3.2.2 Lithological log construction

A 1.5m Jacob's staff, divided into both 0.5m and 0.1m increments, with attached brunton was used to determine the thickness of each lithological unit. The brunton ensured that measurements were made from a horizontal surface, reducing potential measuring errors from sight alone. The lithology was determined in the field, and was recorded onto lithological logs. Sandstones were classified with the use of a grain size card. Mudstones were identified based on their bentonitic component. They exhibit a green-grey colouring and a 'popcorn' style weathering caused by the bentonitic component. Shales were identified based on the fracture pattern across the cleavage, a red-brown colouring and a smooth weathering surface. Any dinosaur fossils observed were noted, and the bed was laterally traced to see the extent of the fossil composition.

3.2.3 Sampling strategy

3.2.3.1 Sedimentary successions

Systematic sampling was adopted for the analysis of sedimentary successions throughout all Campanian and Maastrichtian Formations, focussing on sampling each individual lithological unit irrespective of whether charcoal was visible to the naked eye within these sediments. This strategy was adopted to ensure that observational biases would not influence the recording of charcoal distribution and relative abundances. For lithological units over 2m in thickness, multiple samples were taken to ensure that even potentially small variations in relative charcoal abundances were not overlooked. Samples were taken from sandstone, mudstone and shale lithologies. 117 lithological samples were collected from the Campanian Oldman and Dinosaur Park Formations. 86 lithological samples were collected from the Maastrichtian Horseshoe Canyon, Battle and Scollard Formations.

3.2.3.2 Vertebrate deposits

In addition to the sampled sedimentary successions, four Campanian vertebrate deposits were also sampled (Chapter 5- section 5.2.3). All four vertebrate deposits were located within the Dinosaur Park Formation. Samples were taken at the stratigraphic level of vertebrate remains. Two vertebrate deposits had been excavated prior to sampling. The exact location and sedimentary level of the original dinosaur remains were previously marked by metal stakes, allowing current sampling to be undertaken in the correct horizon. For these localities a single sample was taken from the lithological unit in which the dinosaur bones were contained. For the vertebrate deposits that were still present, sampling was carried out adjacent to the bones, without damaging the deposit for other palaeontological research. In total 6 lithological samples were collected from sandstone lithologies.

3.2.4 Sampling technique

Prior to sampling an ice pick was used to remove weathered sediments from each lithological unit in order to allow the collection of unaltered sediments, and remove any surface debris and modern vegetation contamination. Due to the large annual temperature range to which Dinosaur Provincial Park is subjected, only sporadic low stature vegetation is present, thereby exposing a fresh surface removed of the majority of modern root contamination. Collection was carried out with the use of the ice pick and a small trowel, with approximately 200g of sediment collected for each sample.

3.2.5 Limitations of fieldwork strategy

The fieldwork strategy, as outlined throughout section 3.2, was affected by a limited time frame for fieldwork (outlined in section 3.2.1). This meant that lithological sampling was prioritised over gathering a greater range of sedimentological data. Further sedimentological investigation would have been beneficial in supporting palaeoenvironmental descriptions and illustrating potential controls on the distribution of charcoal (Chapters 4-6). A focus on documenting palaeocurrent indicators, such as cross laminations and cross bedding within sandstone units, would have allowed a determination to be made regarding the direction of flow of the meandering river system present in southern Alberta throughout the Late Cretaceous. In addition further sedimentological information gathered from palaeochannels, such as scours, may have indicated whether some mudstones represented mud-filled channels as opposed to overbank facies.

Mudstones and shales were separated based on their field appearance and characteristics, the depositional environment for the formation of both lithologies, in both the Campanian and Maastrichtian, has been interpreted to represent overbank facies within a meandering river system. Therefore, the distinction between the two lithologies was linked to appearance rather than facies type. Mudstone and shale are broad classifications that can encompass a range of environments of deposition. Further analysis of the sedimentology (prevented due to time constraints outlined in section 3.2.1) may have allowed further conclusions to be drawn with regard to the environment of deposition. Analysis of mudstones for palaeosol development might have allowed overbank facies to be distinguished from mud filled palaeochannels.

3.3 LABORATORY METHODOLOGY

3.3.1 Subsampling methodology

For each Cretaceous lithological unit, Cretaceous vertebrate deposit and modern sample (Chapters 4-7), a 20g subsample was macerated in 30% hydrogen peroxide for twenty four hours in order to disaggregate the sediment. 20g subsamples were selected to be representative of the bulk samples, whilst allowing a short disaggregation time. This residue was diluted with cold water prior to sieving. Those samples that did not disaggregate (approximately ten shale samples) were subsequently covered with 10% HCl for twenty-four hours prior to dilution and neutralisation. These samples were not disaggregated by the HCl so were subjected to hydrofluoric acid (by Sharon Gibbons) for a week in order to disaggregate the sediment. Neutralisation by dilution and decanting was undertaken prior to sieving.

Each diluted residue was wet sieved with warm water into four size fractions (>2.5mm, 1mm-2.5mm, 500μm-1mm, 500μm-125μm) in order to give information on the range of charcoal sizes. The sieve size fractions were selected to correspond with grain size boundaries with 2.5mm representing greater than very coarse sand, 1mm representing the grain size boundary between coarse and very coarse sand, 500μm representing the grain size boundary between coarse and medium sand and 125μm representing the grain size boundary between fine and very fine sand.

Fine charcoal can be transported large distances as part of wildfire associated smoke plumes (Chapter 1- Fig. 1.1) and therefore is unlikely to be representative of localised fire activity (further discussion of fine charcoal transportation is given in Chapter 8- section 8.4.5.1). Only the larger three charcoal size fractions have been investigated within this thesis, in order to try and negate the effects of windblown charcoal and attempt to document localised wildfire activity.

3.3.2 Charcoal quantification

Charcoal quantification techniques have been widely used by researchers across a range of disciplines including archaeology, archaeobotany, palaeobotany and Quaternary lacustrine investigations (Winkler, 1985; Clark et al., 1998; Blackford, 2000; Scott et al., 2000; Tinner and Hu, 2003; Hudspith et al., 2012; Sass and Kloss, 2014). However a standard methodology has not been widely adopted across all disciplines, posing a problem for continuity across charcoal research. In addition many of the currently used methodologies have associated problems (Chapter 8- section 8.1.1-8.1.3), which call into question the validity of the calculated relative charcoal abundances.

Various charcoal particle count techniques have been used within many of the disciplines (Scott et al., 2000). Major flaws are associated with these techniques, with the differential fragmentation potential of charcoal not taken into consideration (refer to Chapter 8- section 8.1.1 for discussion of limitations associated with these techniques). Therefore this methodology was rejected for use within this thesis.

Other potential quantification techniques, such as the use of weight percentages and relative volumes of charcoal, were trialled and were found to be unsuitable for determining the variation in relative charcoal abundances temporally throughout the Late Cretaceous (refer to Chapter 8- sections 8.1.1-8.1.3 for discussion of alternate methodologies and associated problems). Therefore a new charcoal quantification technique was developed for use throughout this thesis, in order to address the issues raised by other techniques. The suitability of this new technique for widespread use in charcoal research, is discussed in Chapter 8 (section 8.1.4).

3.3.3 Novel approach to charcoal quantification

The residue of each sieved size fraction was dispersed in distilled water within a petri dish and a grid, comprising 32 squares each 1cm by 1cm, was placed underneath (Fig. 3.5). A domin (as used in ecology) score of abundance (Kent and Coker, 1992) was recorded for charcoal coverage within each of twenty individual squares. A slightly modified ACFOR domin scale was developed, combining the categories of occasional and rare under the category of rare. Up to a quarter coverage of an individual square was classified as rare charcoal, quarter-third coverage as frequent charcoal, third-half coverage as common and greater than half coverage as abundant (Fig. 3.6).

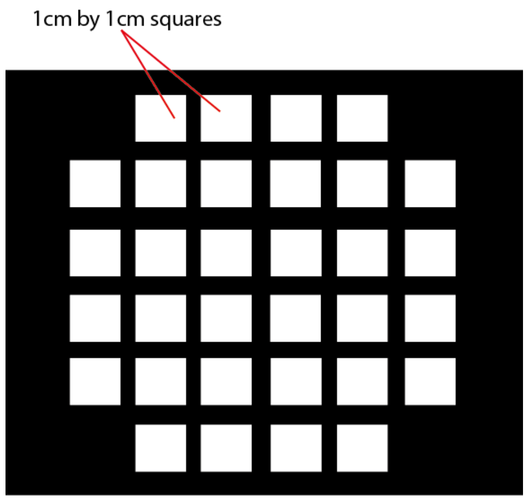


Fig. 3.5 Sketch of 32 cm grid placed under binocular microscope in order to determine domin values.

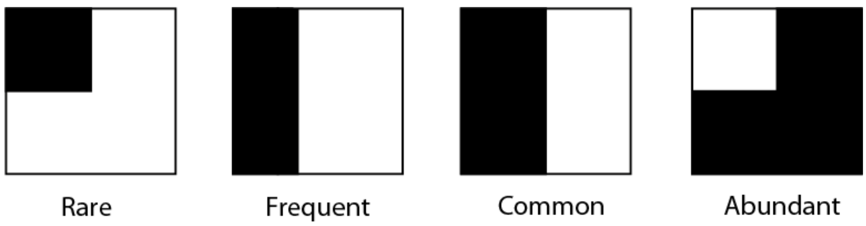
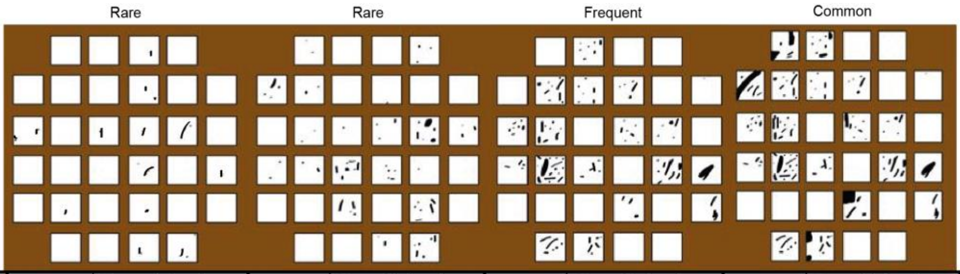


Fig. 3.6 Sketches of charcoal coverage of a single grid square and the associated domin score.

The domin scores for twenty squares (determined through rarefaction tests- section 3.3.3.1) were combined to give an overall domin classification and a numerical cover value for the sample. The numerical value is used to capture the range of variation within each overall domin classification. This was calculated based on the number of individual squares with each domin score multiplied with an 'X' specific to each score. The value of 'X' was selected so that a sample with all twenty squares with a domin score of abundant would yield a numerical value of 100; all twenty squares with a domin score of common a numerical value 50, frequent 30 and rare 20. Thus the overall domin classification for a sample becomes rare = 1-19.5; frequent = 20-29.5; common = 30-49.5; abundant >50. Fig. 3.7 gives worked examples of the domin classification based on samples from the Campanian Oldman and Dinosaur Park Formations. Examples of charcoal residues are shown in Fig. 3.8.



Domin score values	X	No. of squares	Overall domin score/ numerical value	No. of squares	Overall domin score/ numerical value	No. of squares	Overall domin score/ numerical value	No. of squares	Overall domin score/ numerical value
Abundant	5	0	0	0	0	0	0	1	5
Common	2.5	0	0	0	0	5	12.5	7	17.5
Frequent	1.5	0	0	6	9	5	7.5	3	4.5
Rare	1	6	6	10	10	5	5	7	7
None	0	14	0	4	0	5	0	2	0
Overall			Rare / 6		Rare / 19		Frequent/ 25		Common/ 34

Fig. 3.7 Domin sketches showing examples of the overall domin classification and numerical cover value for charcoal, based on 20g sediment samples from the Campanian Oldman and Dinosaur Park Formation. Sketches are based on the following samples, from left to right: 1-10- 1mm-2.5mm size fraction from a shale unit within the Oldman Formation sampled from transect 1; 6-3- 1mm-2.5mm size fraction from a sandstone unit within the Dinosaur Park Formation from transect 6; 1-22- 500µm-1mm size fraction from a sandstone unit from the Dinosaur Park Formation from transect 1; BB43- 500µm-1mm size fraction from a sandstone unit from bone bed 43 (refer to Chapters 4-5 for geographical and stratigraphic location of samples).

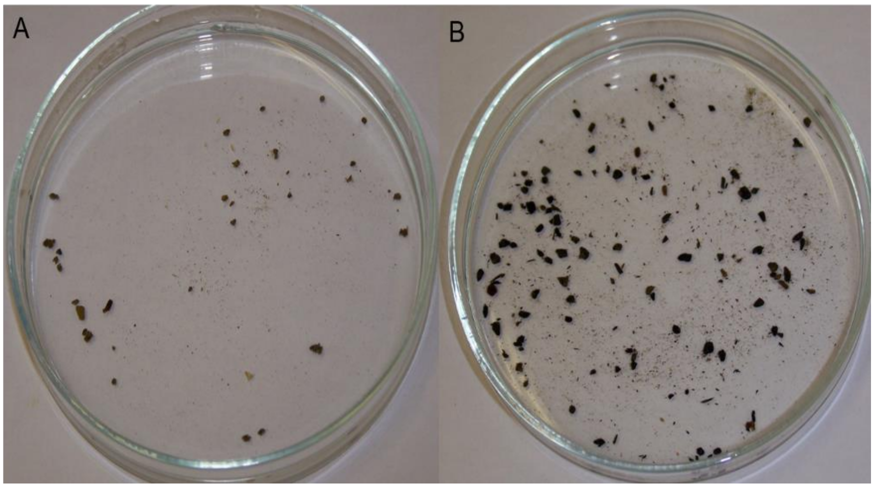


Fig. 3.8 Examples of charcoal residues from the Campanian of southern Alberta, with domin classifications of rare (A) and frequent (B).

3.3.3.1 Rarefaction tests

Rarefaction tests were undertaken in order to determine a suitable number of domin squares for analysis (Figs. 3.9-3.11). Three tests were undertaken on sandstone subsamples 1-22, 1-22b and 1-22c, with a range of domin squares analysed (Fig. 3.9-3.11). These tests indicate a plateau at twenty squares, therefore this number was selected for use within the quantification methodology.

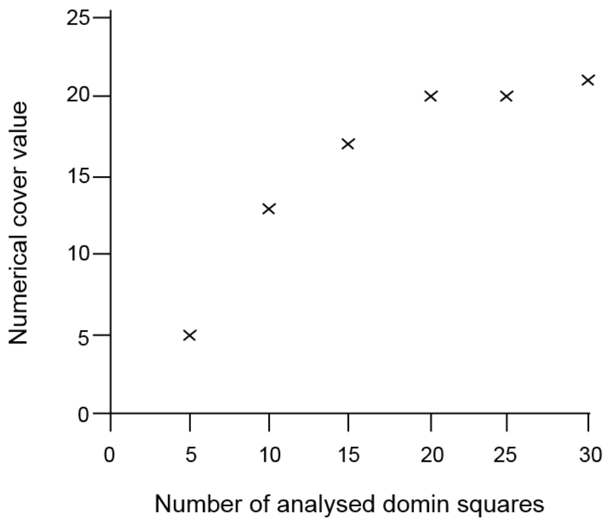


Fig. 3.9 Rarefaction test on sandstone subsample 1-22. Numerical charcoal cover values plateau at approximately 20 domin squares, with only slight variation recorded above this.

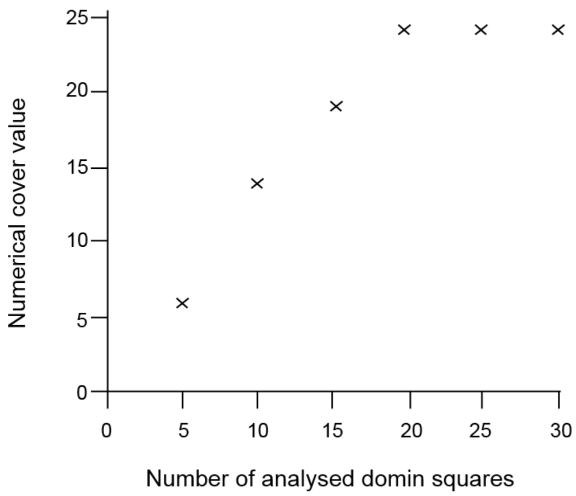


Fig. 3.10 Rarefaction test on sandstone subsample 1-22b. Numerical cover values plateau at 20 domin squares.

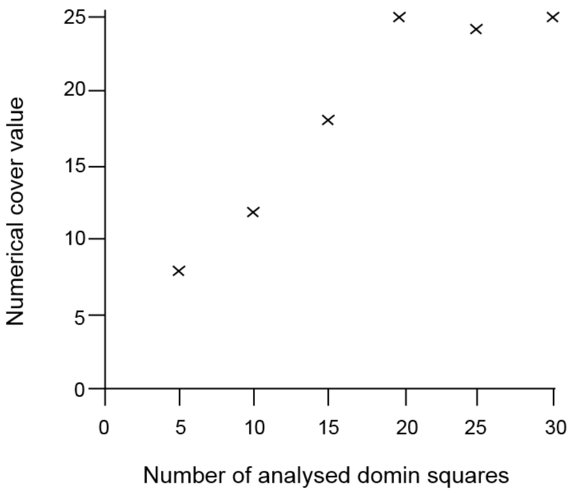


Fig. 3.11 Rarefaction test on sandstone subsample 1-22c. Numerical cover values plateau at 20 domin squares.

3.3.3.2 Testing repeatability of charcoal counts

Repeats for multiple test samples were undertaken to observe if variation of charcoal abundances occurred within the 200g bulk sediment samples. Test samples were selected from each lithology (sandstone, shale and mudstone) and were undertaken for Campanian, Maastrichtian and modern samples. Three sub-samples of 20g of sediment from the same bulk sample were disaggregated, sieved, and charcoal quantified using the methodology in sections 3.3.1 and 3.3.2 (Tables 3.1-3.3).

The repeatability tests show that similar numerical cover values of charcoal are obtained from each 20g subsample, irrespective of sediment type or age of sample (Tables 3.1-3.3) with all subsamples having the same domin classification for each of the size fractions (Tables 3.1-3.3). The repeatability tests indicate that the domin classifications, and associated numerical cover values of sub-samples are representative of relative charcoal abundances within the bulk lithological samples.

Campanian sediments	DPP-10-1-22	DPP-10-1-22b	DPP-10-1-22c
>2.5mm	6.5 (Rare)	6 (Rare)	4 (Rare)
1mm-2.5mm	20 (Frequent)	24 (Frequent)	26 (Frequent)
500µm-1mm	14 (Rare)	17 (Rare)	16 (Rare)
Maastrichtian sediments	**DRH-1-60**	**DRH-1-60b**	**DRH-1-60c**
>2.5mm	22 (Frequent)	20 (Frequent)	23 (Frequent)
1mm-2.5mm	23 (Frequent)	24 (Frequent)	21 (Frequent)
500µm-1mm	19 (Rare)	17 (Rare)	16 (Rare)
Modern sediments	**ARI-1**	**ARI-1b**	**ARI-1c**
>2.5mm	11 (Rare)	10 (Rare)	12 (Rare)
1mm-2.5mm	26 (Frequent)	28 (Frequent)	24 (Frequent)
500µm-1mm	31 (Common)	30 (Common)	31 (Common)

Table 3.1 Domin numerical values for charcoal abundances within replicas of sandstones samples for each size fraction. Three subsamples of samples DPP-10-1-22 (Chapter 4), DRH-1-60 (Chapter 6) and ARI-1 (Chapter 7) were investigated.

Campanian sediments	DPP-10-2-17	DPP-10-2-17b	DPP-10-2-17c
>2.5mm	0	0	0
1mm-2.5mm	11 (Rare)	9 (Rare)	12 (Rare)
500µm-1mm	13 (Rare)	12 (Rare)	10 (Rare)
Maastrichtian sediments	**DRH-3-5**	**DRH-3-5b**	**DRH-3-5c**
>2.5mm	2 (Rare)	6 (Rare)	13 (Rare)
1mm-2.5mm	1 (Rare)	8 (Rare)	10 (Rare)
500µm-1mm	1 (Rare)	3 (Rare)	15 (Rare)

Table 3.2 Domin numerical values for charcoal abundances within replicas of shale samples for each size fraction. Three subsamples of samples DPP-10-2-17 (Chapter 4) and DRH-3-5 (Chapter 6) were investigated.

Campanian sediments	**DPP-10-1-28**	**DPP-10-1-28b**	**DPP-10-1-28c**
>2.5mm	3 (Rare)	1 (Rare)	2(Rare)
1mm-2.5mm	2 (Rare)	2 (Rare)	5 (Rare)
500µm-1mm	3 (Rare)	5 (Rare)	4 (Rare)
Maastrichtian sediments	**DRH-3-21**	**DRH-3-21b**	**DRH-3-21c**
>2.5mm	0	0	0
1mm-2.5mm	0	0	0
500µm-1mm	2 (Rare)	3 (Rare)	5 (Rare)

Table 3.3 Domin numerical values for charcoal abundances within replicas of mudstone samples for each size fraction. Three subsamples of samples DPP-10-1-28 (Chapter 4) and DRH-3-21 (Chapter 6) were investigated.

3.3.4 Light microscopy of charcoal

Charcoal identification was undertaken through the use of light microscopy, with subsamples viewed under a binocular microscope prior to quantification (Fig. 3.12). Charcoal can be identified according to characteristics outlined by Scott (1989, 2000, 2010) (refer to Chapter 1- section 1.2 for full characteristics). Charcoal fragments are characteristically black, and will produce a black streak or residue when touched (Scott, 2000, 2010). Charcoal is considered lustrous, sometimes displaying a silver sheen (Scott, 1989, 2000, 2010). Charcoal is splintery (Scott, 2010), easily fragmenting into smaller particles under very little pressure (for further discussion on the fragmentation potential of charcoal refer to Chapter 8- section 8.1.1).

Fig. 3.12 Example of charcoal deposit showing characteristic black colouring. Lath-like particles with evidence of the associated black streak left as a residue within the petri dish. 1cm scale bar.

Charcoal fragmentation typically results in cuboidal or lath-like (thin and elongate) particles (Fig. 3.12), and can easily be distinguished from coaly particles based on this fracture pattern (Scott, 1989, 2010). Coalified material fractures concoidally, resulting in rounded particles (Scott, 2010).

Cellular detail is visible in charcoal particles under light microscopy (Scott, 2000, 2010). This feature, coupled with the black colour and associated streak, allows differentiation of charcoal from both partially charred and uncharred plant debris. Uncharred and partially charred plant debris can be identified through a dark red/brown colour, and an absence of a black streak. However low temperature charcoal can be difficult to distinguish under light microscopy. Any particles that could not be reliably classified as charcoal were not included for determining relative charcoal abundances (refer to Chapter 8- section 8.1.2 for further discussion).

In addition to the identification of charcoal, the range of particle shapes were observed and documented through light microscopy, along with a determination of the range of plant organs present within the sub-samples.

3.3.5 Scanning electron microscopy

Scanning electron microscopy was undertaken with the aim of confirming the range of identified plant organs recognised through light microscopy. Charcoal fragments were also observed with the aim of identifying broad botanical affinities. Charcoal fragments of 1mm or greater were examined using light microscopy and random particles selected for SEM analysis. In addition particles representing the range of plant organs within each sample were selected. Charcoal >1mm was selected as shape and plant organs were potentially discernible in this size fraction and above. Smaller charcoal fragments could not be identified for the purposes of determination of plant organs with the same confidence under light microscopy. In total 91 charcoal particles were analysed under SEM.

Test samples (n=5) were also undertaken in order to confirm that the determination of charcoalification classified under light microscopy was correct. The presence of homogenised cell walls is characteristic of charcoal, therefore the test sample were analysed for the presence of these. These test samples highlighted that correct classification was being made under light microscopy, allowing domin classifications to be undertaken for all Late Cretaceous and modern samples (Fig. 3.13).

Fig. 3.13 SEM image of charcoal fragment from the Dinosaur Park Formation, with homogenised cell walls shown by the white arrow. This specimen was not cleaned in HF for long enough, and is still covered in debris. Cleaning in HF was extended to two days duration in order to ensure debris removal.

Charcoal pieces for SEM analysis were picked under a binocular microscope with a needle and paintbrush and covered with 10% HCl for twenty-four hours and then subjected to hydrofluoric acid for two days to remove any remaining sediment or mineralisation attached to the particles. Following neutralisation, fragments were dried, picked up using a paintbrush, and attached to stubs using double sided sticky carbon discs. For larger fragments (>2.5mm) agar silver paint was used as an additional adhesive. The stubs were gold coated prior to SEM imaging. The samples were studied using a Hitachi S30000 SEM at 20KV using the SE detector.

Identification of charcoalified wood fragments was undertaken using SEM, with the aim of identifying gymnosperm or angiosperm affinity. Angiosperms were identified through the presence of vessels and their specialised perforation plates (e.g. *scalariform* perforations). Gymnosperms were identified through the absence of vessels and the presence of tracheids with bordered pits (resin canals were sometimes present).

Chapter 4:

Temporal, spatial and environmental distribution of charcoal in the Campanian of Alberta, Canada

4.1 INTRODUCTION

Evidence for global Cretaceous charcoal distribution has been documented in Chapter 2, however there are fewer recorded examples in the Campanian and Maastrichtian than would be expected given the modelled atmospheric oxygen levels (Chapter 2- Fig. 2.1). The expanse of late Campanian sediments exposed within 72km^2 of Dinosaur Provincial Park (Chapter 3- Fig. 3.2), represents a suitable test locality to investigate Cretaceous charcoal distribution throughout a succession of Campanian age sediments. 117 lithological samples from the Oldman and Dinosaur Park Formations within Dinosaur Provincial Park, representing 1.8Ma, have been investigated to determine the presence/absence of charcoal, and to establish whether the low number of data points on Fig. 2.5 (Chapter 2) is due to fewer Campanian/Maastrichtian fires or a lack of investigation into this age of Cretaceous sediment.

In addition to documenting the presence or absence of charcoal, this chapter examines the variation in the temporal and spatial distribution of charcoal to establish the area influenced by wildfires, and potentially identify whether regional or localised wildfires were influencing this Late Cretaceous landscape throughout the 1.8Ma. A focus on lithologies and charcoal content will establish whether wildfires were restricted to particular areas within the depositional catchment.

4.2 MATERIALS AND METHODS

In order to document charcoal distribution and relative abundance within the sediments of the Oldman and Dinosaur Park Formations, sampling was undertaken for each lithological unit throughout the upper 20m of the Oldman Formation and 50m of the Dinosaur Park Formation where accessible within Dinosaur Provincial Park. This locality is a UNESCO World Heritage Site, containing abundant articulated and disarticulated dinosaur remains, along with other fossils (Fig. 4.1) (Currie and Koppelhus, 2005; further discussion of dinosaur biota in Chapter 5- section 5.2.2).

The Dinosaur Park Formation lies disconformably over the Oldman Formation, with a total outcropping thickness of 70m within Dinosaur Provincial Park. The disconformity between the two Formations was observable in the field through slight differences in sandstone and mudstone colours, differences in unit thicknesses along with differences in weathering characteristics (Eberth, 2005). Typically the Dinosaur Park Formation contained thicker units and darker sandstones with highly rounded and rilled surfaces (Eberth, 2005).

Three sedimentary successions were sampled; DPP-10-1 (GPS: base- 12:0463308;5622155; top- 12:0462793;5622417) (Figs. 4.2, 4.3A), DPP-10-2 (GPS: base- 12:0464631;5621309; top- 12:0464713;5620817) (Figs. 4.2, 4.3B-C), and DPP-10-6 (GPS: base- 12:0472695;5623919; top- 12:0473324;5622811) (Figs. 4.2, 4.3D). The selection of these successions was based on the exposure of the Oldman Formation, the completeness of the Dinosaur Park Formation and ease of access to sites. In addition the successions were selected from different parts of the 72km^2 of exposed Cretaceous sediments in order to observe any spatial variation in charcoal occurrence.

DPP-10-1 had the greatest continuous exposure of the Oldman Formation, in addition to approximately 50m of the Dinosaur Park Formation, and was selected because it exposed the largest continuous stratigraphic succession. DPP-10-2 was chosen as it exposed the uppermost part of the Oldman Formation along with approximately 45m of the Dinosaur Park Formation. This succession is located ~1km away from DPP-10-1. DPP-10-6 was selected as it also exposed the uppermost part of the Oldman Formation and approximately 50m of the Dinosaur Park Formation. This succession is located ~6km away from DPP-10-1 and so spatial variation in charcoal occurrence could be documented.

Fig. 4.1 Field photographs of an assortment of fossils and fossil beds found within Dinosaur Provincial Park, displaying the variability in assemblages. All dinosaur bones were found within sandstone units. A- Turtle scute fragments within the Oldman Formation. B- Bivalve bed within the Oldman Formation with a thickness of 0.4m. C- End of dinosaur leg bone, likely to be a hadrosaur (D.R. Braman personal communication, 2010), within the Dinosaur Park Formation. D- Fragments of dinosaur tendon found within the Dinosaur Park Formation, affinity unknown. E- Vertebrae belonging to a hadrosaur found within the Dinosaur Park Formation. F- Iron stained hadrosaur femur found within the Dinosaur Park Formation.

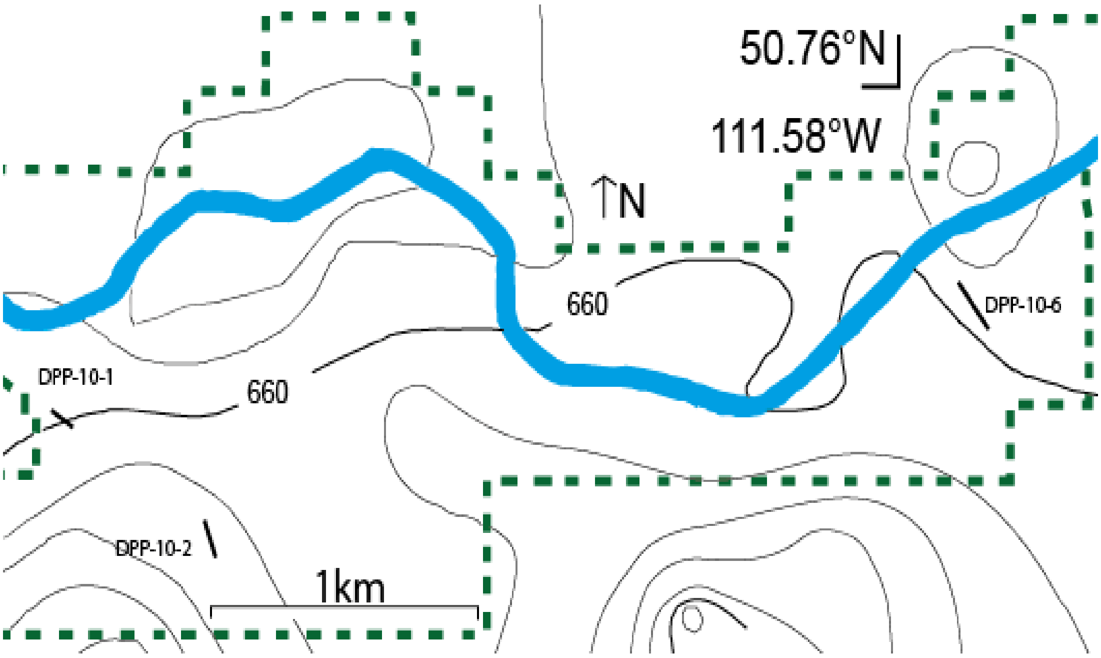


Fig. 4.2 Map of Dinosaur Provincial Park highlighting the three sedimentary successions DPP-10-1, DPP-10-2, DPP-10-6 (Enlargement of Fig. 3.4)

For each sedimentary succession generalised lithological logs were constructed in the field and each lithological unit was sampled, irrespective of whether charcoal was visible to the naked eye. Samples were processed according to the methodology outlined in Chapter 3 (section 3.3).

However, due to the badland topography, many of the individual lithological units cannot be laterally traced for more than a few metres. There is a single dated lithological unit within the exposed Oldman and Dinosaur Park Formations in Dinosaur Provincial Park (Chapter 3- Fig. 3.3). This poses a problem for investigating the variability of charcoal abundances in a known time frame, therefore charcoal abundances are compared between the two Formations.

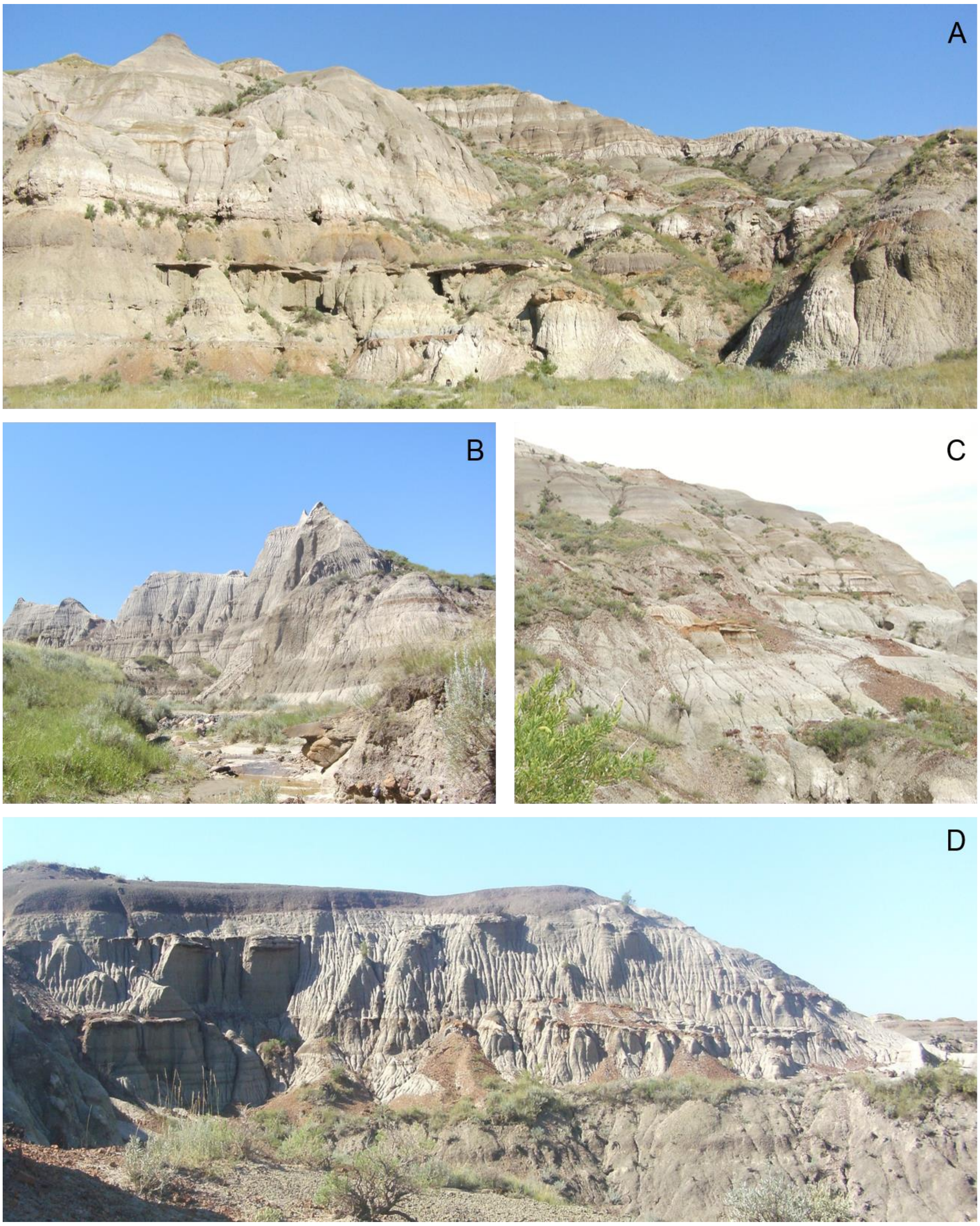


Fig. 4.3 Sedimentary successions sampled within Dinosaur Provincial Park. A- Lower part of the succession at DPP-1, B- Lower part of the succession at DPP-2, C- Middle part of the succession at DPP-2, D- Middle part of the succession at DPP-6. Refer to Fig. 4.2 for sedimentary succession locations.

4.2.1 Palaeoclimate and Palaeoenvironmental context

The Judith River Group, containing both the Oldman and Dinosaur Park Formations, represents sedimentation throughout the late Campanian after a major phase of uplift within the Canadian Cordillera (Eberth and Hamblin, 1992). The Oldman Formation was deposited during a major transgression on the Bearpaw Sea, and has a total outcropping thickness of 20m within Dinosaur Provincial Park (Brinkman, 1990). This Formation was deposited on a low sinuosity, fluvially influenced, low relief coastal to alluvial plain (Eberth and Hamblin, 1992; Eberth, 2005).

The lithologies are dominated by palaeochannel sandstones (not exceeding 5m in depth) which are characteristically light coloured, very fine to fine grained, with blocky unrilled surfaces. Small overbank mudstones (not exceeding 1m) and shales are also present. (Eberth, 2005). The Oldman Formation contains a range of fossils, including turtle fragments, bivalves, *Champsosaurus*, *Taxodioxylon* wood and some dinosaur bones. However no articulated dinosaurs have been found within this Formation (Brinkman, 2005; Brinkman et al., 2005; Eberth, 2005).

Small lateral and vertical variations in sandstone grain sizes have been previously linked to variable water levels within channels, indicating ephemeral fluvial activity (Eberth, 2005). Further evidence for ephemerality has been indicated through the presence of internal scour and erosional surfaces within palaeochannels, lateral and vertical variations in sedimentary structures, and the widespread occurrence of root traces within the Oldman Formation (Eberth, 2005). Eberth (2005) has linked the above structures and variations to varying in-channel water levels and flow velocities, thus indicating an ephemeral flow.

Ephemerality during the deposition of the Oldman Formation has also been reported by Dodson (1971) and Brinkman (1990), however no description or evidence for this phenomenon was recorded. In addition, the variations in sedimentary structures, as outlined by Eberth (2005), were not described in detail or quantified. Therefore, there is little well-documented evidence to support the hypothesis of ephemeral fluvial activity during the deposition of the Oldman Formation.

Climatic conditions during the deposition of the Oldman Formation were believed to be warm and wet, indicated by the presence of growth rings in wood and *Champsosaurus* vertebrae, along with the presence of turtle taxa (Dodson, 1971).

Seasonally wet conditions have been indicated through the presence of fern and lycopod pollen (Dodson, 1971). Whilst there have been few leaf macrofossils recovered from this Formation, the presence of entire leaf margins indicates a frost free environment (Dodson, 1971).

The Dinosaur Park Formation was deposited on a high sinuosity, fluvially influenced coastal to alluvial plain (Eberth, 2005). The lithologies are dominated by palaeochannel sandstones and overbank mudstones and shales (Eberth, 2005). The lower part of the Dinosaur Park Formation is dominated by large, fine to medium grained palaeochannel sandstones, with highly rilled surfaces (Eberth, 2005). Extraformational pebbles can be observed in the lowermost 20m of the Dinosaur Park Formation, often occurring as small layers. The upper part of the Dinosaur Park Formation is dominated by thick, bentonitic mudstones and shales, with the presence of coal seams at the top of this Formation.

Climatic conditions during the deposition of the Dinosaur Park Formation are considered to be warm temperate to subtropical, with annual rainfall of 120cm a year or more (Wood et al., 1988). The presence of turtle taxa supports the interpretation of a seasonally wet climate (Dodson, 1971).

4.3 DISTRIBUTION OF CHARCOAL

4.3.1 DPP-10-1

The Oldman Formation contains 19 sampled lithological units (Fig. 4.4). 11 units were found to contain charcoal**.** Charcoal is distributed throughout the Formation, however the domin classifications never exceeded rare, with low numerical values (below 10). Charcoal of >2.5mm was found in only a single unit near the top**.**

The Dinosaur Park Formation contains 23 sampled lithological units (Fig. 4.4). 16 units were found to contain charcoal. Charcoal is distributed throughout the Formation, with almost all charcoal having a domin classification of rare, with low numerical cover values (below 10). Only a single unit (c.22m- Fig. 4.4) contained charcoal with higher numerical cover values, with a domin classification of frequent for the 1mm-2.5mm size fraction and rare, with a numerical cover value greater than 10, for the 500µm-1mm size fraction. This lithological unit contained the greatest relative abundances of charcoal for all size fractions within DPP-10-1. Almost all charcoal within the upper part of the Dinosaur Park Formation (40-70m) was in the 500µm-1mm size fraction.

Only a single unit (c.41m) contained larger charcoal. Charcoal abundances throughout DPP-10-1 have been compared, based on the lithology of the unit in which they are contained, in order to establish whether wildfires were influencing all catchment areas during the deposition of the Oldman and Dinosaur Park Formations, or were confined to specific environmental settings. For the sedimentary succession DPP-10-1 there is little overall variation in charcoal abundances within the three different lithologies (Fig. 4.5). For the 1mm-2.5mm size fraction, charcoal abundances are the same for shales and mudstones. Sandstone units contain greater charcoal abundances for the 1mm-2.5mm size fraction than the other lithologies, with a domin classification of frequent being recorded for this lithology only. There is some variation in charcoal abundance between the lithologies for the 500µm-1mm size fraction.

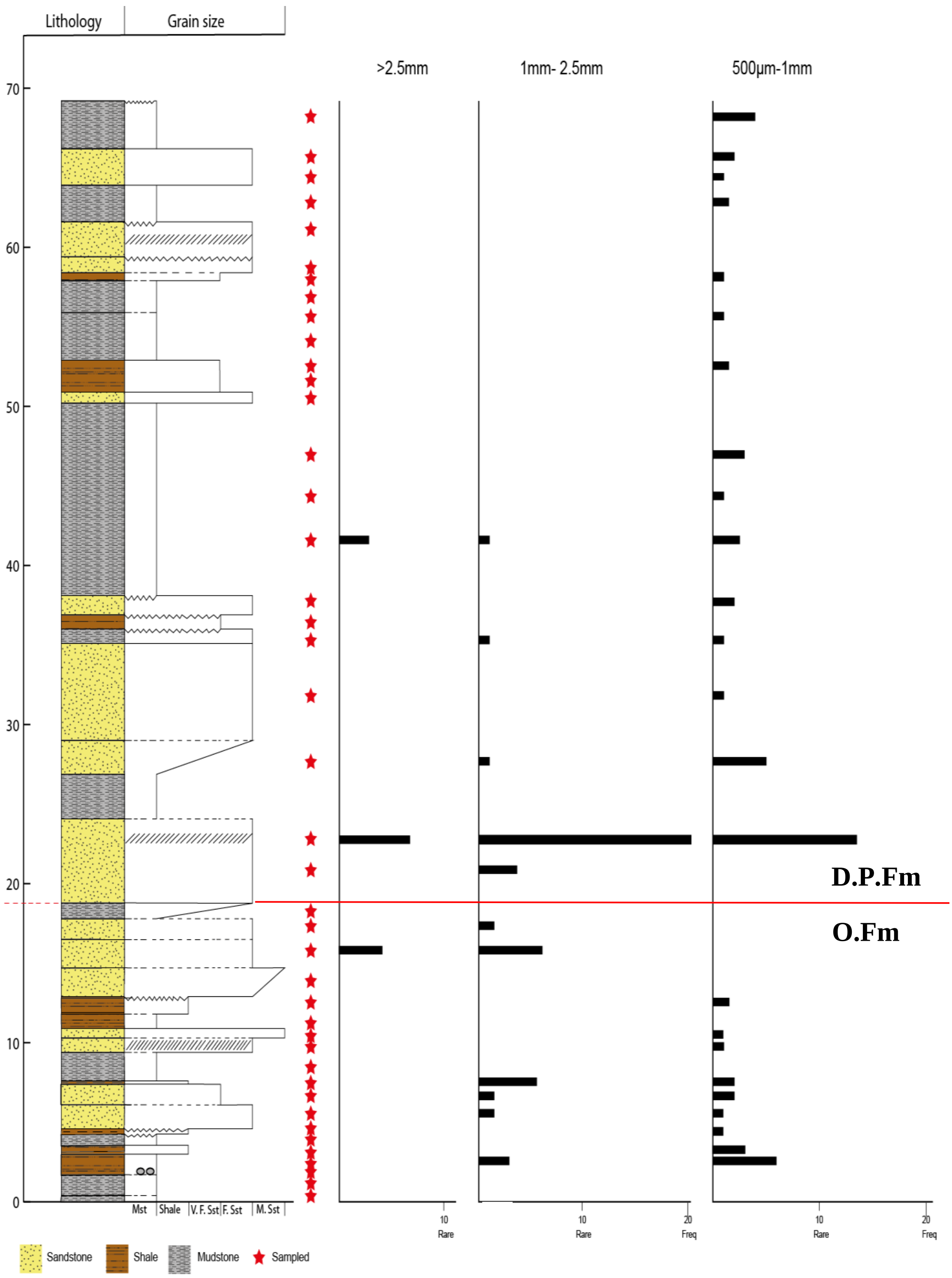


Fig. 4.4 Domin classification and numerical cover value for charcoal in 20g subsamples throughout the Oldman and Dinosaur Park Formations, DPP-10-1, Dinosaur Provincial Park. The red line represents the boundary between the Oldman and Dinosaur Park Formations.

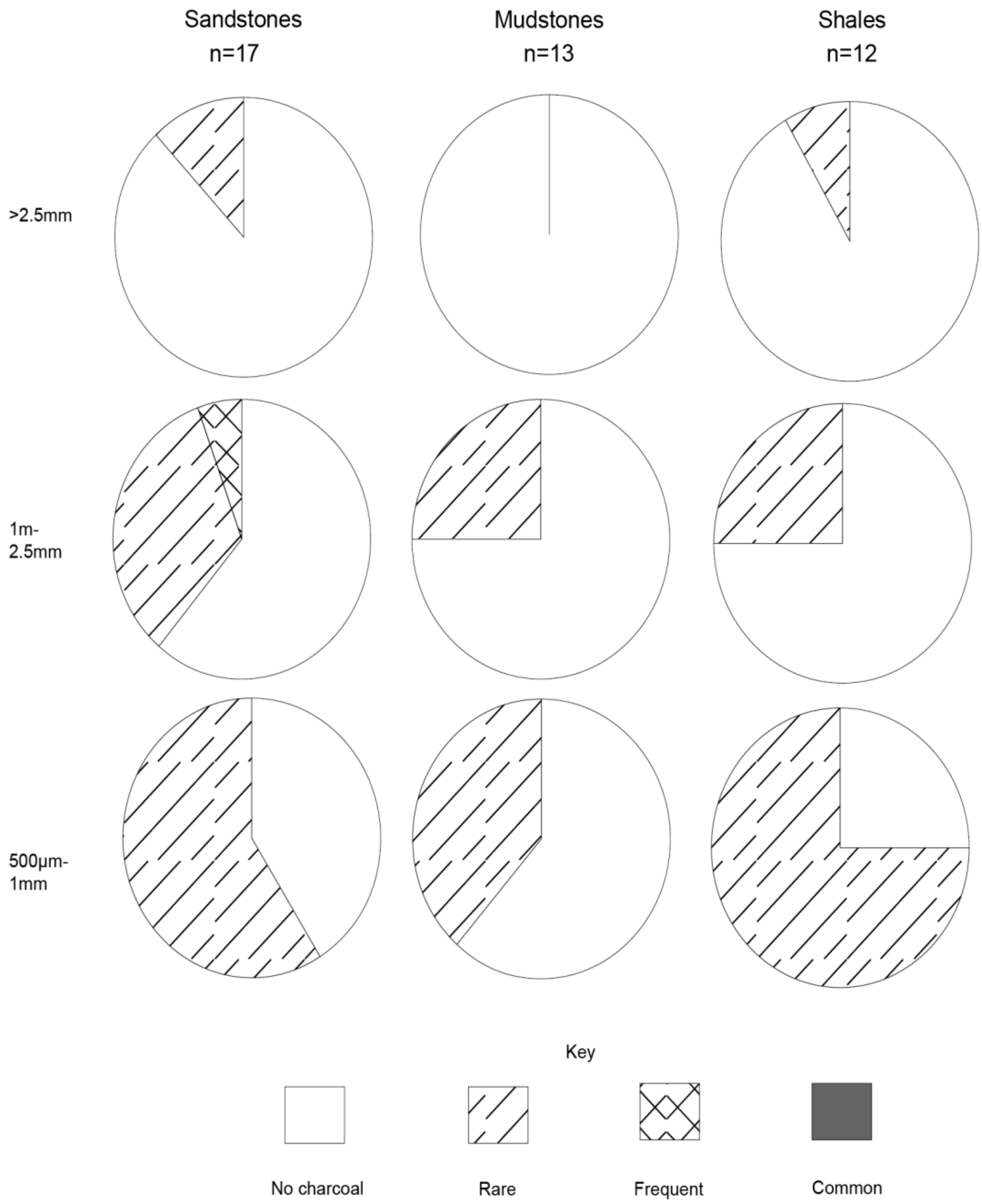


Fig. 4.5 The proportions of domin classifications for charcoal abundances within 20g subsamples from all sedimentary units within the uppermost 18m of the Oldman Formation and lowermost 50m of the Dinosaur Park Formation (DPP-10-1) showing little correlation between lithology and charcoal abundance.

4.3.2 DPP-10-2

The Oldman Formation contains a single lithological unit lacking charcoal of any size fraction (Fig. 4.6). The Dinosaur Park Formation contains 42 sampled lithological units (Fig. 4.6). 15 units were found to contain charcoal. Charcoal is distributed sporadically throughout the Formation, with all charcoal having a domin classification of rare, and almost all having low numerical cover values (below 10). Only a single unit (c.23m) contained charcoal with a numerical cover value greater than 10, belonging to the 500µm-1mm size fraction. The upper part of the Dinosaur Park Formation (28m-47m) contained a single unit with charcoal >2.5mm, representing the only occurrence of this size fraction.

There is little overall variation in charcoal abundances relative to lithologies within the sedimentary succession at DPP-10-2 (Fig. 4.7), particularly between the sandstone and shale units. The mudstones also contain charcoal of similar abundances to that of the other two lithologies.

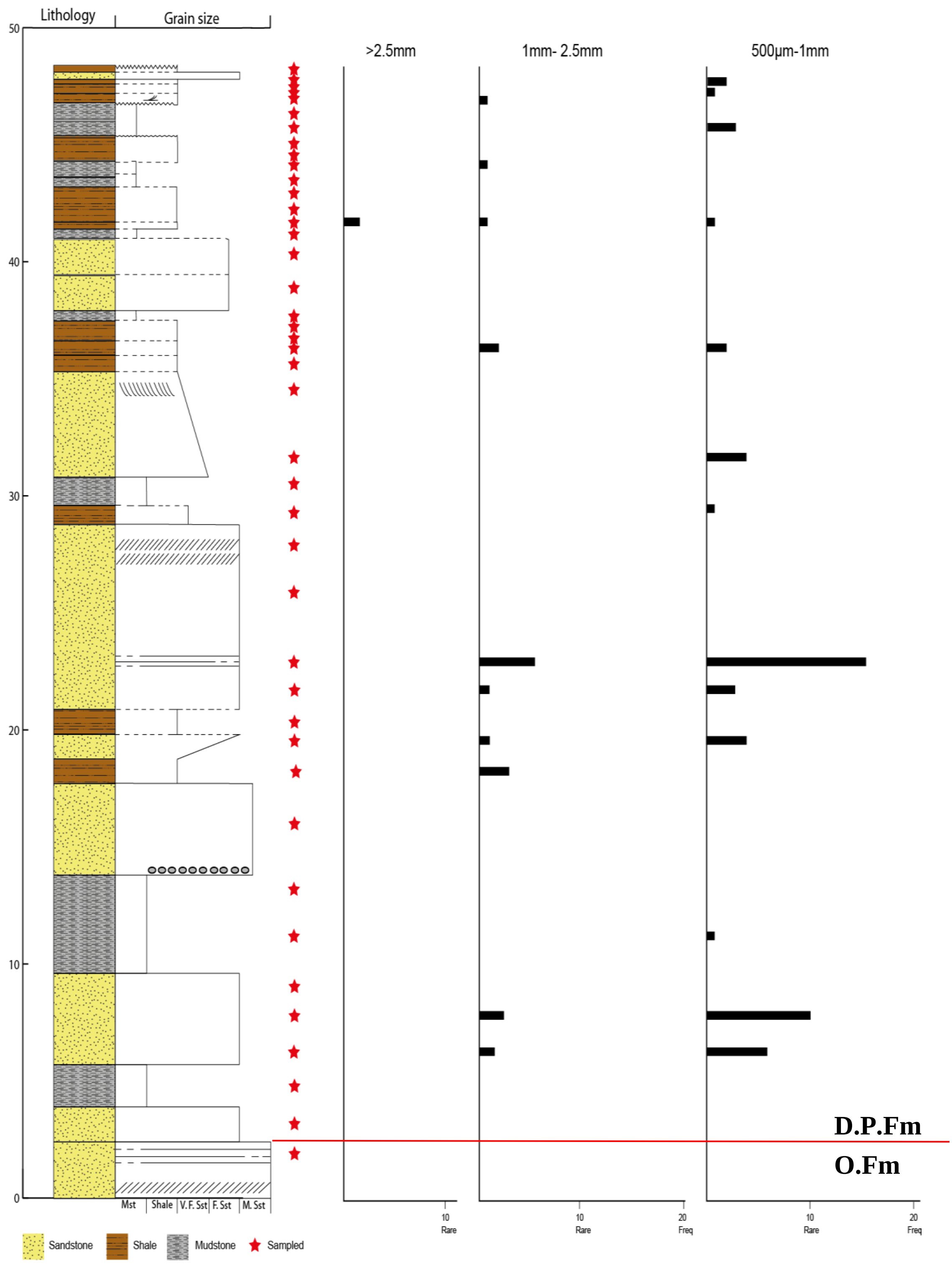


Fig. 4.6 Domin classification and numerical cover value for charcoal in 20g subsamples throughout the Oldman and Dinosaur Park Formations, DPP-10-2, Dinosaur Provincial Park. The red line represents the boundary between the Oldman and Dinosaur Park Formations.

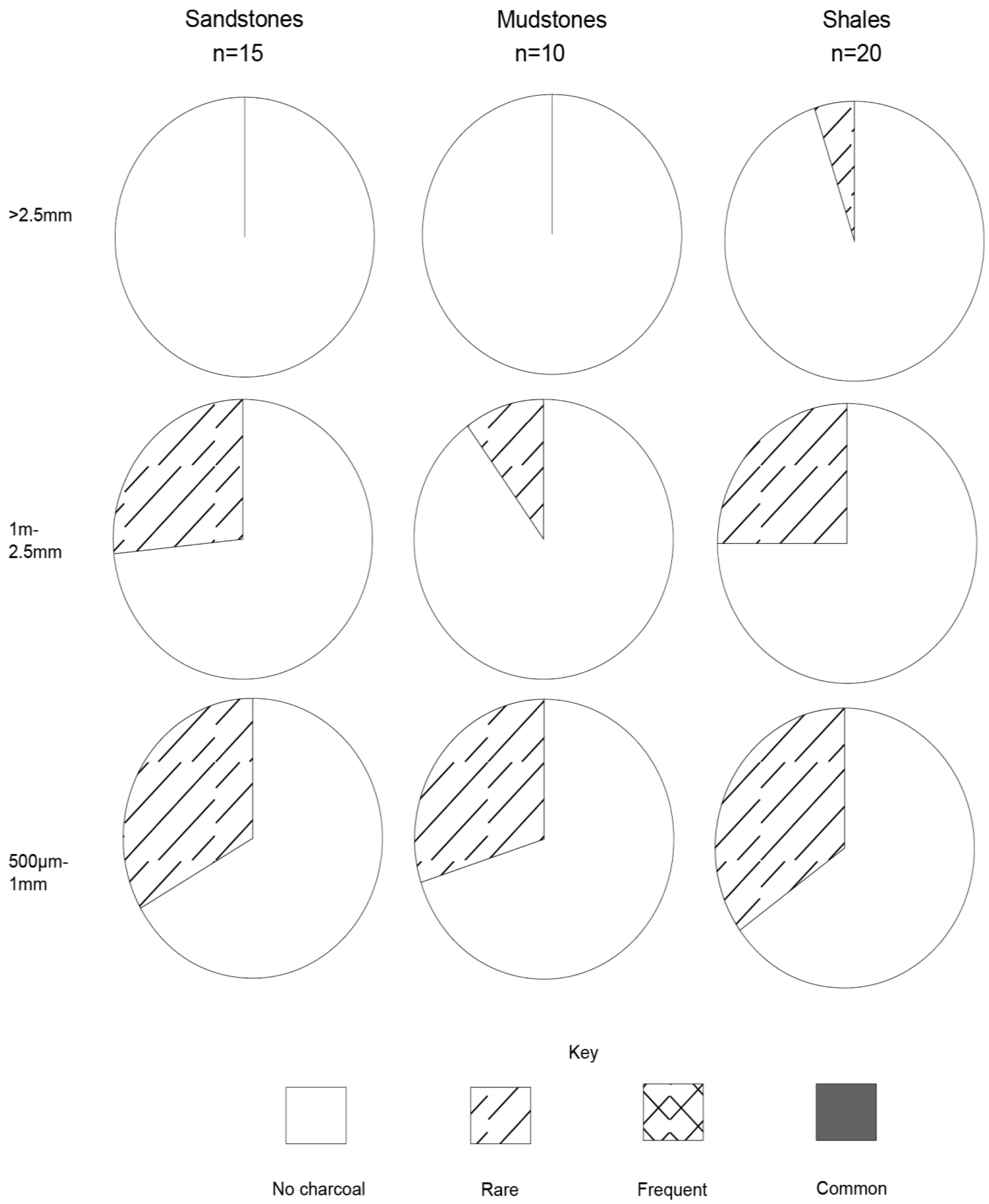


Fig. 4.7 The proportions of domin classifications for charcoal abundances within 20g subsamples from all sedimentary units within the uppermost unit of the Oldman Formation and lowermost 45m of the Dinosaur Park Formation (DPP-10-2) showing that charcoal has similar levels of abundance irrespective of the sediment it is contained within.

4.3.3 DPP-10-6

The Oldman Formation contains a single lithological unit lacking charcoal of any size fraction (Fig. 4.8). The Dinosaur Park Formation contains 31 sampled lithological units (Fig. 4.8). 15 units were found to contain charcoal. Charcoal is distributed throughout the Formation. The lower part (2m-32m) of the Dinosaur Park Formation has greater relative abundances of charcoal, with a few units with numerical cover values greater than 10 for both the 1mm-2.5mm and 500µm-1mm size fractions.

A single unit (c.7m) contained 500µm-1mm sized charcoal with a domin classification of frequent. This lithological unit contained the greatest relative abundances of charcoal for both the 1mm-2.5mm and 500µm-1mm size fractions. Directly above this unit is a gap with no charcoal of any size fractions. The upper part of the Dinosaur Park Formation (32m-52m) has less charcoal than the lower part, with lower numerical cover values (below 10). There is a gap with no charcoal near the base (c.32m) of this section and another near the top (c.46m).

There is little overall variation in charcoal abundances within the three different lithologies at DPP-10-6 for all size fractions (Fig. 4.9). The charcoal abundances in both sandstone and shale units are very similar. However, the domin classification of frequent only occurs in sandstone. The mudstones contain similar charcoal abundances to the other lithologies for the >2.5mm and 1mm-2.5mm size fractions. There are lower abundances of 500µm-1mm charcoal in the mudstones.

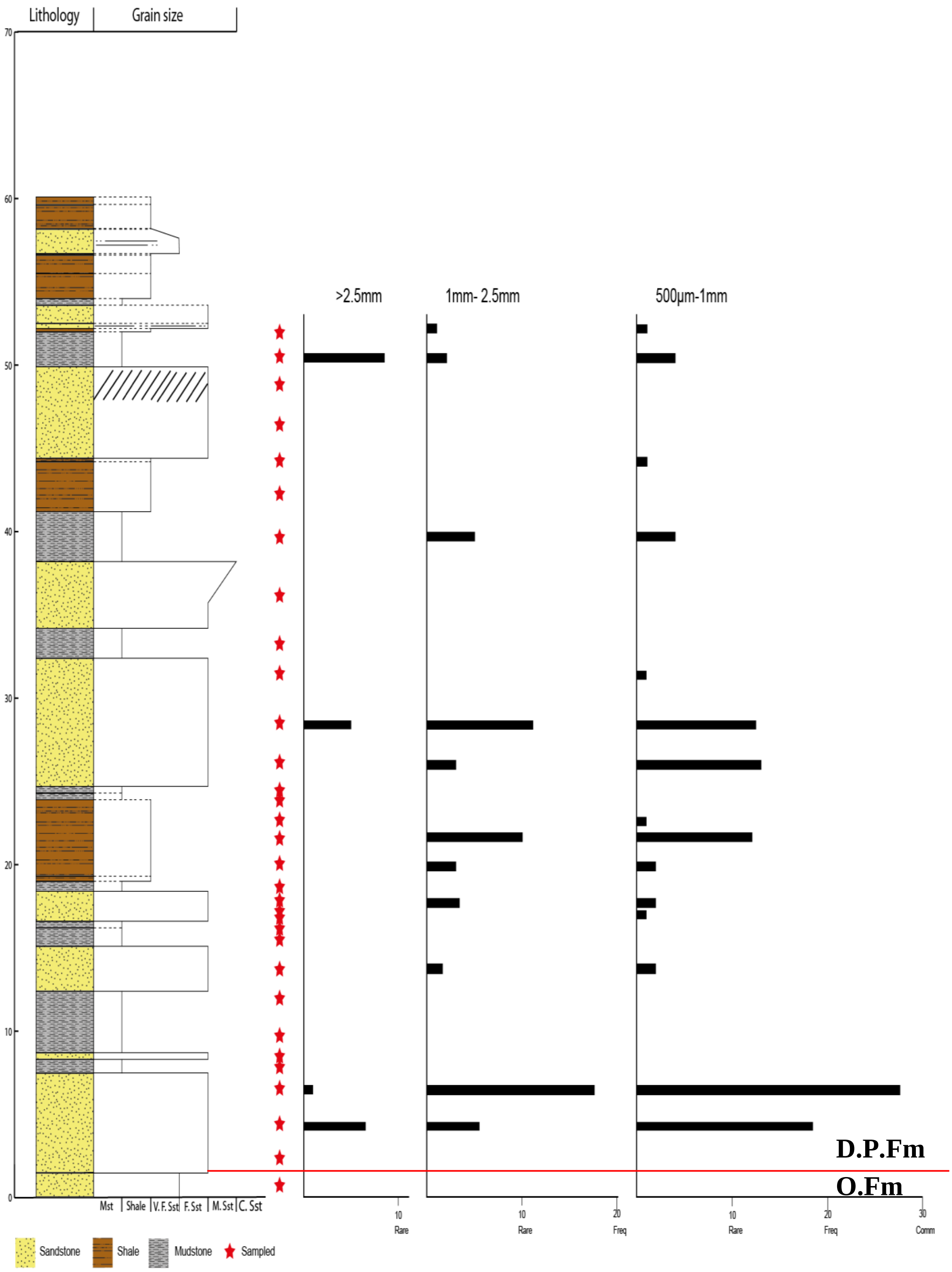


Fig. 4.8 Domin classification and numerical cover value for charcoal in 20g subsamples throughout the Oldman and Dinosaur Park Formations, DPP-10-6. The red line represents the boundary between the Oldman and Dinosaur Park Formations.

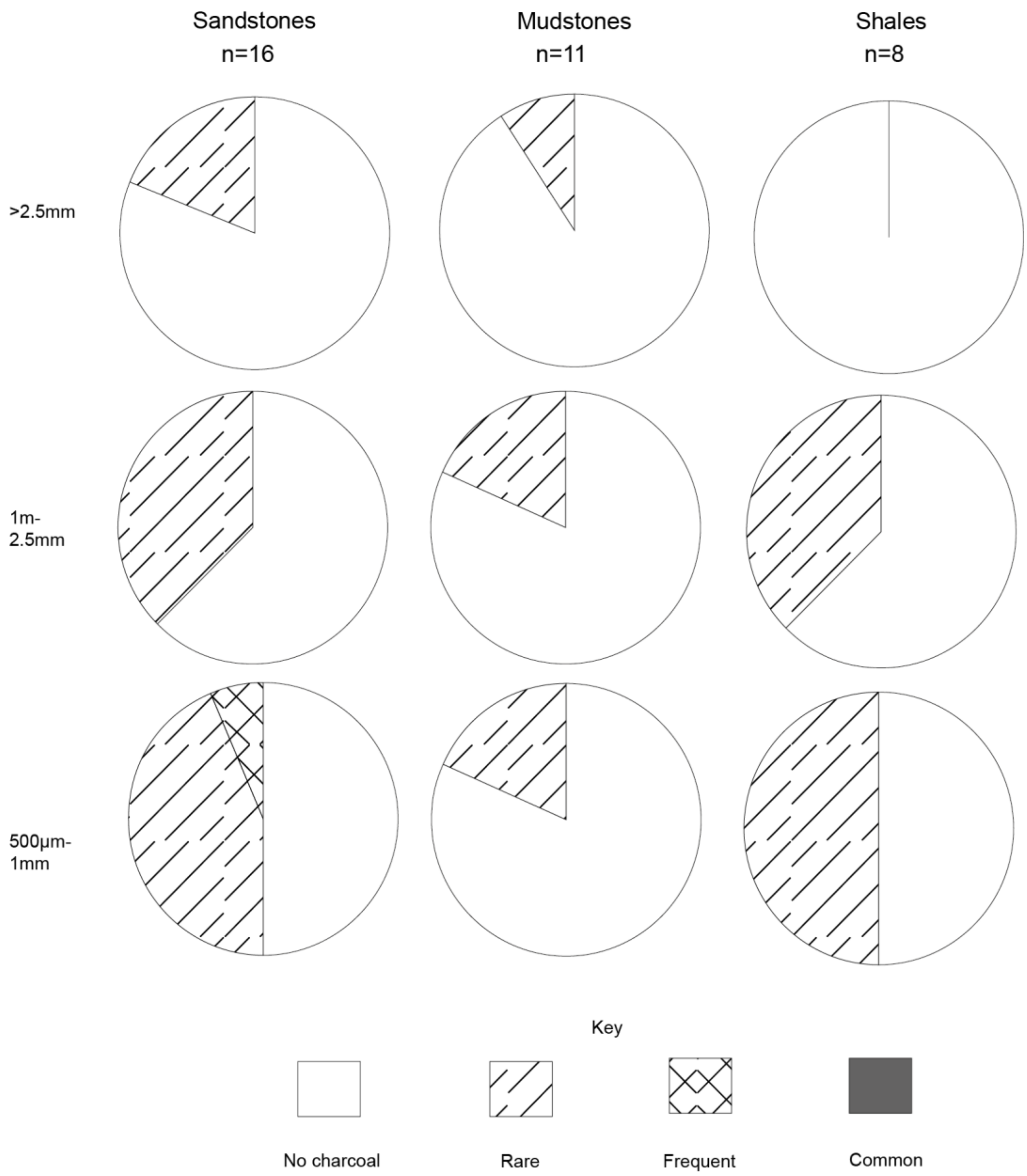


Fig. 4.9 The proportions of domin classifications for charcoal abundances within 20g subsamples from all sedimentary units within the uppermost unit of the Oldman Formation and lowermost 58m of the Dinosaur Park Formation (DPP-10-6) showing little correlation between lithology and charcoal abundance.

4.3.4 Plant organs and particle shapes

Thirty-three charcoal fragments were analysed using SEM (Chapter 3- section 3.3.5). The charcoal assemblages for both the Oldman and Dinosaur Park Formations were comprised of wood fragments only. The charcoal pieces were predominantly cubic or lath like in shape (Fig. 4.10). SEM analysis shows that the charcoal assemblages are dominated by gymnosperm wood throughout the 1.8Ma succession. Angiosperm wood was recorded in a single charcoal piece only from DPP-1 (c.22m on Fig. 4.4).

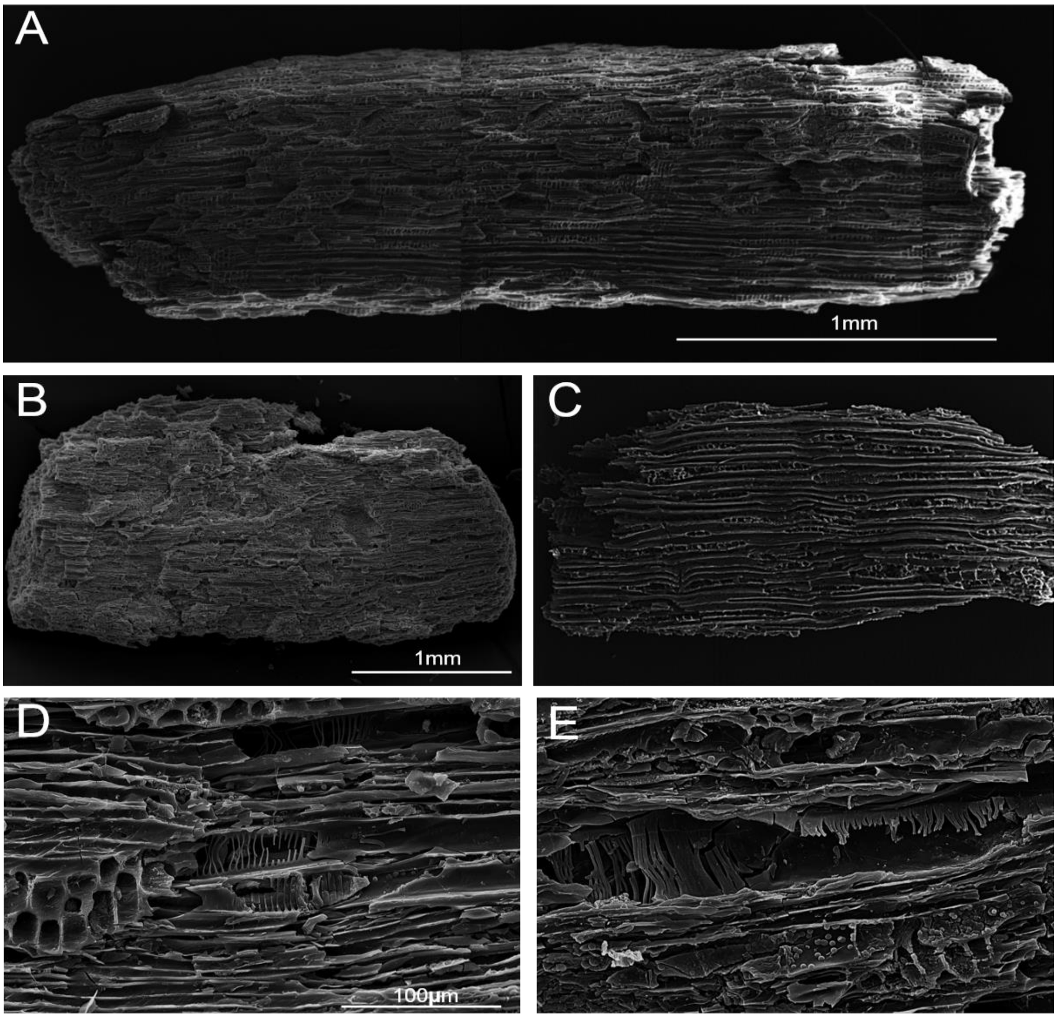


Fig. 4.10 Range of wood charcoal particle shapes from the Dinosaur Park Formation. A- gymnosperm wood, B- angiosperm wood, C- gymnosperm wood, D-E- enlargement of B, angiosperm wood with scalariform perforations. B and C have a 1mm scale. D and E have a 100µm scale.

4.4 DISCUSSION

4.4.1 Charcoal distribution within lithologies

The alternating sandstones, mudstones and shales of the Oldman and Dinosaur Park Formation have been interpreted as palaeochannel and overbank deposits in a fluvial environment on a low-relief coastal plain (Eberth, 2005). Previous research has interpreted a climate with seasonal and fluctuating rainfall during the Campanian (section 4.2.1). Rainfall following a wildfire event can enhance the possibility of charcoal transportation (Chapter 1- section 1.4; Chapter 8- section 8.2.1). Charcoal can be transported across the landscape in overland flow, with wildfires enhancing this through patchy soil hydrophobicity and reduction of vegetation; influencing interception, surface storage and evapotranspiration (Chapter 1- section 1.4; Chapter 8- section 8.2.1).

It is possible that wildfires may have occurred in specific environmental settings and catchment areas during the deposition of the Oldman and Dinosaur Park Formations, such as burning restricted to floodplain or hinterland vegetation. Differences in charcoal abundances with respect to the lithology in which it is contained can give an indication of whether wildfires were influencing specific environmental settings. If charcoal is recorded in the shales and mudstones, and not in the channel sandstones, this may be indicative of wildfires burning floodplain vegetation only. Charcoal domin classifications and the lithologies in which they were contained have been compared in order to address the broad location of the wildfires, and whether the observed distribution of charcoal in the Oldman and Dinosaur Park Formations was determined solely by wildfire location.

There is little overall variation in the domin classifications between the three different lithologies (Fig. 4.11), with similar abundances for all lithologies and size fractions. The domin classification of frequent is only present in sandstones units, however there are few units with this domin classification. There is some variation in the percentage of non-charcoal bearing samples for all size fractions within each lithology. 40% of sandstones, 48% of shales and 60% of mudstones contain no charcoal. Whilst there is variation, there is not a large difference between these percentages. Over 30 samples of each lithology have been analysed, indicating that the similarities in charcoal abundances within the three lithologies is not due to a preferential sampling of certain lithologies.

The lithological data, showing similar charcoal abundances (Fig. 4.11), suggests that wildfires may not have been confined to a specific environmental setting but impacted all of the landscape during the deposition of the Oldman and Dinosaur Park Formations. The exclusive burning of floodplain vegetation has been ruled out, but the location of the wildfires cannot be determined beyond this (e.g flooding may have introduced charcoal into floodplain muds). Charcoal is entering the river catchments and being deposited across the floodplain, hence the distribution in all lithologies, however due to the potential of charcoal transportation (Chapter 8- section 8.4) it is not possible to determine if the wildfires were local or regional, or both.

There is very little charcoal greater than >2.5mm recorded in these Cretaceous sediments (Figs. 4.11-4.12). Some charcoal was visible with the naked eye in the sediments of the Dinosaur Park Formation, however this was not prevalent, and could easily be overlooked by those not studying the sediments for the purpose of charcoal research. The small charcoal particle sizes may explain the lack of charcoal documentation within these sediments.

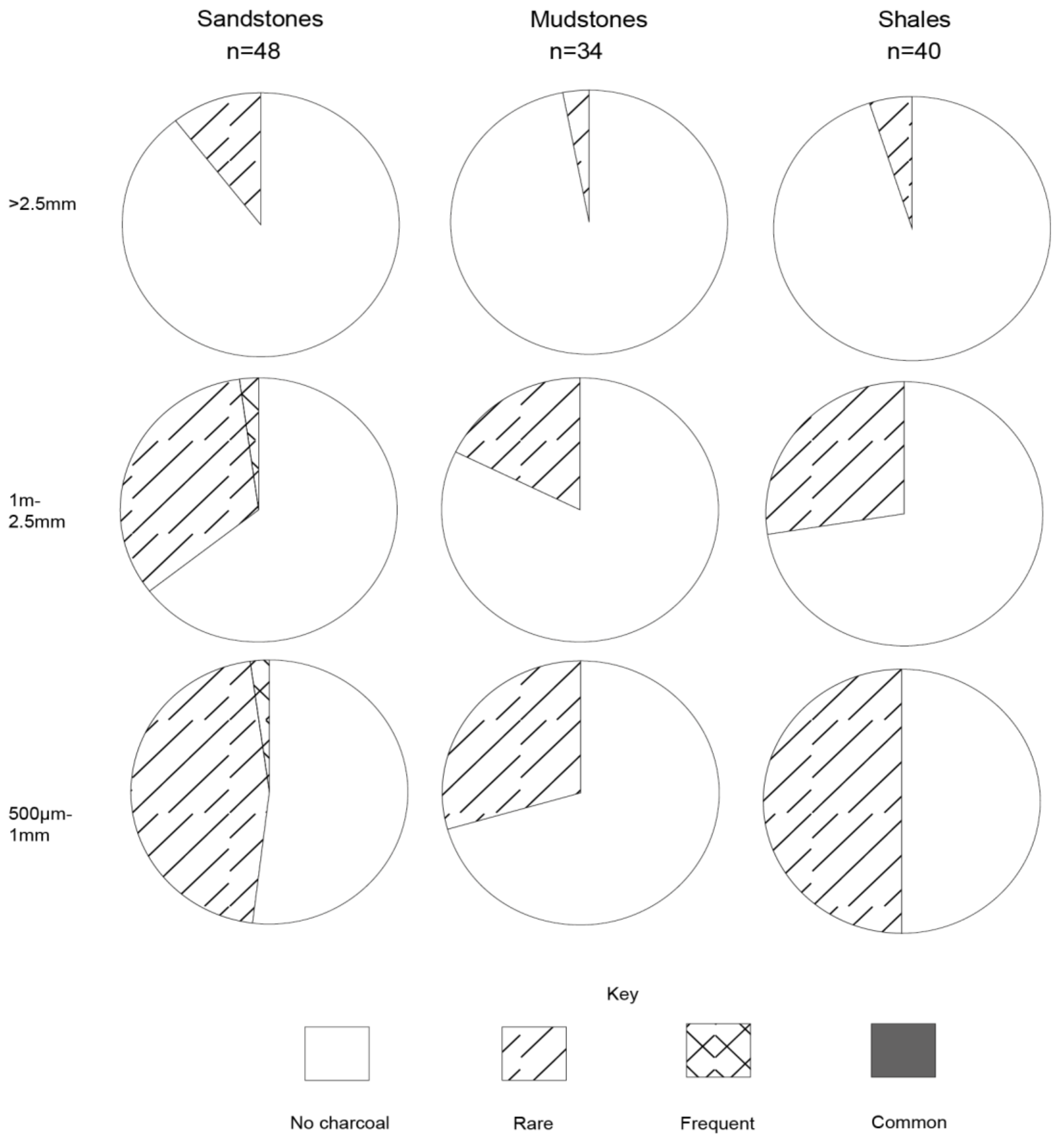


Fig. 4.11 The proportions of domin classifications for charcoal abundances within 20g subsamples from all sedimentary units within the sampled Oldman Formation and Dinosaur Park Formations (DPP-10-1, DPP-10-2, DPP-10-6). Similar proportions of charcoal are recorded within all lithologies.

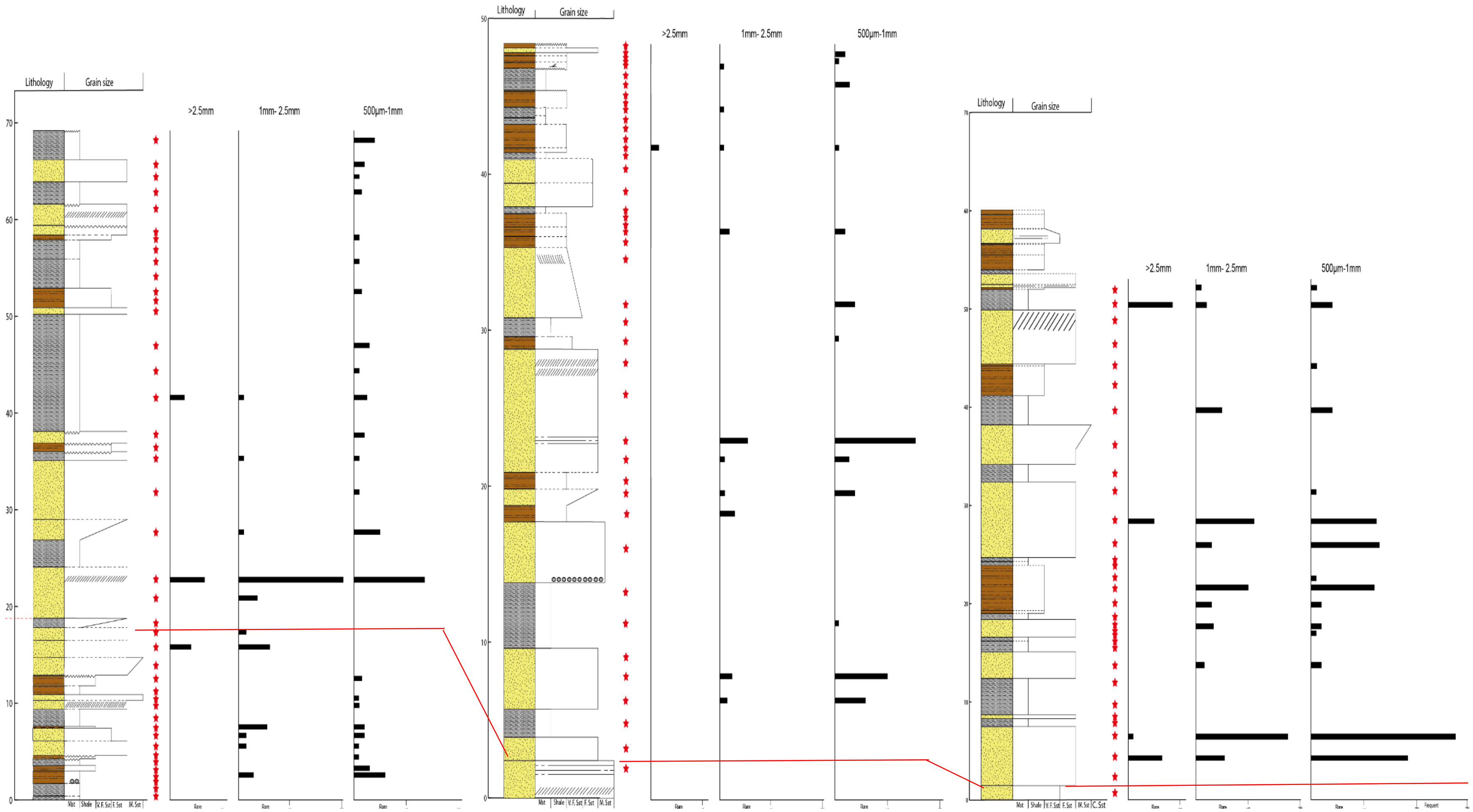


Fig. 4.12 Lithological logs for all three sedimentary successions sampled within Dinosaur Provincial Park. Red stars indicate sampled lithological units. Red line indicates boundary between the Oldman and Dinosaur Park Formations.

4.4.2 SPATIAL DISTRIBUTION OF CHARCOAL

The three sedimentary successions have been compared in order to establish the spatial distribution and relative abundances of charcoal (Fig. 4.12). The lithological data indicates that wildfires were influencing the river catchments within this depositional setting, with charcoal entering all lithologies for all sedimentary successions (section 4.4.1). Therefore any variation in spatial distribution is not a result of wildfires influencing specific environments. Modern wildfires are patchy in nature (Fig. 4.13), with areas of burnt and unburnt vegetation often adjacent to one another. The preferential burning of some vegetation is influenced by vegetation type and moisture content (Chapter 1- section 1.3.3). A similar patchy burn pattern would be expected in the Campanian, with different areas being burnt and therefore leading to variation in the distribution of charcoal abundances between the three sedimentary successions.

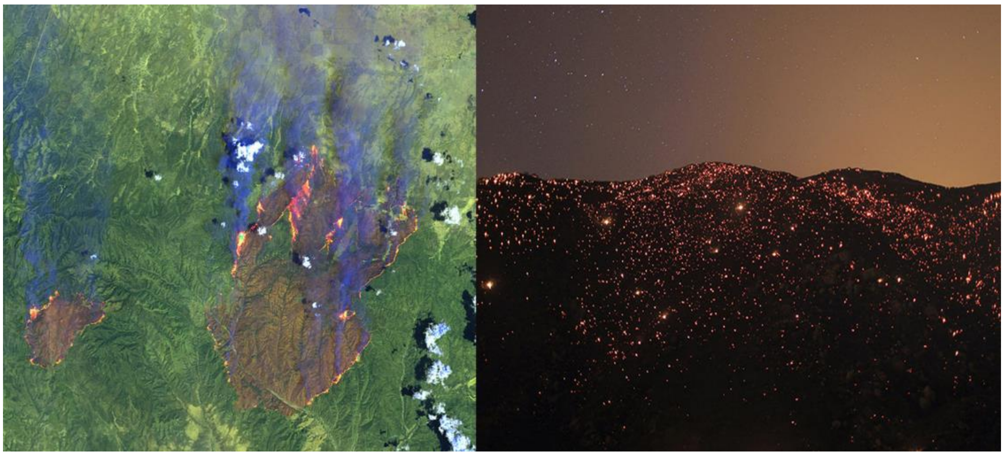


Fig. 4.13 Images showing the patchy nature of modern wildfires. A- Rodeo-Chediski Fire, Arizona, June 2002. Source- en.wikipedia.org/wiki/Rodeo-Chediski_Fire. B- Silver Fire, California, August 2013. Source www.guardian.com

The Oldman Formation cannot be compared across the sedimentary succession, as only a single unit outcrops at DPP-10-2 and DPP-10-6, and there is no means of correlation (Chapter 3- section 3.2.1.1). Therefore spatial distribution cannot be considered for this Formation.

Similar broad trends in temporal distribution of charcoal in the Dinosaur Park Formation are observed in all three sedimentary successions (section 4.4.3), however there is spatial variation in distribution across the 7km area (Fig. 4.12). Charcoal is distributed throughout all the successions, however charcoal occurrences are more sporadic in DPP-10-2.

All three successions show the greatest abundances of charcoal within the lower part of the Dinosaur Park Formation (DPP-10-1 19m-38m, Figs. 4.4, 4.12; DPP-10-2 3m-28m, Figs. 4.6, 4.12; DPP-10-6 2m-32m, Figs. 4.8, 4.12). The greatest relative abundances of charcoal in all size fractions (with the exception of >2.5mm size fraction in DPP-10-2) were recorded in this part of the Formation.

There is a gap in charcoal bearing units in DPP-10-6 for approximately 5m above the abundant charcoal horizon, which is not observed in DPP-10-1. There are two other gaps in charcoal bearing units in the upper part of DPP-10-6 which are not observed in DPP-10-1, indicating a difference in potential fire activity across the 7km area. These gaps in charcoal occurrence could be due to the previous wildfire removing all the vegetation, resulting in little biomass to burn, or vegetation regrowth stabilising the soil and reducing overland flow (Chapter 8- section 8.2.4).

The broad similarities in charcoal abundances within the three sedimentary successions indicate that wildfires were prevalent during the deposition of the Dinosaur Park Formation. Small variations in spatial distribution may be due to the patchy burning of vegetation, with some areas left unburnt or partially burnt.

4.4.3 TEMPORAL DISTRIBUTION OF CHARCOAL

The presence of charcoal throughout the Oldman and Dinosaur Park Formations (Fig. 4.12) indicates that the Campanian landscape was routinely influenced by wildfires. At Dinosaur Provincial Park the Oldman Formation contains charcoal, distributed throughout the Formation, not exceeding the domin classification of rare with low numerical cover values.

The lower part of the Dinosaur Park Formation contains greater charcoal abundances for all three sedimentary successions than those observed within the Oldman Formation at DPP-10-1. All successions show an interval of abundant charcoal close to the disconformity between the Upper Oldman and Lower Dinosaur Park lithological packages, with DPP-10-1 and DPP-10-6 containing a unit with frequent charcoal. For both DPP-10-1 and DPP-10-6 these units had the greatest abundance of charcoal throughout all of the sedimentary succession. Therefore there are several possible explanations for the greater abundance of charcoal in the lower part of the Dinosaur Park Formation including larger wildfires, more vegetation being burnt or greater frequencies in wildfire occurrence.

The upper part of the Dinosaur Park Formation contains charcoal bearing units, however the charcoal abundances are reduced (not exceeding rare with low numerical values) in comparison with those of the lower part of the Dinosaur Park. The 500µm-1mm size fraction dominates this package.

The pattern of temporal charcoal distribution is broadly similar for all three sedimentary successions. The time interval represented by deposits of the lower part of the Dinosaur Park Formation may have experienced greater wildfire activity which could explain the higher numerical cover values and domin classifications for all size fractions when compared with the upper part. However in the absence of time correlation it is not known if the same time interval is represented in all three successions.

4.5 CONCLUSIONS

Charcoal occurs throughout the Oldman and Dinosaur Park Formations in all three sedimentary successions across 7km, indicating that wildfires influenced a large area throughout a 1.8Ma time interval of the late Campanian of Alberta, Canada. This represents the first documentation of charcoal within the Dinosaur Park Formation. Charcoal is found within all lithologies indicating that wildfires were not confined to specific environmental settings, such as floodplain vegetation only, and hence probably fires impacted all of the landscape. The lower part (10-30m) of the Dinosaur Park Formation has higher relative abundances of charcoal at all three sites across the area. This suggests that there may have been greater fire activity during this depositional interval.

This is the first detailed temporal and spatial investigation of charcoal distribution within the Cretaceous, with 117 sedimentary samples studied for the presence of charcoal within a 1.8mya interval of the Late Cretaceous. This study has highlighted the abundance of wildfire activity during this time. The small number of units containing charcoal >2.5mm may mean that charcoal is often not visible in sediments, and therefore the presence of charcoal is likely to be missed by researchers whose focus is not on the charcoal. Routine sieving of sediment samples for charcoal occurrence would help increase the knowledge of global Cretaceous fire activity.

Chapter 5:

Charcoal in vertebrate-rich deposits of the Campanian Dinosaur Park Formation of Canada

This chapter is an adapted version of Brown et al., 2013. The research and initial drafts were undertaken by myself. Editing and contributions were provided by M. E. Collinson and A. C. Scott.

5.1 INTRODUCTION

Charcoal has been documented throughout the Campanian Dinosaur Park Formation (Chapter 4- section 4.3), highlighting the presence of wildfire activity within this ecosystem. The extent of the temporal and spatial distribution (across 7km) of charcoal indicates that wildfires influenced large areas of the Campanian landscape (Chapter 4- section 4.3), therefore it is likely that organisms inhabiting this landscape would have been affected either directly by wildfires or indirectly through the landscape changes as a result of fire events. The Dinosaur Park Formation contains abundant vertebrate deposits, some of which have been extensively researched (Currie and Dodson, 1984; Ryan et al., 2001; Eberth and Currie, 2005; Eberth and Getty, 2005), however the role fire may have played in their formation has never previously been considered. Sander (1987) described vertebrate accumulations that he suggested might have resulted from fire driving animals to their death. A similar scenario was suggested by Scott and Jones (1994) for some Carboniferous vertebrate accumulations.

Major flooding events have been proposed to explain the origin of vertebrate deposits in the Dinosaur Park Formation (Currie and Dodson, 1984; Ryan et al., 2001, Eberth and Currie, 2005; Eberth and Getty, 2005). The possibility that the flooding may have been a consequence of post-fire erosion has never previously been considered, probably because charcoal has not previously been recorded in these sediments. There is now evidence of charcoal occurring throughout the Dinosaur Park Formation (Chapter 4- section 4.3) often in association with isolated dinosaur teeth and bone fragments. With multiple wildfire occurrences documented in the sedimentary record, associated post-fire erosion debris flow or flash flooding events may have been a factor influencing sediment transportation and deposition within the Dinosaur Park Formation. A major flooding event combined with a fire impacted landscape could together influence sediment and dinosaur bone transportation resulting in the formation of vertebrate deposits. The aims of this chapter are, therefore, (i) to establish if charcoal occurs in selected vertebrate deposits within Dinosaur Provincial Park and (ii) to determine whether flooding events across a fire-impacted landscape could be a mechanism for the origin of vertebrate deposits. If so, then the same explanation may apply to similar deposits at many other sites of varying ages.

5.2 MATERIALS AND METHODS

5.2.1 Stratigraphic context

Seventy metres of the Campanian Dinosaur Park Formation is exposed out throughout Dinosaur Provincial Park, Alberta, Canada, disconformably lying above the Oldman Formation (Eberth, 2005). The Dinosaur Park Formation is dominated by fluvially derived fine-grained sandstones, often occurring as stacked palaeochannel sandstones, along with mudstones and shales. The palaeoenvironment has been interpreted to represent a low gradient meandering river system on an alluvial to coastal plain, with a seasonal temperate climate with abundant rainfall (Eberth and Getty, 2005; for further detail see Chapter 4). The ‘badland’ topography within Dinosaur Provincial Park offers the opportunity to study three-dimensional exposures of the Dinosaur Park Formation although it is at times difficult to trace lateral relationships because of the fluvial origin of the strata.

5.2.2 Dinosaur biota within Dinosaur Provincial Park

The Campanian sediments of Dinosaur Provincial Park contain a highly diverse dinosaur biota, preserving the most diverse dinosaur assemblage currently known (Mallon et al., 2013). Dinosaur biota includes Hadrosauria, Ankylosauria, ceratopsians, and theropods represented by fossil bones and teeth occurring as isolated specimens, microvertebrate sites, extensive bone beds and articulated specimens (Ryan and Evans, 2005; Mallon et al., 2013). Within the sediments of the Park, approximately 50% of dinosaur remains belong to hadrosaurs, which tend to dominate microvertebrate sites (occurring as isolated bone), whereas ceratopsians, which represent 25% of dinosaur fossils, appear to be concentrated in monodominated bone beds (Ryan and Evans, 2005).

Thirty-three herbivorous and omnivorous dinosaur species are currently recognised from the Dinosaur Park Formation, which represents the most diverse assemblage of large-bodied herbivorous dinosaurs from Laramidia (Ryan and Evans, 2005; Brown (C.M) et al., 2013; Mallon et al., 2013). Hadrosaurids comprised 40% of the herbivorous dinosaur assemblage within the Dinosaur Park Formation (Mallon et al., 2013). Biostratigraphy indicates that dinosaur taxa are distributed heterogeneously throughout the Formation (Mallon et al., 2013). Feeding height stratification amongst the herbivorous dinosaurs is hypothesised to have facilitated their co-existence within the southern Albertan ecosystem during the deposition of the Dinosaur Park Formation (Mallon et al., 2013).

5.2.3 Vertebrate deposits sampled from Dinosaur Provincial Park

5.2.3.1 Location of vertebrate deposits

Two bone beds and two articulated skeleton quarries within Dinosaur Provincial Park were sampled, all located in the central region of the Park within $3km^2$ (Fig. 5.1), within the lowermost 25m of the Dinosaur Park Formation. These vertebrate deposits were selected for analysis as they were in close proximity to accessible stratigraphic successions also being sampled, and permission for collection was available only for a limited number of sites. The four vertebrate deposits vary in fossil composition and the quantity of dinosaur material preserved. For a bone bed to be named for specific dinosaur taxa, such as ceratopsians, 50% of the disarticulated bones need to belong to ceratopsians (Eberth and Getty, 2005).

5.2.3.2 Bone bed 50

Bone bed 50 is located ~18m above the Oldman-Dinosaur Park Formation contact (D. R. Braman, personal communication, 2012). The bone bed is ~1m in thickness and laterally extensive over hundreds of square metres (Eberth and Evans, 2011). Bone bed 50 represents a multitaxic bone bed with disarticulated and articulated hadrosaur remains, including articulated leg bones (Fig. 5.2), representing at least three individuals, along with abundant disarticulated material (D. R. Braman, personal communication, 2012). The bone bed is contained within fine-grained, stacked-palaeochannel sandstones. Micro-vertebrates are present throughout the bone bed, representing terrestrial and non-terrestrial biota; including turtles, fish, amphibians, champsosaurs, crocodiles, hadrosaurs, ceratopsians, ankylosaurs, theropods and mammals (Eberth and Evans, 2011). Dinosaurs and micro-vertebrates from this bone bed have been collected, but there has been little research published on this deposit.

5.2.3.3 Quarry 213

Quarry 213 is located within a fine-grained sandstone unit 23.69m above the Oldman-Dinosaur Park Formation contact and a single articulated hadrosaur was excavated in 1993 (D. R. Braman, personal communitcation, 2012). The vertebrate deposit is ~2m thick and is laterally extensive over ~9m. Cranial and post cranial material belonging to *Prosaurolophus maximus,* which is now housed within the Royal Tyrrell Museum, has been recorded from this locality (D. R. Braman, personal communication, 2012). The specimen and quarry are referred to in Ryan and Evans (2005) and Mallon et al. (2012).

5.2.3.4 Quarry 11

Quarry 11 is located within a fine-grained sandstone bed 0.712m above the Oldman-Dinosaur Park Formation contact and contained three partially articulated juvenile hadrosaurs (*Corythosaurus casuarius),* including both cranial and post cranial material (D. R. Braman, personal communication, 2012) which had previously been collected from the quarry. Skin impressions have also been recovered (Eberth and Evans, 2011). The vertebrate bearing bed is ~3m thick and extends laterally in excess of ten metres. Despite the dinosaur fossils having been collected, there has been no published research on this material.

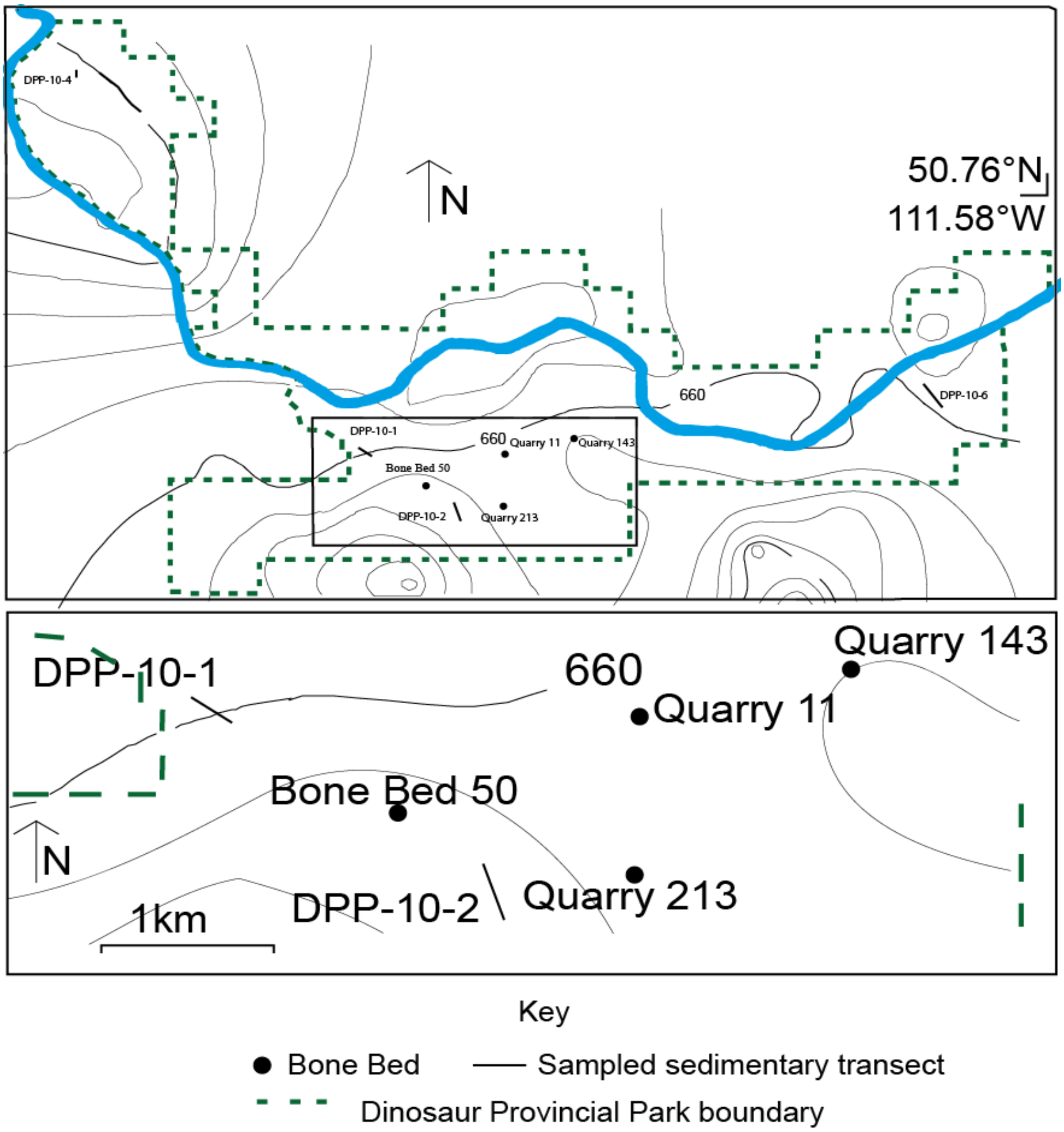


Fig. 5.1- Location of the vertebrate deposits within Dinosaur Provincial Park, Alberta, Canada (Map after Currie and Koppelhus, 2005). The line (DPP-10-1) represents the stratigraphic sequence sampled for charcoal containing either isolated bones or no bones. The solid circles represent the four dinosaur vertebrate deposits. The dashed line represents the Park boundary. DPP-10-1 and DPP-10-2 are discussed in Chapter 4 (sections 4.2-4.3).

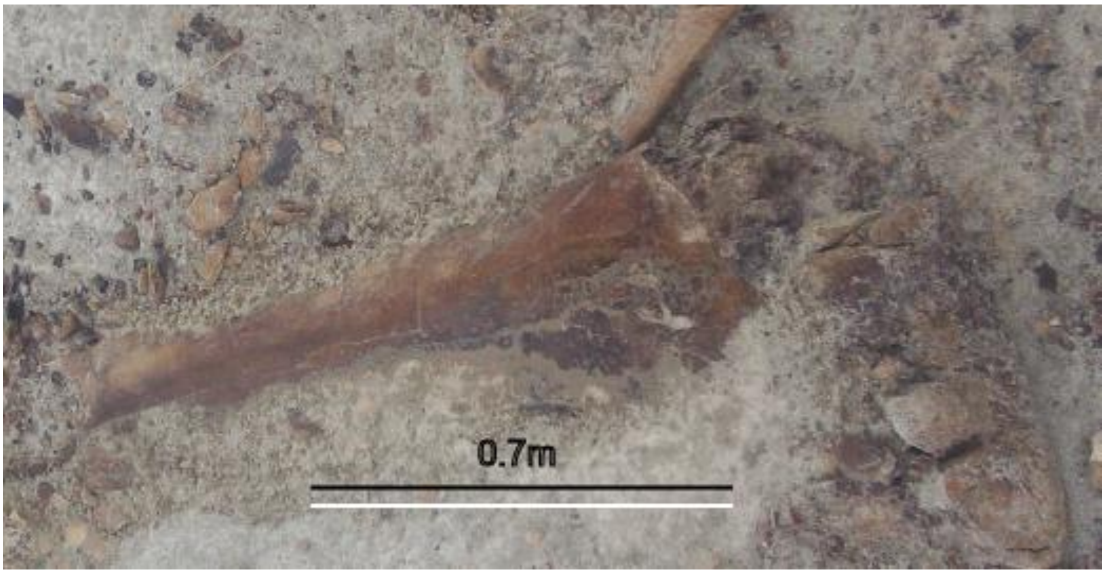


Fig. 5.2 Fragmented hadrosaur leg bones in bone bed 50. Some iron staining has occurred. The dark fragments on the surface are ironstone deposits that formed after the deposition of the bone bed

5.2.3.5 Bone bed 43 (Quarry 143)

Bone bed 43 is laterally extensive, with ~13,000m^2 of fossil bearing horizon preserved (Ryan et al., 2001) 10.5m above the Oldman-Dinosaur Park Formation contact (Eberth and Getty, 2005). This unit is part of a set of three fine-grained, stacked palaeochannel sandstone deposits and can be interpreted as a lag deposit due to the presence of basal scours (Ryan et al., 2001; Eberth and Getty, 2005). The bones are contained within a coarse-medium fining upwards sandstone with well rounded grains. Approximately 10-cm-scale trough cross-bedding and ripples occur within a very fine grained sandstone close to the top of the unit (Ryan et al. 2001).

There are more than twenty known ceratopsian bone beds (Eberth and Currie, 2005; Eberth and Getty, 2005; Eberth et al., 2010) within Dinosaur Provincial Park, with bone bed 43 (Fig. 5.3) representing one of eight monodominant bone beds. Fossil evidence of ceratopsians is common within the Dinosaur Park Formation, occurring in a range of preservational states, including isolated bone fragments, articulated and partially articulated specimens, disarticulated elements which is the usual case in bone beds, and disarticulated teeth scattered throughout the park (Ryan et al., 2001).

Fig. 5.3 Part of bone bed 43 containing a minimum of 57 disarticulated Centrosaurus apertus

Ceratopsian fossils comprise 80.4% of the 1,576 bones that have been extracted from bone bed 43 and analysed to date; however, this is likely to be an underestimate as selective collecting was undertaken, with a bias towards non-ceratopsians (Ryan et al., 2001). Micro-vertebrate components of this bone bed include theropod teeth and bone fragments, hadrosaur teeth, *Myledaphus* teeth, *Champsosaurus* ribs, ankylosaur scutes, turtle fragments, crocodile teeth, fish scales, amphibian vertebrae, a lizard tooth and a mammal tooth (Ryan et al., 2001).

Bone bed 43 contains a minimum of 57 individual *Centrosaurus apertus* dinosaurs, based on the total number of braincases and loose occipital condyles, and is therefore referred to in the literature as the Centrosaurus bone bed (Ryan et al., 2001). The bones are disarticulated with the exception of a partial series of distal caudals which were associated with a skin impression (Ryan et al., 2001). There is also a single articulated *Chasmosaurus* skull, which is the only fossil representing this species within this bone bed (Ryan et al., 2001).

Unlike many of the isolated bones within the Dinosaur Park Formation, the dinosaur bones within this bone bed are in excess of ten centimetres in length; with a range between 10.6cm and 20.2cm and an average length of 15.1cm. Wood impressions reaching 250cm, which have not been reported in the other three vertebrate deposits, are a major non-vertebrate component (Ryan et al., 2001).

5.2.4 Sampling strategy

Four vertebrate deposits (section 5.2.3) were sampled along with sediments from each distinct lithological unit throughout the 50m of the Dinosaur Park Formation (DPP-10-1 Fig. 5.1, Chapter 4- section 4.3), including units containing isolated dinosaur bone fragments (referred to as isolated bone (N=6)) and no bone (N=23). For Q11 and Q213, the dinosaur bones had been excavated prior to this research. The exact location and sedimentary level of the original dinosaur remains were previously marked by metal stakes, allowing current sampling to be undertaken in the correct horizon. For these localities a single sediment sample was taken from the sedimentary unit in which the dinosaur bones were contained. At the time of sampling, dinosaur bones were still exposed in bone bed 50 and bone bed 43. Sampling was undertaken in the sediments adjacent to the bones, as close as possible without destroying the bones. Bone bed 50 was much thicker than other beds so was split into two 0.5m thick horizons for sampling. The upper horizon of the bone bed was traced laterally 4m and resampled. For each lithological unit sampled (Total N= 29), the exposure was surveyed for a minimum of 10m laterally in order to determine the presence/absence of dinosaur bone material, although this was constrained by the nature of the badland terrain. Samples were processed according to the methodology outlined in Chapter 3 (section 3.3).

5.3 RESULTS

5.3.1 Charcoal in vertebrate deposits

The sediments from each of the four vertebrate deposits contained charcoal, representing the first records of charcoal associated with bone beds within the Dinosaur Park Formation (Fig. 5.4). The charcoal assemblages in the vertebrate deposits were dominated by the <2.5mm size fractions particularly 1mm-2.5mm which is dominant in all the vertebrate deposits except bone bed 43 where 500μm-1mm charcoal is more common. The >2.5mm size fraction is absent within quarry 11 and bone bed 43 and rare in the other two studied sites. Lateral and vertical samples through bone bed 50 show that charcoal is consistently present throughout the bone bed (Fig. 5.5).

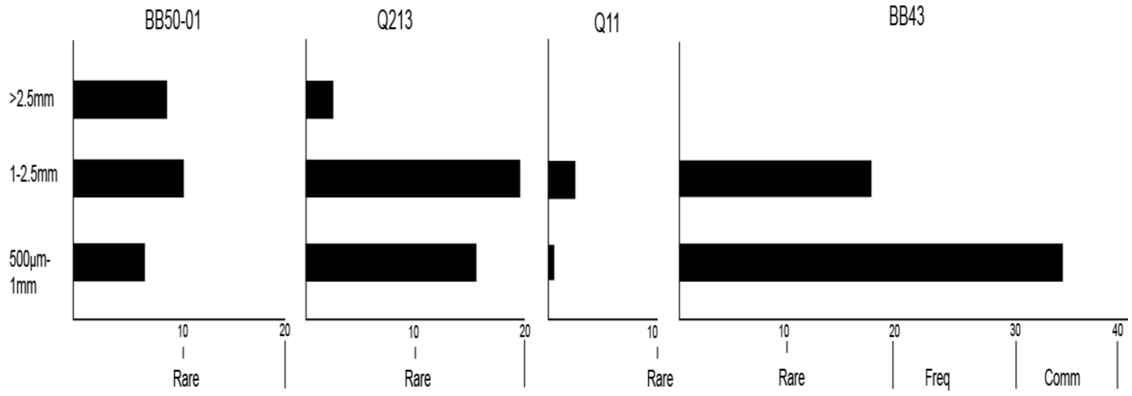


Fig. 5.4 Domin classification and numerical cover value for charcoal in a 20g subsample from the four vertebrate deposits of the Dinosaur Park Formation.

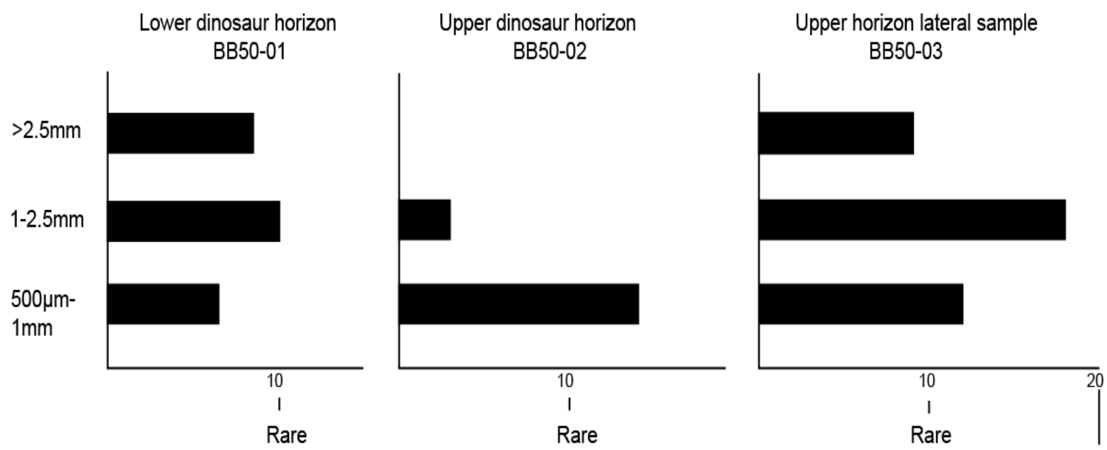


Fig. 5.5 Domin classification and numerical cover value for charcoal within 20g subsamples from bone bed 50. The bone bed was split into two 0.5m dinosaur rich horizons, with the lateral sample taken approximately 4m from the upper horizon sample. There is charcoal present throughout bone bed 50.

5.3.2 General occurrence of charcoal

The vertebrate deposits contain greater abundance of charcoal than the lithological units in comparable stratigraphic positions in the main stratigraphic sequence studied (DPP-10-1, refer to Chapter 4- section 4.3 for full succession and relative charcoal abundances). Charcoal is present in various beds with isolated bones or no bones elsewhere within the Dinosaur Park Formation (DPP-1-10) including the lowermost 25m of the Formation which corresponds to the relative position of the vertebrate deposits. Typically these other lithological units have a charcoal domin classification of rare with very low numerical values (Fig. 5.6).

Charcoal abundances within the studied vertebrate deposits are compared with sediments containing isolated bones and no bones (Fig. 5.7). The vertebrate deposits have greater abundances of charcoal than sediments containing isolated bones and sediments containing no bones. Palaeochannel sandstones lacking bones contain less charcoal than vertebrate deposits from the same lithofacies (Fig. 5.7). Therefore, charcoal relative abundance is not simply a function of sedimentological context.

5.3.3 Plant organs and particle shapes

Fifteen charcoal fragments were analysed using SEM (Chapter 3- section 3.3.5). The charcoal assemblages for all the vertebrate deposits contained wood fragments only (Fig. 5.8). The charcoal pieces were predominantly cubic or lath like in shape. Analysis of charcoal through SEM shows that the charcoal assemblages are dominated entirely by gymnosperm wood, with no angiosperm wood recorded.

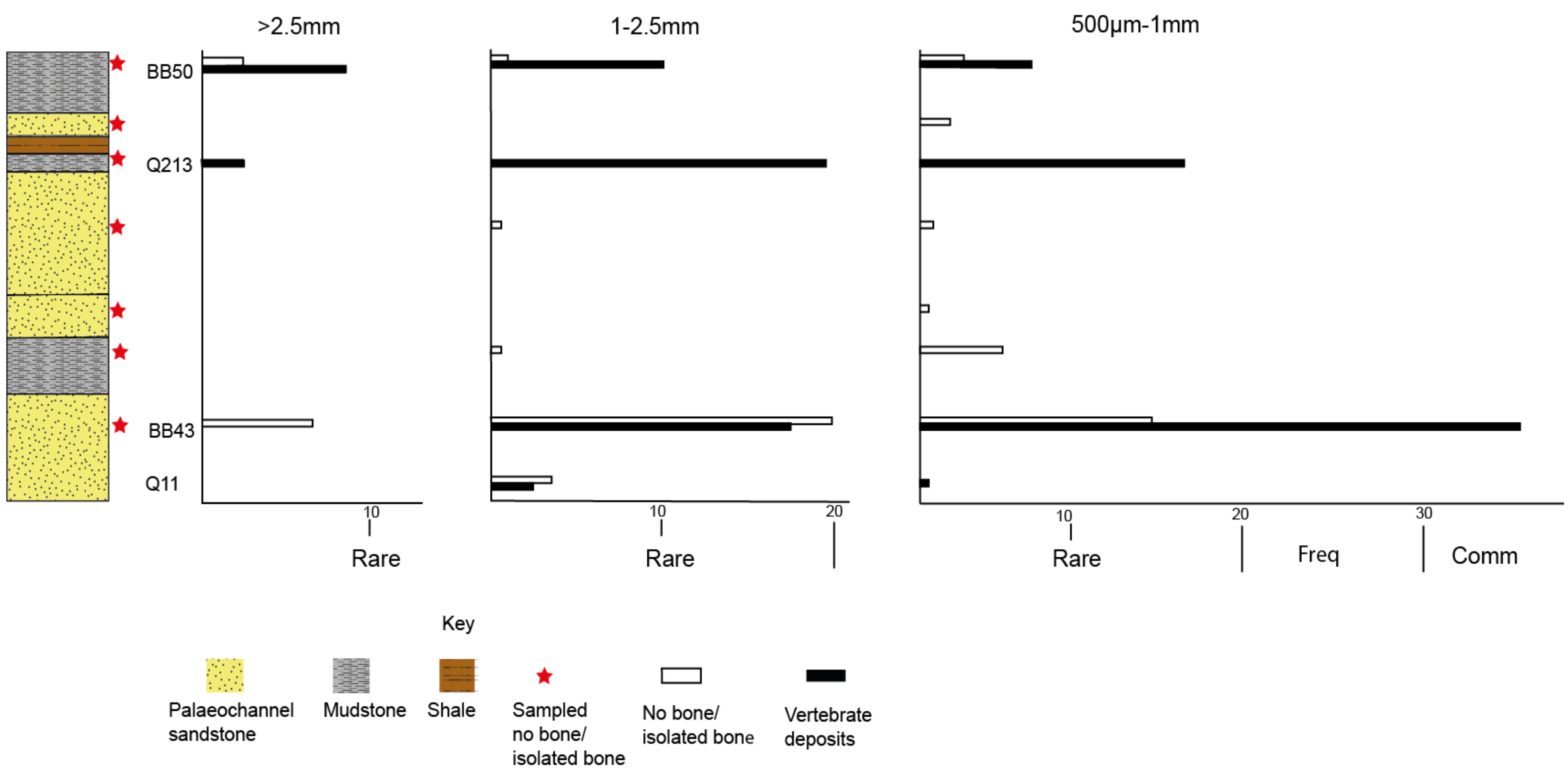


Fig. 5.6 Domin classification and numerical cover values at the lowermost 25m of the Dinosaur Park Formation (see Chapter 4 for full sedimentary succession, domin classifications and numerical cover values at DPP-10-1). The vertebrate deposits have been correlated to the relevant position in the main stratigraphic sequence (DPP-10-1), based upon height above the Oldman/ Dinosaur Park Formation contact. The data shows that there is less charcoal in the main stratigraphic sequence than in the vertebrate deposits.

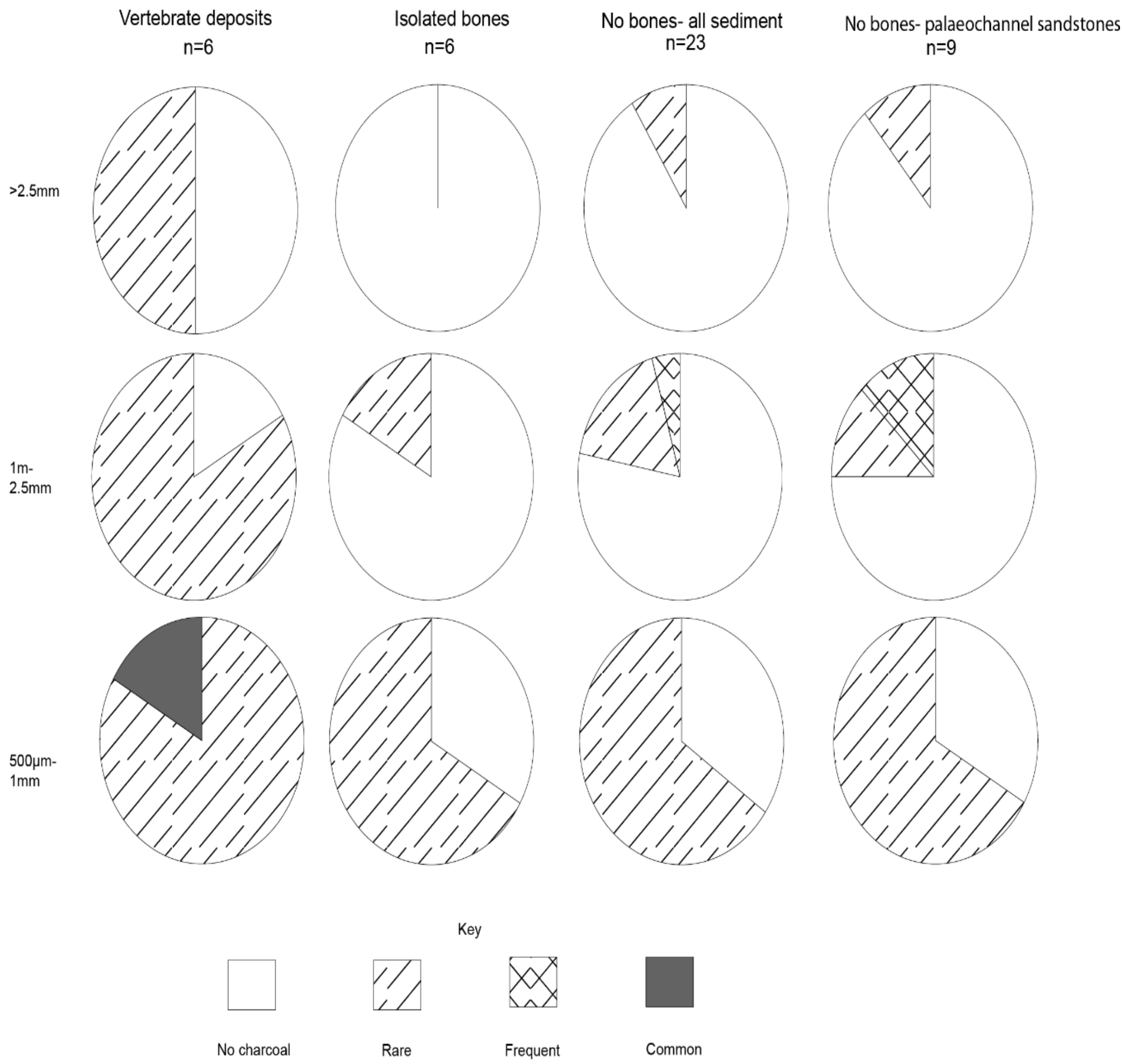


Fig. 5.7 The proportions of domin classifications for charcoal abundances within 20g samples from vertebrate deposits and the 70m of the Dinosaur Park Formation (DPP-10-1, refer to Chapter 4-section 4.3 for further information regarding charcoal distribution within DPP-10-1) showing that charcoal is more abundant in vertebrate deposits than in sediments with isolated bones or no bones including those in identical lithofacies i.e. palaeochannel sandstones

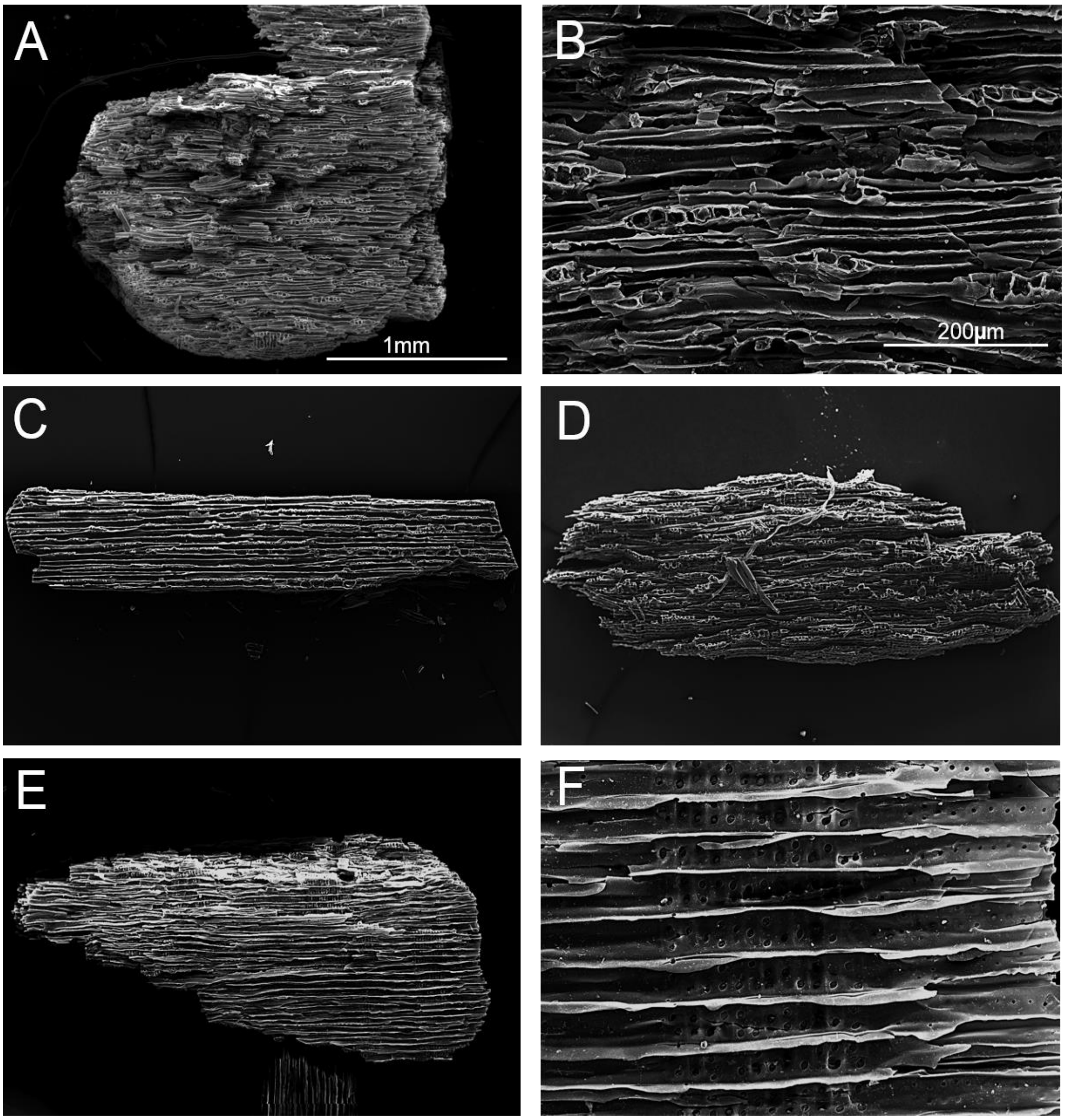


Fig. 5.8 Gymnosperm wood charcoal particles from the Campanian vertebrate deposits in the Dinosaur Park Formation, showing the range or particle shapes and enlargements of key features. A and B- tangential section of conifer wood with short uniseriate rays from BB43, C- gymnosperm wood from Q11, D- gymnosperm wood from Q213, E and F- gymnosperm wood with bordered and cross field pits. A, C-E have a 1mm scale. B and F have a 200µm scale.

5.4 DISCUSSION AND CONCLUSIONS

The Dinosaur Park Formation has been researched extensively since the early twentieth century; however due to the failure to recognise charcoal in the sediments, wildfires have previously never been considered as part of the ecosystem in which the dinosaurs lived. This new evidence of charcoal occurrence demonstrates the presence of wildfires through the time interval during which vertebrate deposits accumulated in the Campanian of present day Alberta, Canada.

Charcoal is present within all four of the sampled vertebrate deposits, especially in the 1mm-2.5mm and 500μm-1mm size fractions. Charcoal is more abundant in the vertebrate deposits than in the sediments with isolated bones or no bones; particularly in the 500μm-1mm size fraction. The palaeochannel sandstones that include the vertebrate deposits have greater charcoal abundance when compared with palaeochannel sandstones containing no bones. This suggests that post-fire sediment erosion and transportation (Chapter 1- section 1.4) may have been a factor in producing the vertebrate deposits.

Lovelace (2006) invoked a low gradient debris flow produced as a result of water saturated slope failure due to destabilisation following a wildfire to explain the formation of a Jurassic vertebrate deposit containing charcoal. Sweetman and Insole (2010) invoked debris flows produced by flooding entraining surface material to explain the formation of Barremian plant beds containing both dinosaurs and charcoal. In order to interpret the vertebrate deposits within the Dinosaur Park Formation, it is therefore important to consider the distinguishing characteristics of debris flow events and flooding events (water flow and hyperconcentrated flow) all of which can result from rainfall following fires. These events and their potential roles in bone bed formation are discussed in Chapter 8 (sections 8.2.2-8.2.3).

Chapter 6:

Temporal and environmental distribution of charcoal in the Maastrichtian of Alberta, Canada

6.1 INTRODUCTION

Evidence for Campanian charcoal within Alberta has been documented in Chapter 4, increasing knowledge of wildfire occurrence during that time interval. However, in order to address the fewer recorded Campanian and Maastrichtian charcoal data points, with respect to modelled atmospheric oxygen (Chapter 2- Fig. 2.5), Maastrichtian sediments also need to be investigated. The area surrounding the town of Drumheller, Alberta (Fig. 6.1), contains a 400m succession of sediments dating to the Maastrichtian. The majority of deposition occurred on a low-relief fluvially influenced coastal-alluvial plain, similar to the depositional environment of the Oldman and Dinosaur Park Formations (Chapter 4). The expanse of Maastrichtian sediments, coupled with a comparable depositional environment, represents a suitable test locality to further investigate Late Cretaceous charcoal distribution.

60 lithological samples from the Horseshoe Canyon, Battle and Scollard Formations (up to the K-Pg boundary) (Table 6.1) have been analysed to determine the presence/absence of charcoal, and to investigate the temporal distribution of charcoal throughout approximately 9.5Ma of sediments. Observations of palaeoclimatic conditions and palaeoenvironments have been undertaken in order to investigate potential controls on charcoal occurrence and distribution.

A small lateral comparison section (27 additional lithological samples) has been sampled with the aim of determining variation in spatial distribution of charcoal, and to establish the extent of wildfire influence during deposition of this part of the sequence. A focus on the type of lithologies and their charcoal content will establish whether wildfires were restricted to particular areas within the depositional catchment.

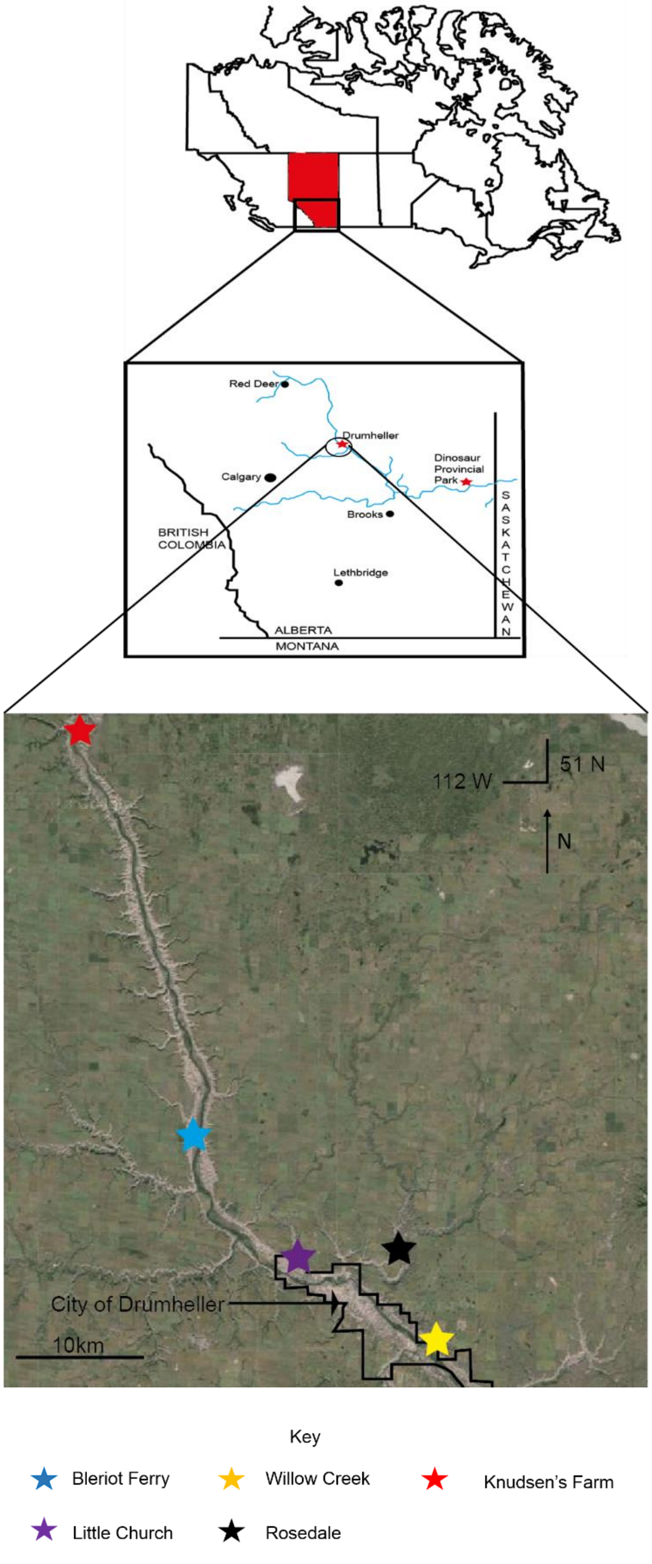


Fig. 6.1 Location map of Canada highlighting Alberta, enlarged locality map of Southern Alberta and enlargement of Drumheller with sampling locations shown with stars. Source- www.googleearth.com

Stage/Period	Age	Coal No.	Member	Formation	Locality
Paleogene	65.2±0.7	#13		Scollard Fm	Knudsen's Farm
Maastrichtian	66.8Ma			Battle Fm	Knudsen's Farm
			Whitemud Member	Horseshoe Canyon Fm	Knudsen's Farm
	67.5Ma	#12	Carbon Member		Knudsen's Farm
	68.4Ma	#11	Tolman Member		Knudsen's Farm
	70.6Ma	#10	Morrin Member		Bleriot Ferry
		#9 #8 #7	Horsethief Member		Little Chruch
	~71.5Ma	#6 #5 #4 #3 #2 #1 #0	Drumheller Member		Rosedale/ Willow Creek
	74.98Ma			Bearpaw Fm	Not exposed

Table 6.1- Sedimentary succession exposed at Drumheller with ages, coal numbers and outcrop location shown. Within this thesis all of the Drumheller Member is considered to be Maastrichtian in age. Much of the literature places the Campanian/Maastrichtian boundary between the Morrin and Tolman Members. However the 2013 International Geologic Timescale places the Campanian /Maastrichtian boundary at 72.1Ma. This date will be used for the boundary throughout this chapter and thesis, therefore treating all the Horseshoe Canyon Formation as Maastrichtian. (After Obradovich, 1993; Hamblin, 2004; Ogg et al., 2004; Eberth and Deino, 2005; Eberth and Braman, 2012; Cohen et al., 2013; Eberth et al., 2013)

6.2 MATERIALS AND METHODS

6.2.1 Methodology

In order to document charcoal distribution and relative abundance within the sediments of the Horseshoe Canyon, Battle and Scollard Formations, sampling was undertaken for lithological units throughout a 400m sedimentary succession using roadside, riverside and badland outcrops at five localities: Willow Creek (GPS: base-12:0393633;5693269; top- 12:0393637;5693415), Rosedale (GPS: base-12:0385958;5697679; top- 12:0385792;5697686), Little Church (GPS: base-12:0375192;5704734; top- 12:0375192;5704372), Bleriot Ferry (GPS: base-12:0369723;5714437; top- 12:0370084;5714373), and Knudsen's Farm (GPS: base-12:0361720;5751667; top- 12:0361479;5622811) (Figs. 6.1-6.2, Table 6.1). Thirteen sub-bituminous coal seams, extending from the Horseshoe Canyon Formation into the Scollard, have previously been mined (Eberth and Braman, 2012). The localities and sedimentary successions were correlated through the use of these numbered coal seams (Table 6.1). These coal seams were thin, and did not exceed a thickness of 1m. Mining had ceased prior to the time of fieldwork. The selection of these localities was based on landowner permission, accessibility, and the completeness of the exposed Formations.

Due to the extent of the sedimentary succession, sampling was undertaken at approximately 5m intervals throughout the sequence, with the aim of encompassing sediments from all lithologies, Members and Formations. This sampling strategy excluded all coal seams and thin shale units directly underlying the coals.

In addition to the main sedimentary succession, sampling was also undertaken for a small lateral comparison succession in order to record any variation in charcoal distribution. A sedimentary succession at Rosedale was selected as it also contained sediments that spanned from coal #2 to coal #4 within the Drumheller Member of the Horseshoe Canyon Formation (Fig 6.1, Table 6.1). Due to the smaller sedimentary succession, sampling was undertaken for each lithological unit between coal #2 and coal #4 for each locality, using the same methodology as Chapter 4. The lateral succession at Rosedale is located approximately 10km from the succession at Willow Creek.

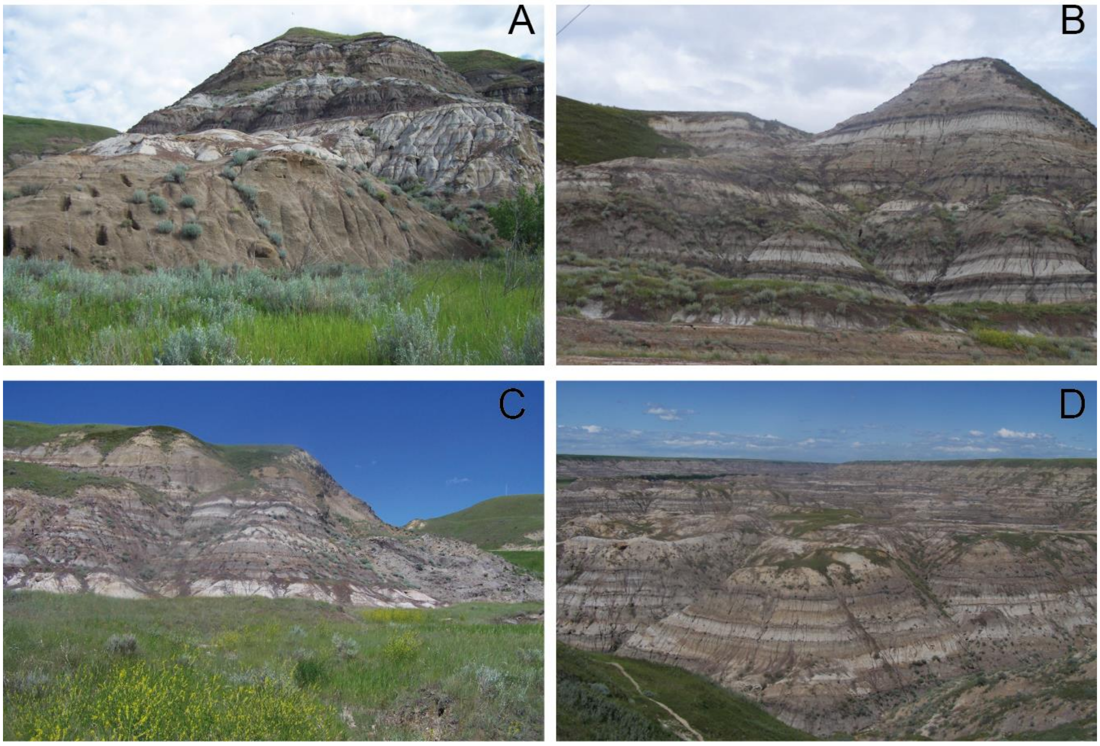


Fig. 6.2 Badland terrain at sampled Drumheller localities. A- Willow Creek, B-Rosedale, C-Little Church, D- Knudsen's Farm

For each locality, generalised lithological logs were constructed in the field and lithological units were sampled, irrespective of whether charcoal was visible to the naked eye. Samples were processed and charcoal quantified according to the methodology outlined in Chapter 3 (section 3.3).

The boundaries between Members and Formations were identified through proximity to numbered coal seams, along with sediment composition and reference to the literature. However, due to the badland topography and the urbanisation of Drumheller, the majority of lithological units cannot be traced laterally for more than a few metres. Many of the Members within this succession have been dated (Table 6.1), therefore charcoal distributions can be constrained within broad time intervals.

6.2.2 Palaeoclimate and Palaeoenvironmental context

The latest Campanian to end Maastrichtian in Alberta was marked by palaeoclimatic changes. The warm and seasonally wet palaeoclimate experienced during the deposition of the Campanian Dinosaur Park Formation (for more detailed palaeoclimatic information refer to Chapter 4- section 4.3) had cooled and become drier by the Maastrichtian (Brinkman, 2003). This climatic change is highlighted by a decrease in turtle diversity across Alberta from the late Campanian onwards, and is supported by leaf margin analysis (Upchurch and Wolfe, 1993; Brinkman, 2003). The Maastrichtian of Alberta was marked by alternating warm and wet, and cool and dry phases throughout the Horseshoe Canyon, Battle and Scollard Formations (Larson et al., 2010; Eberth and Braman, 2012; Eberth et al., 2013).

The Horseshoe Canyon Formation lies conformably over the marine Bearpaw Formation (Fig. 7.2), with a total outcropping thickness of 267m in Drumheller (Straight and Eberth, 2002; Brinkman and Eberth, 2006). Analysis of palaeosols has indicated mean annual temperatures for the deposition of the whole Formation ranging from 9°C-11°C, with mean annual rainfall between 840mm/year-1020mm/year (Quinney et al., 2013).

The lower part of the Drumheller Member was deposited on a fluvially influenced coastal plain, with estuarine and shoreface channels (Eberth and Braman, 2012). The lithologies are dominated by palaeochannel sandstones, interfluvial mudstones and coals. The upper part of the Member was deposited on a prograding coastal plain (Eberth and Braman, 2012). The dominant lithologies remain the same as the lower part of the Member, however there are thicker coal seams. Climatic conditions were believed to be warm and wet, indicated through the presence of *Adocus* (large turtle species) along with crocodylians, low abundances of amphibians and pedogenic features indicative of poor drainage (Larson et al., 2010; Eberth and Braman, 2012; Eberth et al., 2013; Quinney et al., 2013). The increase in coal indicates a transition to saturated landscapes and higher fluctuating water tables throughout the deposition of this Member (Eberth and Braman, 2012; Quinney et al., 2013). The palynology of this Member indicates a dominance of gymnosperm pollen at 60.8% compared with 16.4% angiosperm pollen (Eberth and Braman, 2012 (palynological samples collected across the Red Deer River exposures)).

The Horsethief Member was deposited under the same climatic conditions as the Drumheller Member (Eberth and Braman, 2012). Deposition occurred on a fluvially influenced coastal to alluvial plain, with lithologies dominated by palaeochannel sandstones and interfluvial mudstones (Eberth and Braman, 2012). The presence of coals indicates a saturated landscape with high fluctuating water tables (Eberth and Braman, 2012; Quinney et al., 2013). Similar palynological information has been recorded for this Member with a dominance of gymnosperm pollen at 61.2% compared with angiosperm pollen at 16.4% (Eberth and Braman, 2012).

The deposition of the Morrin Member occurred at a time of fundamental changes in the palaeoclimate, with the start of a cool and dry phase that extended until the end of the Tolman Member (Eberth and Braman, 2012). The change in palaeoclimate has been identified through the decreasing abundance of turtles, absence of crocodylians and the increase in amphibian fossils found across Alberta (Eberth and Braman, 2012).

The Morrin Member was deposited on a well-drained fluvially influenced coastal plain, with the lithologies dominated by laminated sandstones and mudstones, with the presence of some palaeosols (Eberth and Braman, 2012). The presence of some coal units does indicate fluctuating water tables, with waterlogged conditions likely during the deposition of the coals (Quinney et al., 2013). Drier environmental conditions have also been suggested based on the greater abundances of angiosperm pollen at 27.4% compared with 49.5% gymnosperm pollen (Eberth and Braman, 2012).

The overall cool and dry palaeoclimatic conditions were present throughout the deposition of the Tolman Member, with seasonal rainfall indicated through the presence of vertisols (Eberth and Braman, 2012; Quinney et al., 2013). Deposition occurred on an alluvial plain with the lithologies dominated by palaeochannel sandstones and overbank mudstones (Eberth and Braman, 2012). The absence of coals indicates lower water tables and a lack of sediment saturation (Eberth and Braman, 2012). Palynology indicates a decrease in gymnosperm pollen at 33.3% and an increase in angiosperm pollen at 42.9% (Eberth and Braman, 2012).

The deposition of the Carbon Member occurred alongside a return to warm and wet palaeoclimatic conditions (similar to the deposition of the Drumheller Member), with evidence of crocodilian and turtle fossils, a decrease in amphibians and poorly drained palaesols (Larson et al., 2010; Eberth and Braman, 2012; Quinney et al., 2013). The presence of two coal horizons indicates a return to waterlogged conditions. The lithologies are dominated by palaeochannel sandstones. Palynology indicates an increase in gymnosperm pollen at 60.2% and a decrease in angiosperm pollen at 16%; similar in abundance to both the Drumheller and Horsethief Members (Eberth and Braman, 2012).

The Whitemud Member was deposited during cool and dry palaeoclimatic conditions (Larson et al., 2010) in a meandering stream and floodplain environment, with waterlogged conditions leading to the formation of swamps and small lakes (Eberth and Braman, 2012). This Member has been pedogenically altered after deposition, and has been heavily weathered (Eberth and Braman, 2012). The lithologies are dominated by sandstones and mudstones, with no visible sedimentary structures (Eberth and Braman, 2012). There is an absence of vertebrate fossils within this Member. Palynology indicates a decrease in gymnosperm abundance at 21.4% and an increase in angiosperm abundance at 53.4%.

The Battle Formation was deposited in a widespread shallow lake during a colder climatic phase (Binda, 1992; Srivastava, 1994). The lithologies are dominated by bentonitic mudstones, and includes the Kneehill's Tuff layer, a thin volcanic ash derived bentonitic bed (Srivastava, 1994). This Formation contains no previously documented vertebrate remains, and none were observed during this investigation (Brinkman and Eberth, 2006). In addition there is an absence of organic fossils, with only silicified fossils previously recorded (Binda, 1992). Palynology indicates similar proportions of gymnosperm and angiosperm pollen, with levels of 39.8% and 47.1% recorded (Eberth and Braman, 2012).

The Scollard Formation was deposited during a warm temperate palaeoclimatic phase (Srivastava, 1994). The lithologies are dominated by overbank mudstones, with thin palaeochannel sandstones, deposited on a fluvially influenced alluvial plain (Srivastava, 1994). The Nevis coal seam (#13) is located at the top of this section of the Scollard and marks the K-Pg boundary, along with an iridium spike (Srivastava, 1994). The presence of a coal seam indicates waterlogged conditions near the top of this part of the Formation. Palynology indicates a slight decrease in gymnosperm abundance at 23.9% and an increase in angiosperms at 51.3% (Eberth and Braman, 2012).

6.3 DISTRIBUTION OF CHARCOAL

Distribution presented in succession from oldest to youngest.

6.3.1 Drumheller Member- Horseshoe Canyon Formation

Fourteen lithological units were sampled from the Drumheller Member, the lower part sampled at Willow Creek and the upper part sampled at Rosedale (Fig. 6.3, Fig. 6.4). Ten units were found to contain charcoal. There are low relative abundances of charcoal distributed throughout the Member, dominated by the domin classification of rare, with low numerical cover values (below 10). Only a single unit (located in the lower part of the Member between coals #3 and #4) contained charcoal >2.5mm, along with charcoal with higher numerical cover values. Domin classifications of frequent were recorded for both the >2.5mm and 1mm-2.5mm size fractions, and a classification of rare with a higher numerical cover value (above 10) for the 500µm-1mm size fraction. Adjacent sampled lithological units did not contain similar elevated relative charcoal abundances.

Charcoal is contained within all three lithologies within the Drumheller Member (Fig. 6.5). However the domin classification of frequent is only recorded within sandstones, along with the presence of charcoal of >2.5mm and 1mm-2.5mm size fractions.

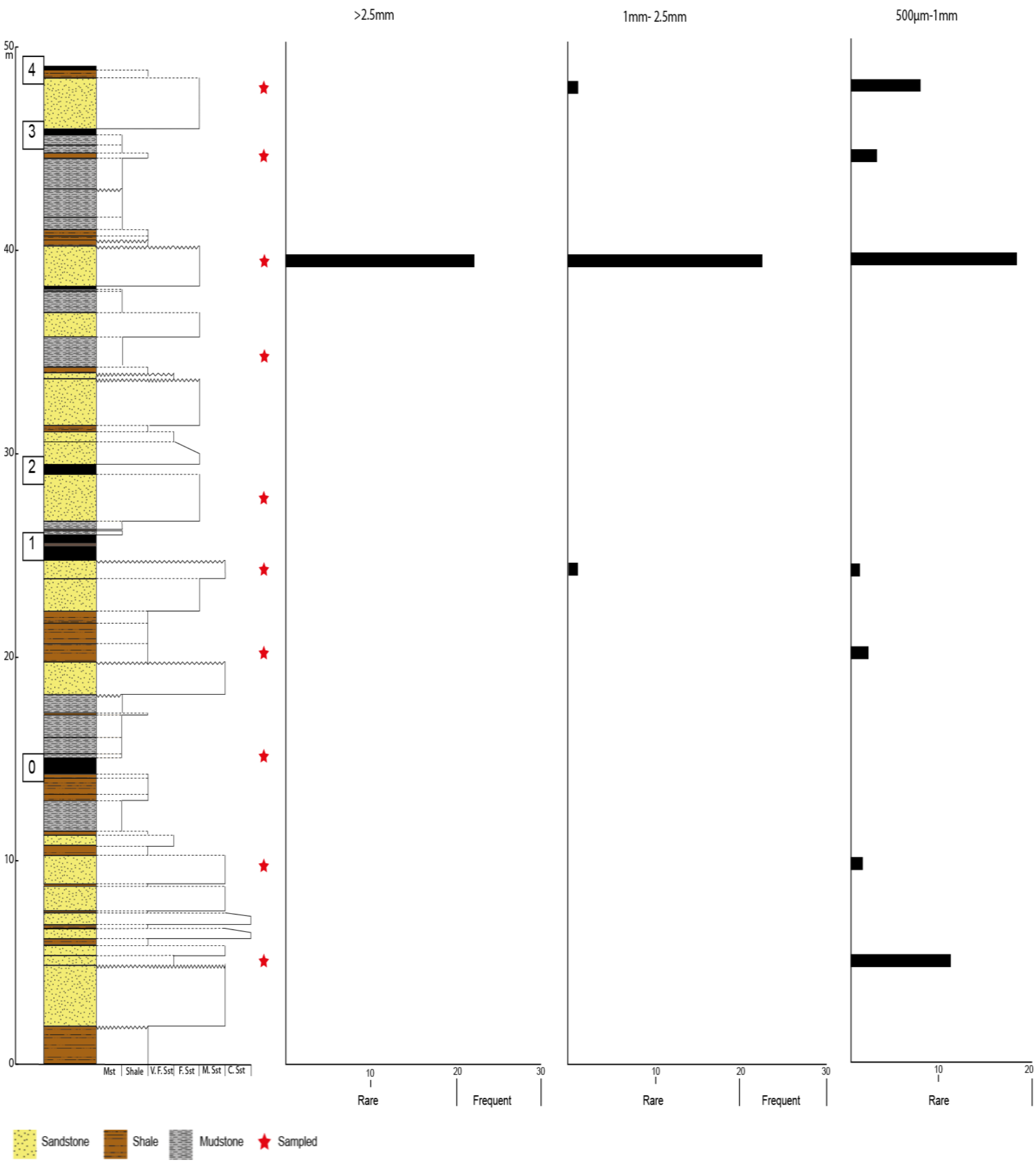


Fig. 6.3 Domin classification and numerical cover value for charcoal in 20g subsamples throughout the lower part of the Maastrichtian Drumheller Member of the Horseshoe Canyon Formation exposed at Willow Creek. The red stars indicate sampled lithological units. Mined coal seams have industry number located in a box adjacent to each of them.

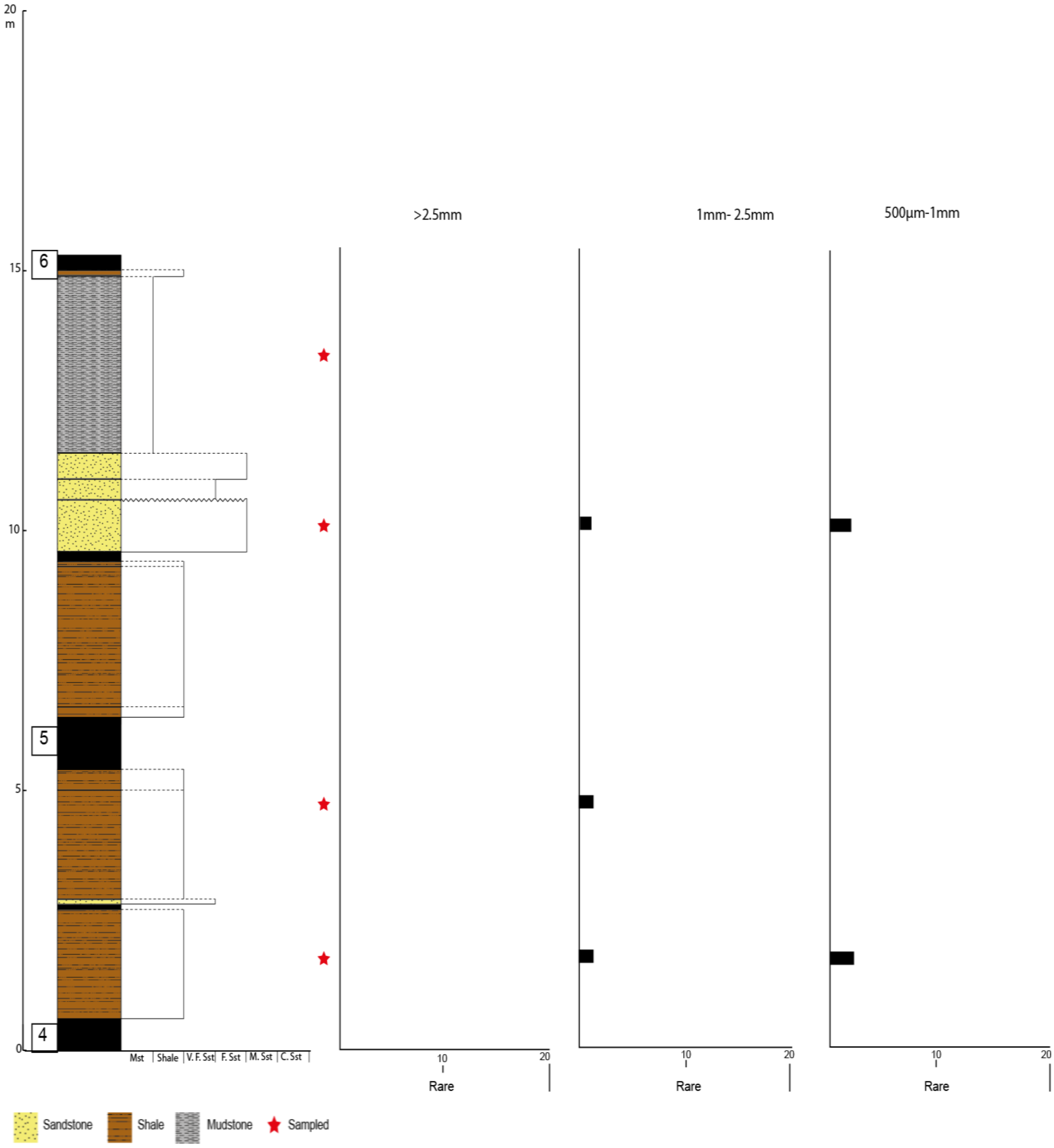


Fig. 6.4 Domin classification and numerical cover value for charcoal in 20g subsamples throughout upper part of the Drumheller Member of the Horseshoe Canyon Formation exposed at Rosedale. The red stars indicate sampled lithological units. Mined coal seams have industry number located in a box adjacent to each of them.

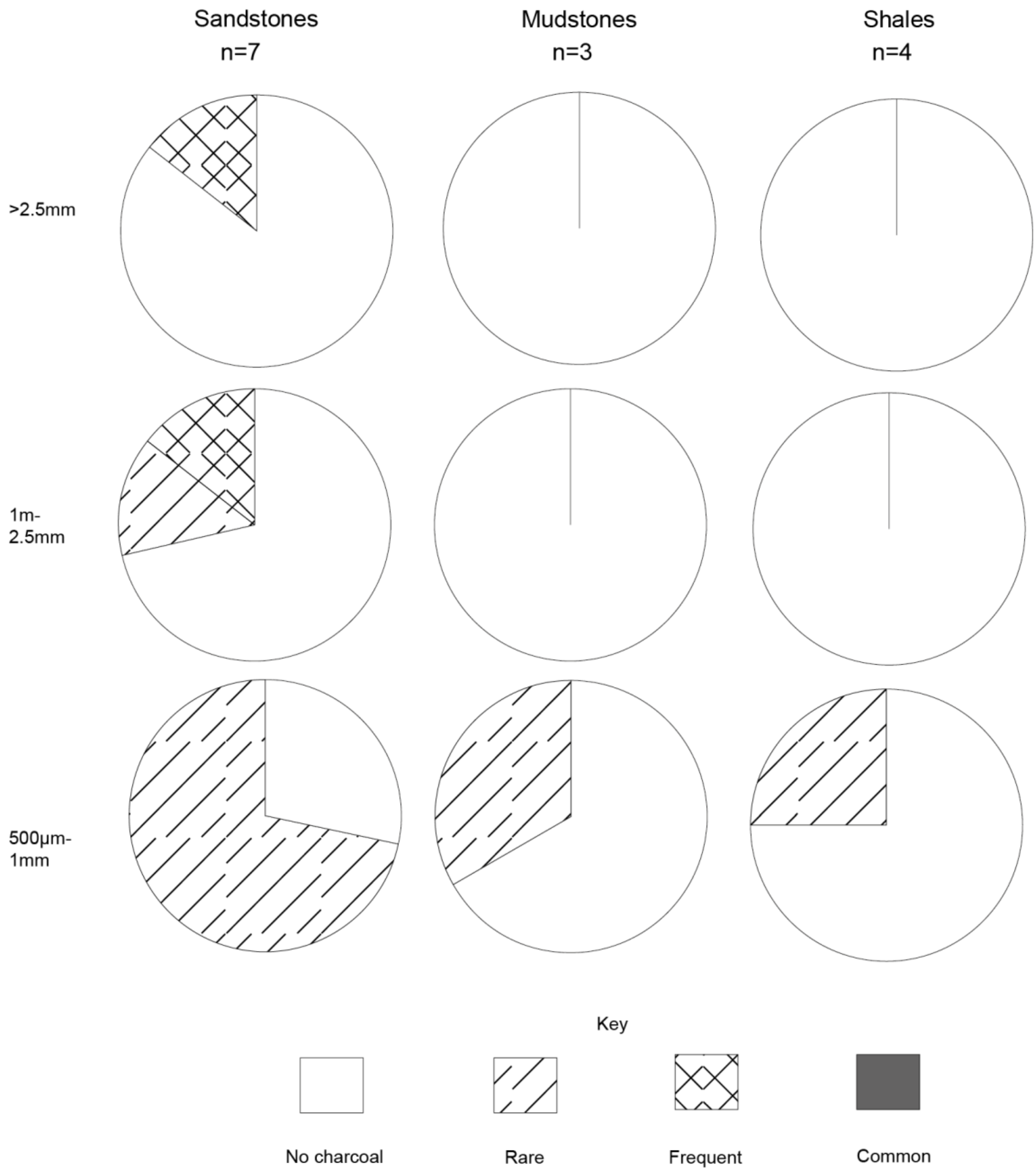


Fig. 6.5 The proportions of domin classifications for charcoal abundances within 20g samples from all sampled lithological units within the Drumheller Member of the Horseshoe Canyon Formation exposed at Willow Creek and Rosedale. Higher relative abundances are recorded within sandstones units. More samples contain 500µm-1mm sized charcoal.

6.3.2 Horsethief Member- Horseshoe Canyon Formation

Ten lithological units were sampled from the Horsethief Member at Little Church (Fig. 6.6). Five units were found to contain charcoal. There are low relative abundances of charcoal, with domin classifications not exceeding rare and low numerical cover values (below 10). Only a single unit (c.5m) contained charcoal with a higher numerical cover value (above 10). The lower part of the member (up to c.20m) contains the majority of lithological units containing charcoal, with a single unit in the upper part of the member containing charcoal belonging to the 1mm-2.5mm size fraction only.

Charcoal is contained within all three lithologies within the Horsethief Member (Fig. 6.7). Similar relative abundances of charcoal are recorded in all lithologies for all size fractions.

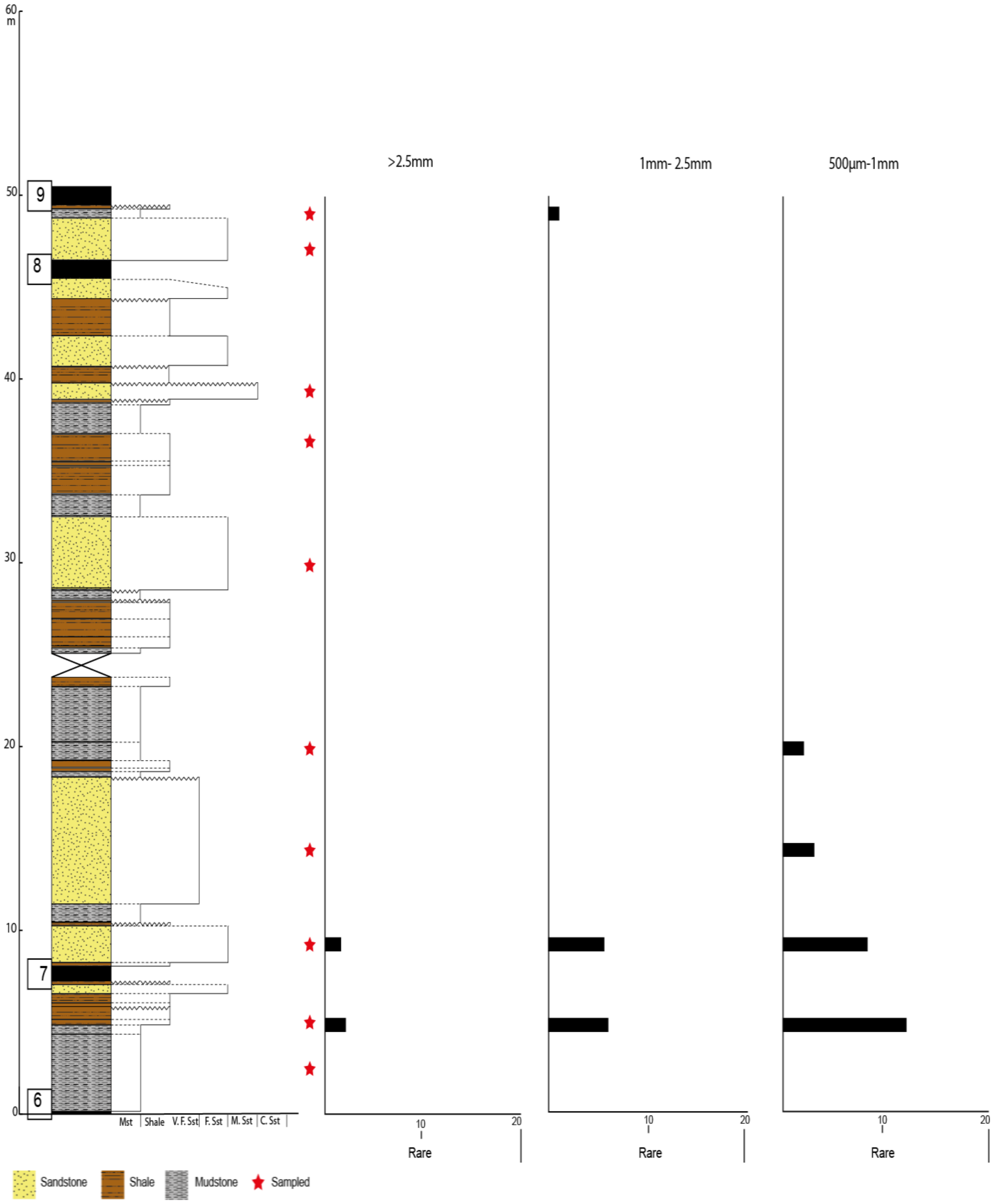


Fig. 6.6 Domin classification and numerical cover value for charcoal in 20g subsamples throughout the Maastrichtian Horsethief Member of the Horseshoe Canyon Formation exposed at Little Church. The red stars indicate sampled lithological units. Mined coal seams have industry number located in a box adjacent to each of them.

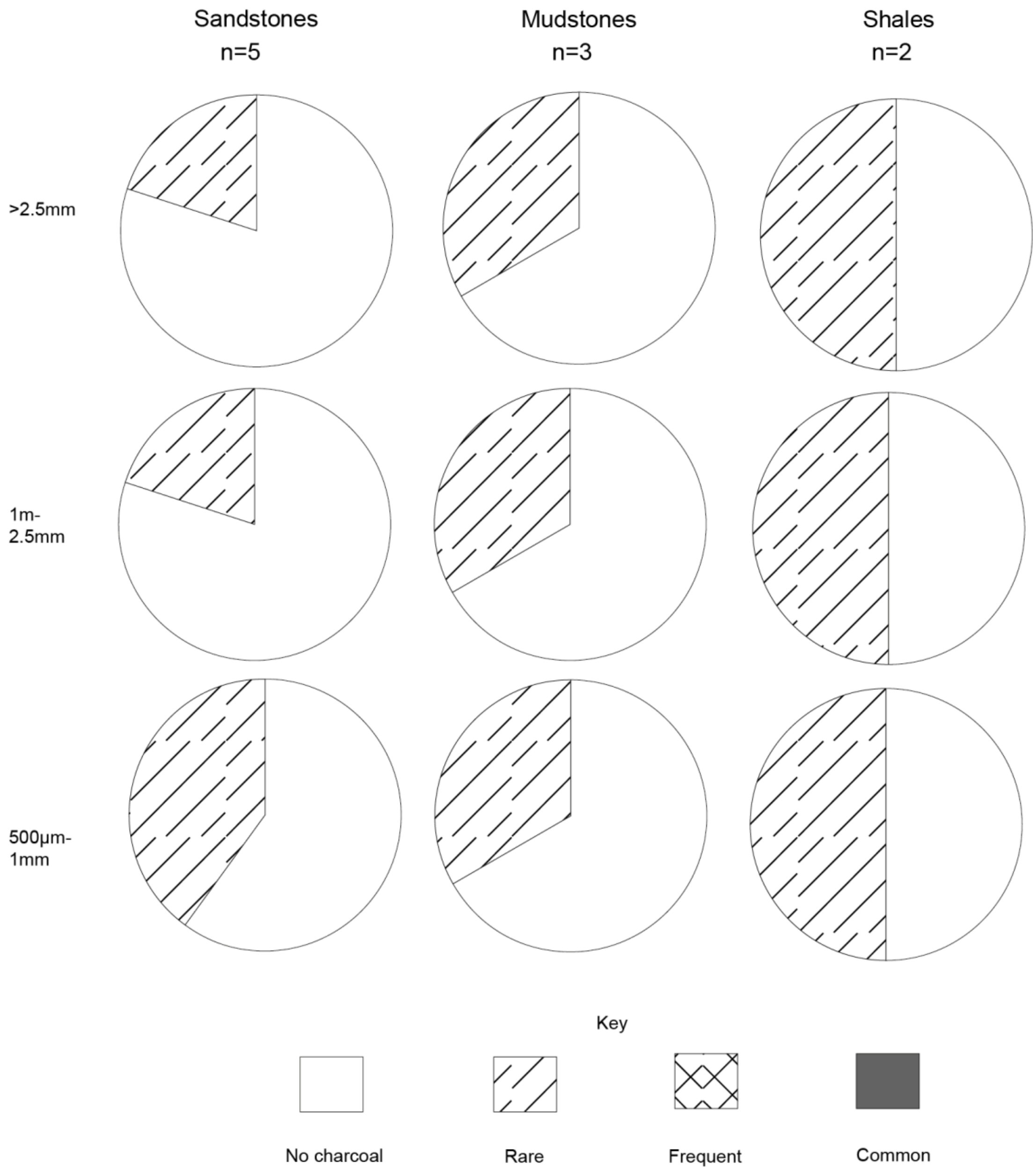


Fig. 6.7 The proportions of domin classifications for charcoal abundances within 20g samples from all sampled lithological units within the Horsethief Member of the Horseshoe Canyon Formation exposed at Little Church. Similar abundances of charcoal are contained within all three lithologies.

6.3.3 Morrin Member- Horseshoe Canyon Formation

Seven lithological units were sampled from the Morrin member at Bleriot Ferry (Fig. 6.8). Four units were found to contain charcoal, which were distributed throughout the Member. Low relative charcoal abundances are recorded in the middle of the Member (c.10m-c.25m) with domin classifications of rare and low numerical cover values (below 10).

Greater relative charcoal abundances were recorded near the base of this Member (c.3m), with domin classifications of frequent for both the 1mm-2.5mm and 500µm-1mm size fractions and rare, with a low numerical cover value (below 10) for the >2.5mm size fraction. Greater relative abundance of >2.5mm charcoal is recorded near the top of this Member (c.31m), with a domin classification of common. Domin classifications of rare were recorded for the other size fractions, with a high numerical cover value (above 10) for the 500µm-1mm size fraction.

Charcoal is recorded within the sandstones and shales within this Member, but is absent in mudstones for all size fractions (Fig. 6.9). Greater relative abundances are recorded for charcoal within sandstones, with domin classifications of frequent and common present.

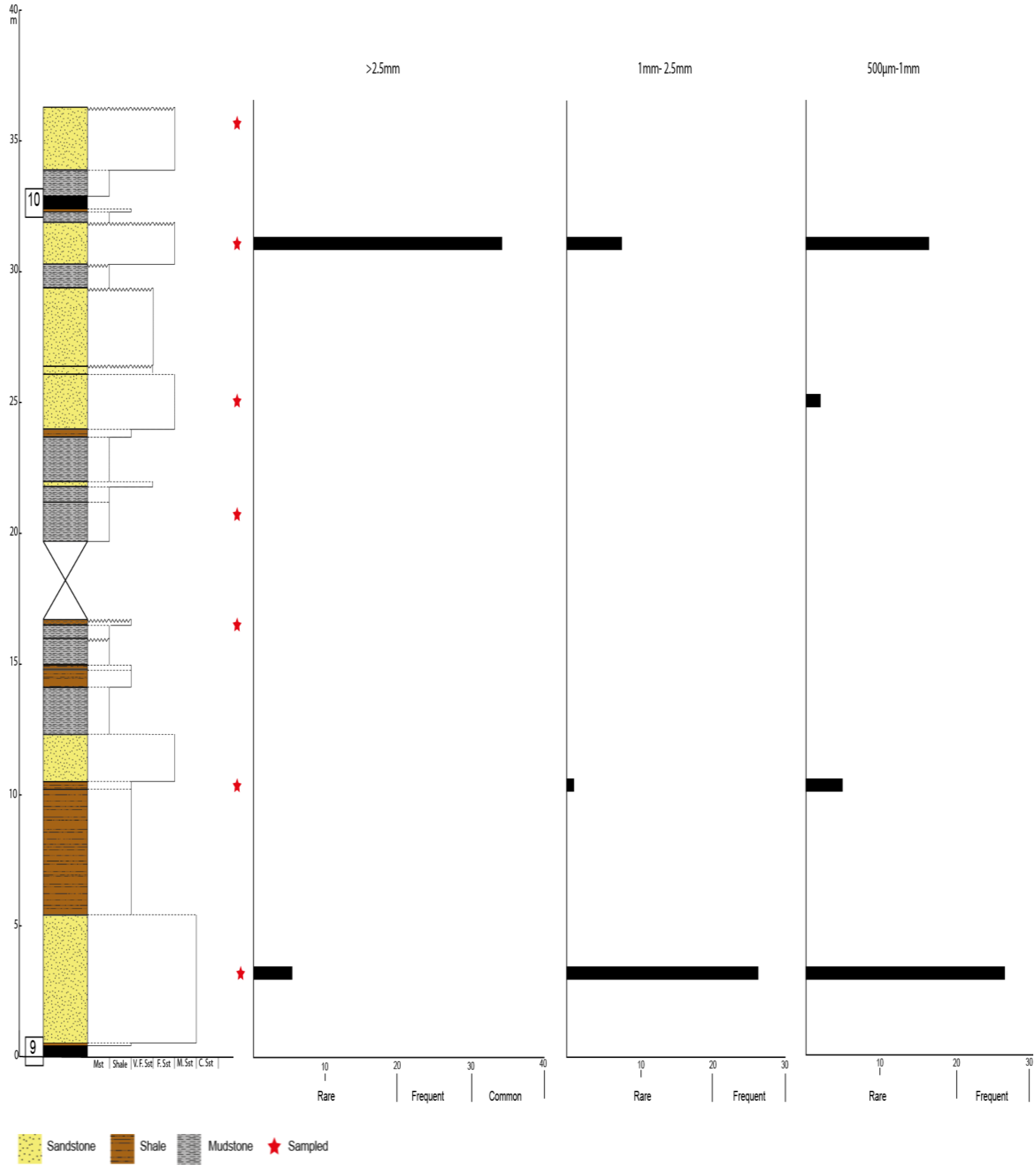


Fig. 6.8 Domin classification and numerical cover value for charcoal in 20g subsamples throughout the Maastrichtian Morrin Member of the Horseshoe Canyon Formation exposed at Bleriot Ferry. The red stars indicate sampled lithological units. Mined coal seams have industry number located in a box adjacent to each of them.

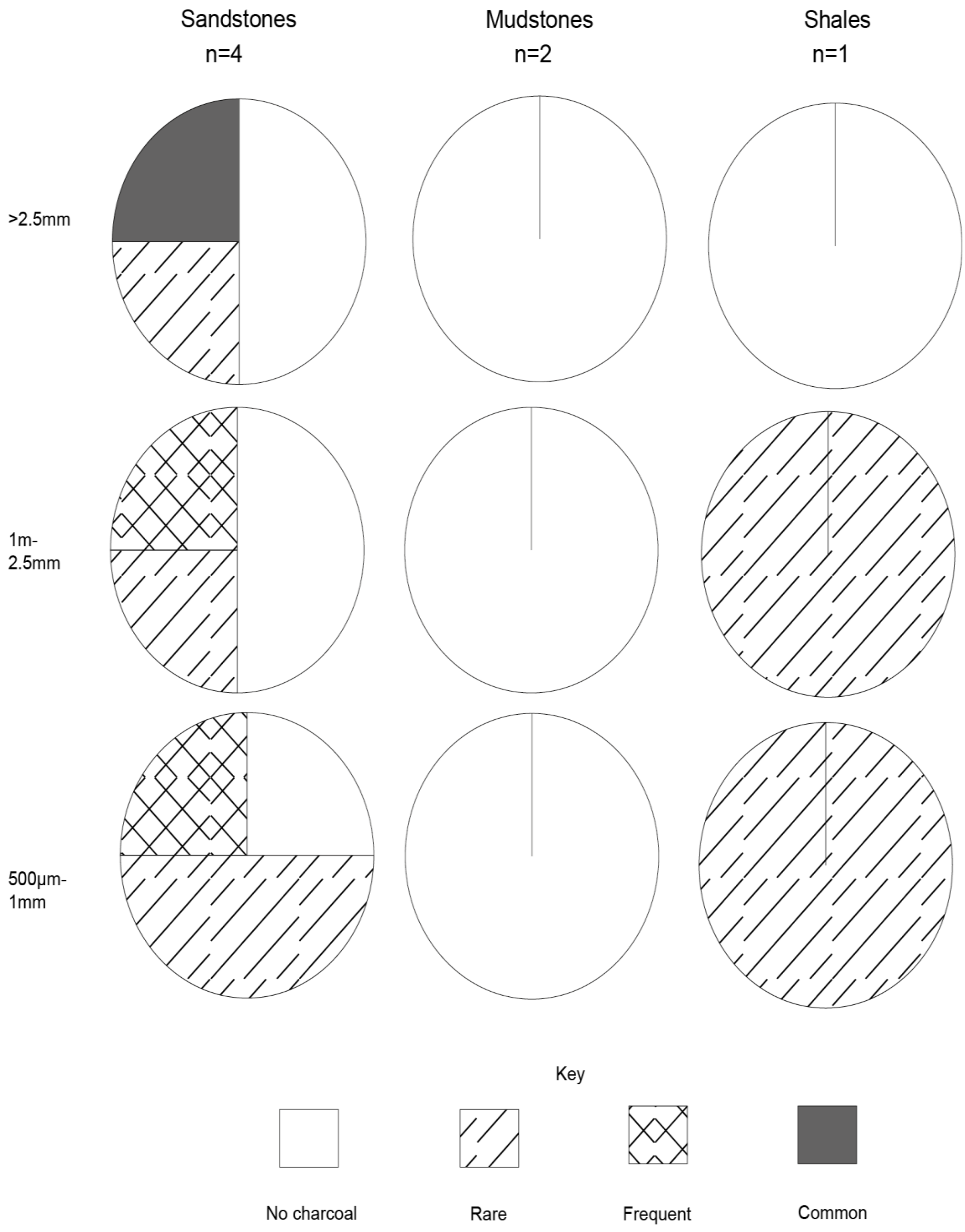


Fig. 6.9 The proportions of domin classifications for charcoal abundances within 20g samples from all sampled lithological units within the Morrin Member of the Horseshoe Canyon Formation exposed at Bleriot Ferry. Greater charcoal abundances are recorded within sandstone units.

6.3.4 Tolman, Carbon and Whitemud Members- Horseshoe Canyon Formation

Ten lithological units were sampled from the Tolman Member at Knudsen's Farm (Fig. 6.10). Two units were found to contain charcoal, both located near the base of the Member. There are very low relative abundances of charcoal, with domin classifications not exceeding rare and low numerical cover values (below 10). There is no charcoal > 2.5mm recorded.

Four lithological units were sampled from the Carbon Member at Knudsen's Farm (Fig. 6.10). Three units were found to contain charcoal. There are low relative abundances of charcoal with domin classifications not exceeding rare and low numerical cover values (below 10). There is no charcoal >2.5mm recorded. One lithological unit was sampled from the Whitemud Member at Knudsen's Farm (Fig. 6.10). It does not contain charcoal of any size fraction (Fig. 6.10).

There is no charcoal belonging to the >2.5mm size fraction. Greater relative abundances of charcoal are recorded in the mudstone units for both the 1mm-2.5mm and 500µm-1mm size fraction (Fig. 6.11).

6.3.5 Battle Formation

Two lithological units were sampled from the Battle Formation at Knudsen's Farm (Fig. 6.10). There is no charcoal of any size fraction (Fig. 6.10).

6.3.6 Scollard Formation

Twelve lithological units were sampled from the Scollard Formation at Knudsen's Farm (Fig. 6.10). Three units were found to contain charcoal. There are low relative abundances of charcoal, with domin classifications not exceeding rare and low numerical cover values (below 10). There is no charcoal >2.5mm recorded. Charcoal bearing units are located towards the top (c.100m and c.125m-c.130m) of the sampled section of this Formation.

Charcoal is recorded within the mudstones and shales within this Formation but is absent from sandstones for all size fractions (Fig. 6.12).

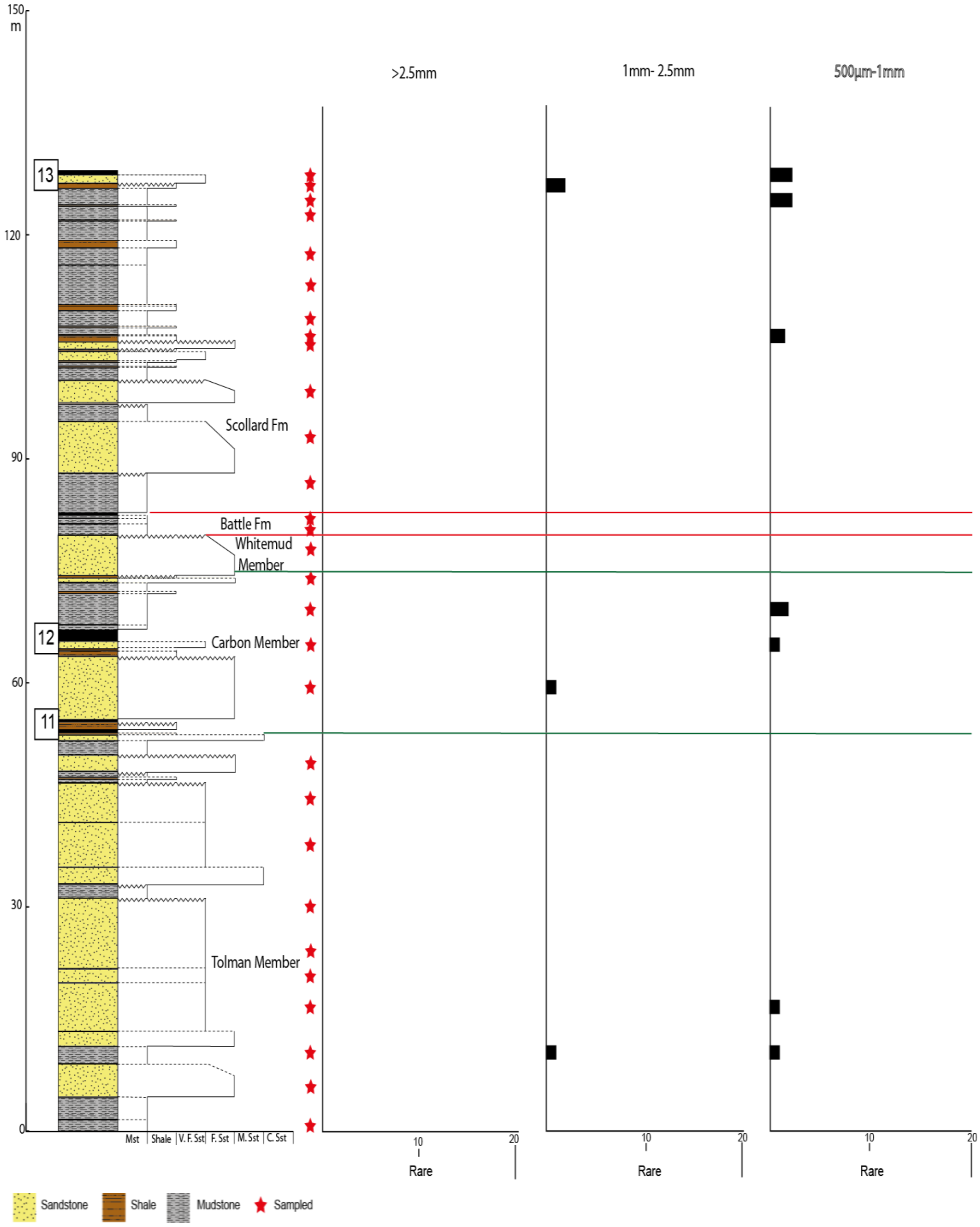


Fig. 6.10 Domin classification and numerical cover value for charcoal in 20g subsamples throughout the Maastrichtian Tolman, Carbon and Whitemud Members of the Horseshoe Canyon Formation, Battle Formation and Scollard Formation exposed at Knudsen's Farm. The red stars indicate sampled lithological units. Mined coal seams have industry number located in a box adjacent to each of them.

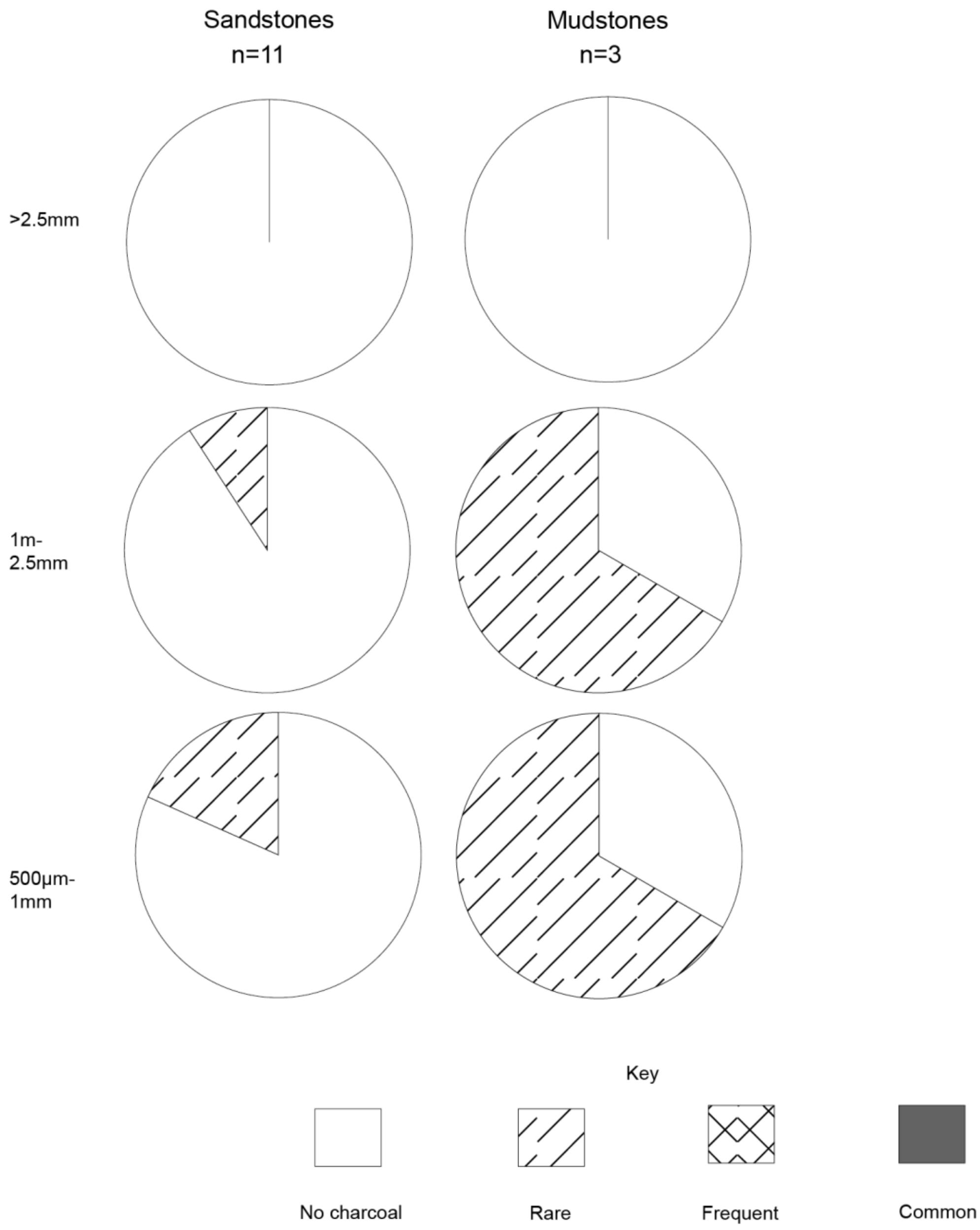


Fig. 6.11 The proportions of domin classifications for charcoal abundances within 20g samples from all upper Horseshoe Canyon Formation Members (Tolman, Carbon and Whitemud Members) exposed at Knudsen's Farm. There is an absence of shales. Greater charcoal abundances are recorded in the mudstones.

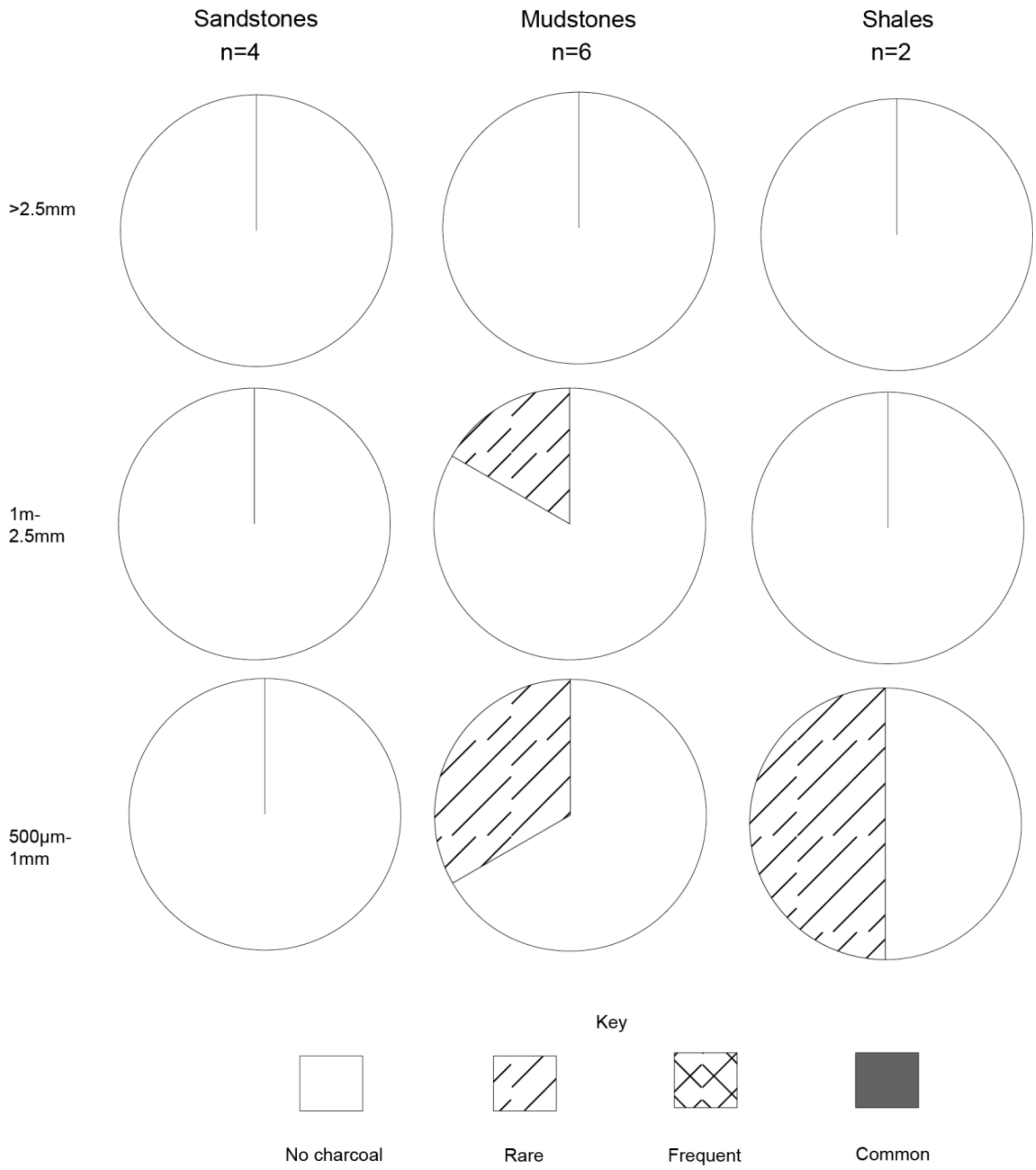


Fig. 6.12 The proportions of domin classifications for charcoal abundances within 20g samples from all sampled lithological units within the Scollard Formation exposed at Knudsen's Farm. Greater charcoal abundances are recorded in the mudstone and shale units.

6.3.7 Plant organs and particle shapes

Thirty-one charcoal fragments were analysed using SEM (Chapter 3- section 3.3.5). The charcoal assemblages for all Formations contained a very limited range of plant organs, and were dominated almost entirely by wood fragments (Fig. 6.13, 6.14). Some small twiglets and a single leaf fragment were also recorded (Fig. 6.13-E, 6.14-A). The charcoal pieces were predominantly cubic or lath like in shape. Analysis of charcoal through SEM shows that the charcoal assemblages are dominated by gymnosperm wood throughout the 9Ma succession. Angiosperm wood was recorded in two charcoal pieces only (Fig. 6.14-E-F).

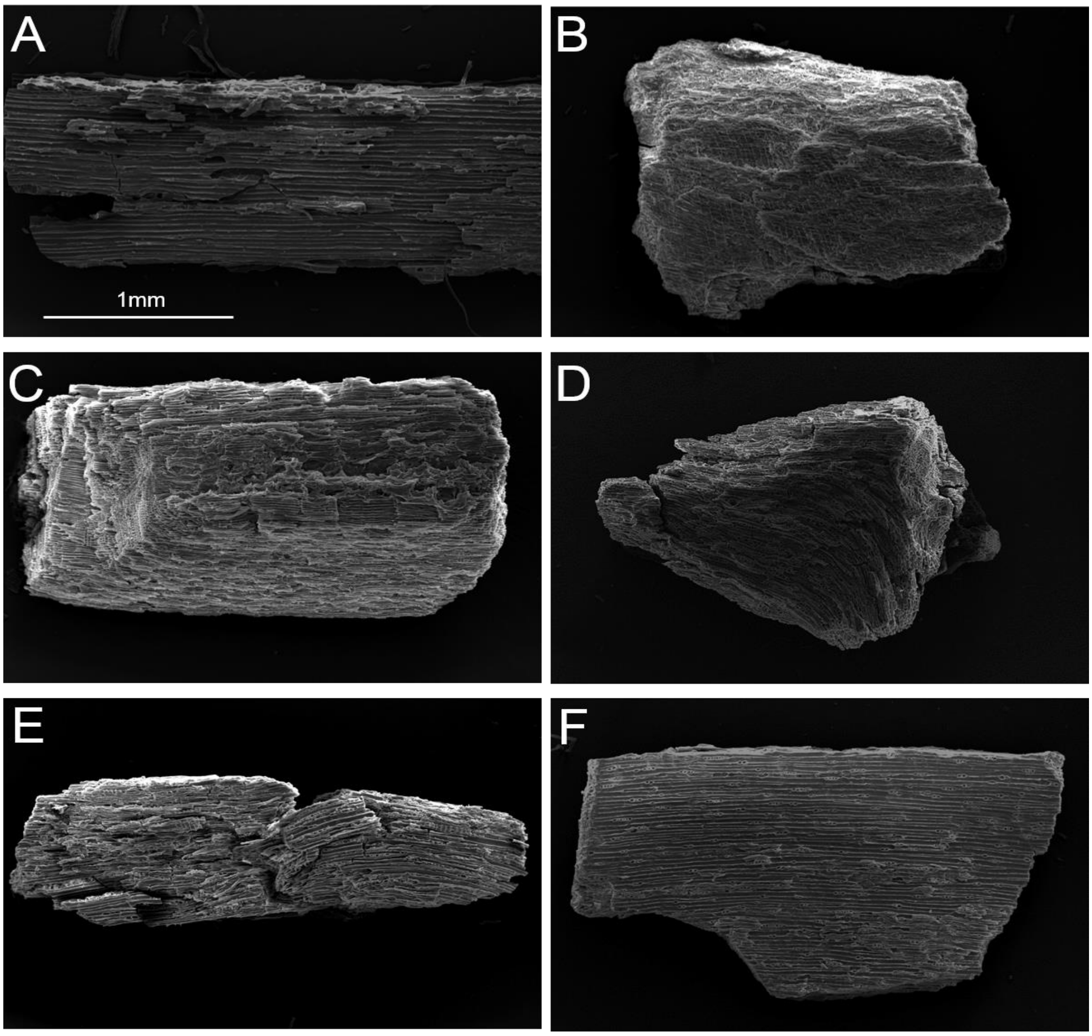


Fig. 6.13 Range of wood charcoal particle shapes from the Maastrichtian of Drumheller. All images same scale.

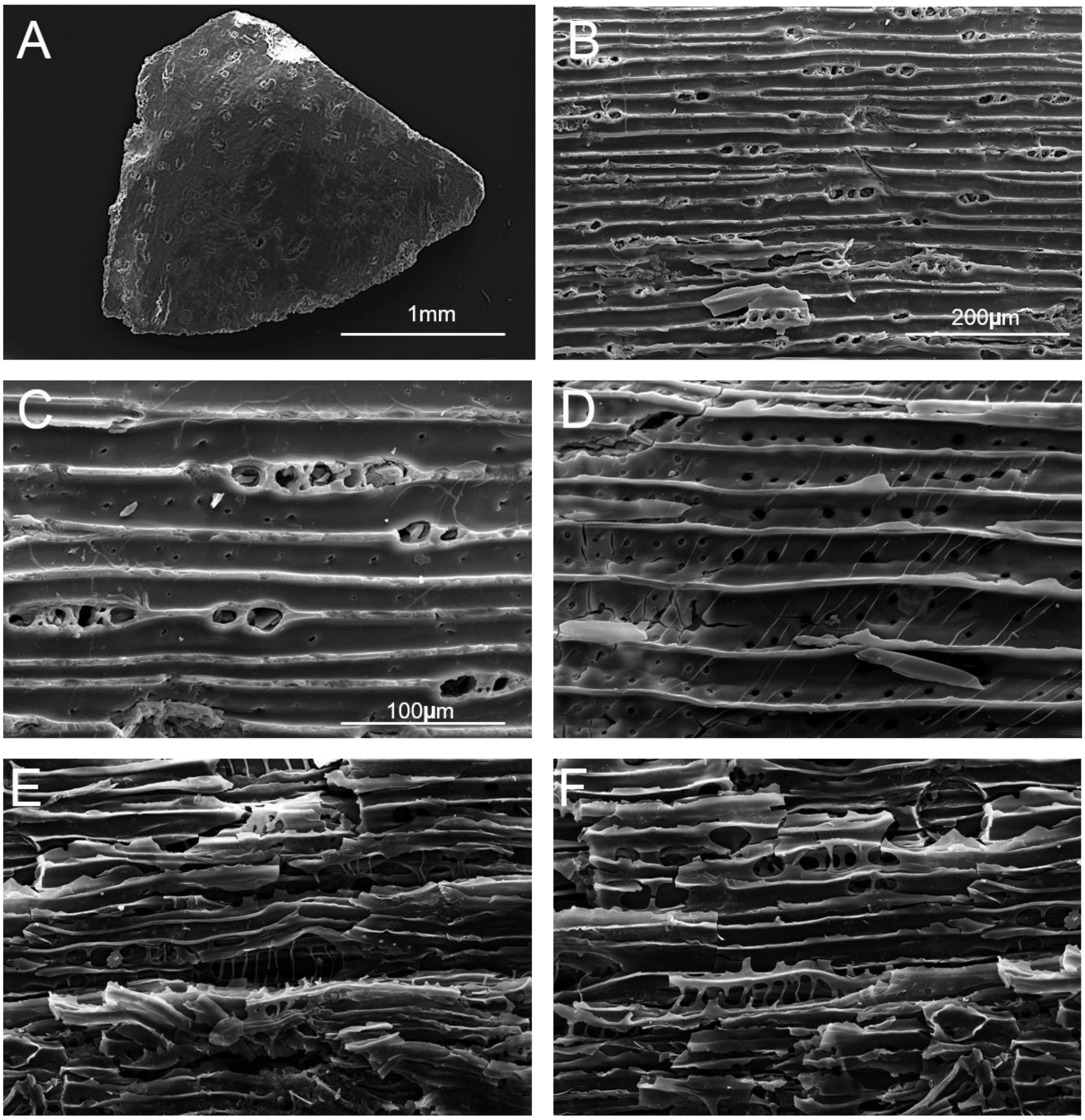


Fig. 6.14 Range of charcoal from the Maastrichtian of Drumheller, C-F have the same scale. A- angiosperm leaf fragment with stomata, B- tangential section of conifer wood with short rays, C- tangential section of conifer wood with short rays and bordered pits, D- radial section of conifer wood with bordered pits and crossfield pits, possibly branch wood, E-F angiosperm wood with scalariform perforations. C-F have a 100µm scale.

6.4 DISCUSSION

6.4.1 Charcoal distribution within lithologies

The alternating sandstones, mudstones and shales of the Horseshoe Canyon and Scollard Formations have been interpreted as palaeochannel and interfluvial deposits in a fluvially influenced coastal to alluvial plain (section 6.2.2). Fluctuating high water tables, leading to saturated landscapes and poor drainage, have been linked to coal formation throughout the Horseshoe Canyon and Scollard Formations (section 6.2.2). The palaeoenvironment differed for the Battle Formation with deposition occuring in a wide, shallow lake (Binda, 1992; Srivastava, 1994).

Previous research has interpreted a palaeoclimate with alternating warm and wet, and cool and dry phases, with seasonal and fluctuating rainfall throughout the Maastrichtian of Alberta (section 6.2.2). Rainfall immediately following wildfire events can enhance the possibility of charcoal transportation and distribution through overland flow (Chapter 1- section 1.4, Chapter 4- section 4.4.1, Chapter 5; for full discussion of charcoal transportation refer to Chapter 8- section 8.2).

As outlined in Chapter 4 (section 4.4.1) wildfires may have been restricted to specific environmental settings and/or catchment areas, thus potentially influencing charcoal distribution. Charcoal distribution can also be influenced by the prevalence and scale of overland flow, and through deposition and transportation within fluvial systems (further discussion in Chapter 8- section 8.2). Greater relative abundances of charcoal may preferentially accumulate in sands due to charcoal being washed into channels through flooding events (Chapter 4- section 4.4.2).

Many of the shales and mudstones in the Maastrichtian succession are associated with coal units, indicating deposition in waterlogged conditions. An absence of charcoal in these units, particularly those stratigraphically close to coal units, may be indicative of environmental conditions less susceptible to wildfires, potentially due to damp litter layers (Chapter 1, section 1.3; for further discussion refer to Chapter 8). Charcoal occurrence, and domin classifications, and the lithologies in which they were contained have been compared to address potential palaeoenvironmental controls on charcoal distribution.

Charcoal is present in all three lithologies for all size fractions within the Horseshoe Canyon Formation (Fig. 6.15), however there is variation in relative abundances of charcoal with respect to the lithology throughout the Formation. For the Drumheller and Morrin Members greater relative abundances of charcoal are recorded within the sandstones, when compared with mudstones and shales, with domin classifications of frequent and common recorded (Fig. 6.5, Fig. 6.9). There is variation in the percentage of samples containing no charcoal from all size fractions within each lithology, with similar percentages recorded in both the Drumheller and Morrin Members for each lithology. For the Drumheller Member 14% of sandstones, 0% shales and 100% of mudstones contain no charcoal. For the Morrin Member 25% of sandstones, 0% of shales and 100% of mudstones contain no charcoal. The sandstones were likely to have been deposited during low water table conditions. This may have resulted in drier litter layers that could have easily ignited, resulting in greater relative abundances of charcoal (Chapter 1, further discussion in Chapter 8).

The Horsethief Member and upper part of the Horseshoe Canyon Formation contain similar relative abundances of charcoal for all lithologies and all size fractions (Fig. 6.7, Fig. 6.11). There is variation in the percentage samples containing no charcoal from all size fractions within each lithology. However similar percentages are recorded in both the Horsethief Member and upper part of the Horseshoe Canyon Formation for each lithology. For the Horsetheif Member 40% of sandstones, 50% shales and 33% of mudstones contain no charcoal. For the upper part of the Horseshoe Canyon Formation 27% of sandstones and 33% of mudstones contain no charcoal. This indicates that charcoal is entering all catchments within this depositional environment. Wildfires may not have been confined to specific environmental settings but affected all of the landscape during deposition.

The absence of charcoal within the Whitemud Member may be due to pedogenic alteration and heavy weathering of the thin lithological units. From the lithological data, charcoal is entering the majority of catchment areas. The depositional environment of the Horseshoe Canyon Formation is similar throughout the succession (fluvially influenced coastal to alluvial plain), therefore it is unlikely that this absence of charcoal is influenced by environmental conditions.

Charcoal was not recorded in the Battle Formation, where deposition occurred in a lacustrine setting. This could be due to an absence of wildfire activity during deposition, or may be due to chacoal not entering the lacustrine catchment. Charcoal may be transported within fluvial channels and distributed across floodplains during flooding events, with deposition occuring away from the lacustrine setting.

The Scollard Formation contains very low relative abundances of charcoal, in shales and mudstones only (Fig. 6.12). The low levels of charcoal within this Formation may be due to waterlogged conditions that resulted in damp litter layers that were less susceptible to ignition and the spread of wildfires (discussed further in Chapter 8- section 8.3).

Throughout the Maastrichtian succession charcoal is recorded within all lithologies, however charcoal occurrence and relative abundance within lithologies does vary. The 500µm-1mm size fraction contains more samples with charcoal present than the other size fractions, for all three lithologies. Charcoal abundances, similar to those recorded for bone bed 43 (Chapter 4- section 4.4), are not greater within the palaeochannel sandstones, indicating that hyperconcentrated flow events were unlikely to be occurring (refer to Chapter 4- section 4.4). The variation in charcoal occurrence is likely to be due to waterlogged conditions during the deposition of some shales and mudstones leading to a reduction in ignition and wildfire spread (discussed further in Chapter 8).

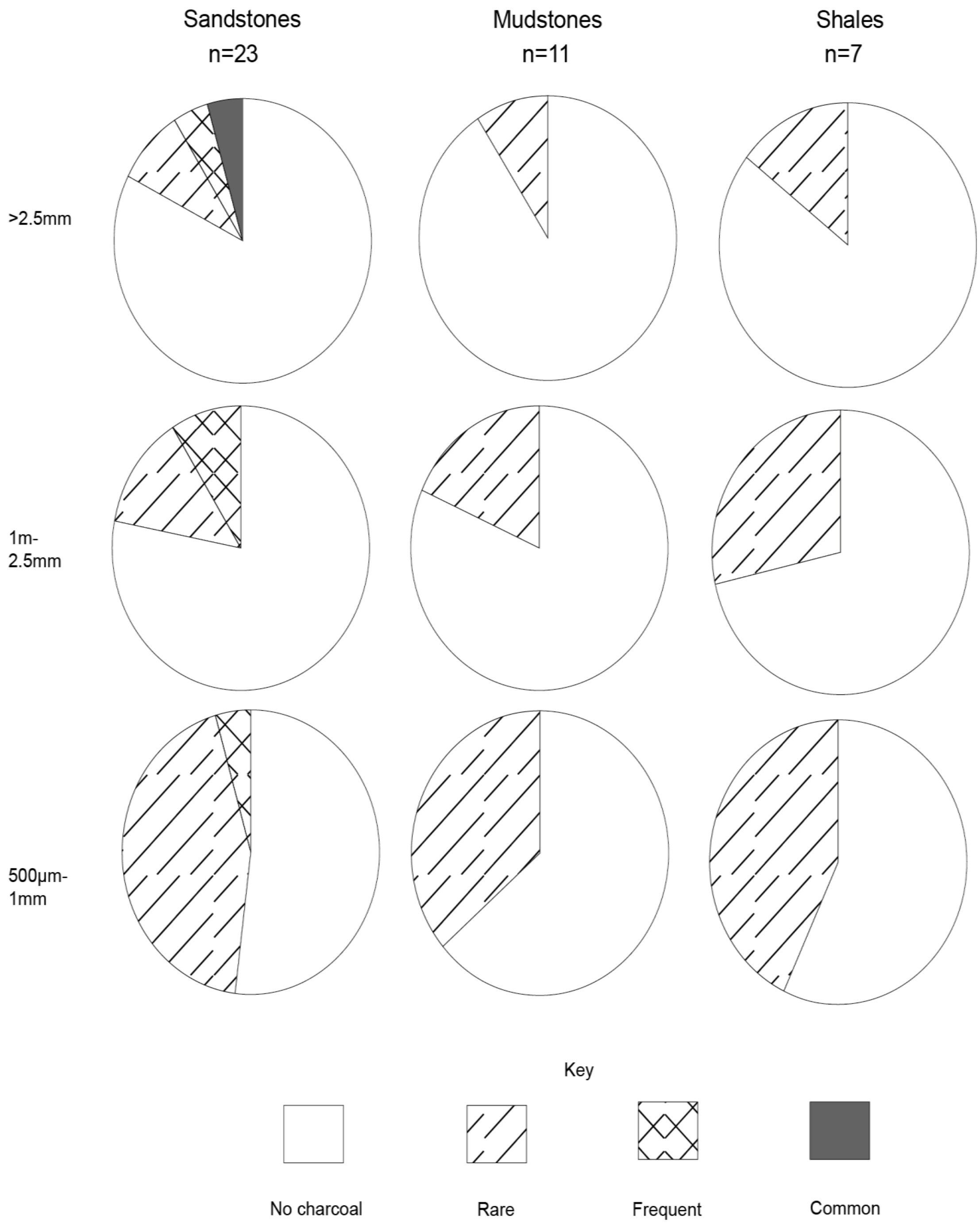


Fig. 6.15 The proportions of domin classifications for charcoal abundances within 20g samples from all sampled lithological units from all the Members within the Horseshoe Canyon Formation outcropping across Drumheller. Higher relative charcoal abundances occur in sandstones. The 500µm-1mm size fraction contains the more samples with charcoal present than the other size fractions, for all three lithologies.

6.4.2 Spatial distribution of charcoal

Two short sedimentary successions from the Drumheller Member of the Horseshoe Canyon Formation, located 10km apart, have been compared in order to establish the spatial distribution and relative abundances of charcoal (Fig. 6.16). The lithological data indicate that wildfires were influencing the majority of catchments within this depositional setting, with charcoal entering all lithologies. Greater charcoal abundances were recorded within the sandstones of the Drumheller Member, with no charcoal recorded in mudstones. Variation in spatial distribution may be the result of wildfires influencing specific environments across the Maastrichtian landscape. In addition, as outlined in Chapter 4, wildfires are patchy, with areas of burnt and unburnt vegetation often adjacent, so a degree of spatial variation can be expected. The spatial variability will be compared for the interval of time between coals #2-#3 and coals #3-#4.

The interval of time from coal #2-#3 was likely to have experienced greater wildfire activity when compared with the interval from coal #3-#4. Both lithological logs show the greatest proportion of lithologies containing charcoal for the time interval between the deposition of coal #2 and coal #3, with 38% of lithological units containing charcoal at Willow Creek and 60% at Rosedale. There is some spatial variation in charcoal distribution for this time interval between the two localities, with regard to the proportion of lithologies containing charcoal, and the relative abundances recorded. This spatial variation might result from differences in lithology, with a sandstone dominated lithology at Willow Creek and a shale dominated lithology at Rosedale. Whilst the lithologies and palaeoenvironments are not comparable between the localities, the same broad trends in charcoal distribution are recorded at both localities (Fig. 6.16).

There are fewer recorded charcoal occurrences, with low relative abundances, between coal #3 and coal #4 at both localities. There is spatial variation in charcoal distribution with 50% of lithological units containing charcoal at Willow Creek (although only two lithological units were sampled) compared with 20% at Rosedale. The broad trend in a reduction in charcoal is recorded across both localities, and may indicate a decrease in wildfire activity.

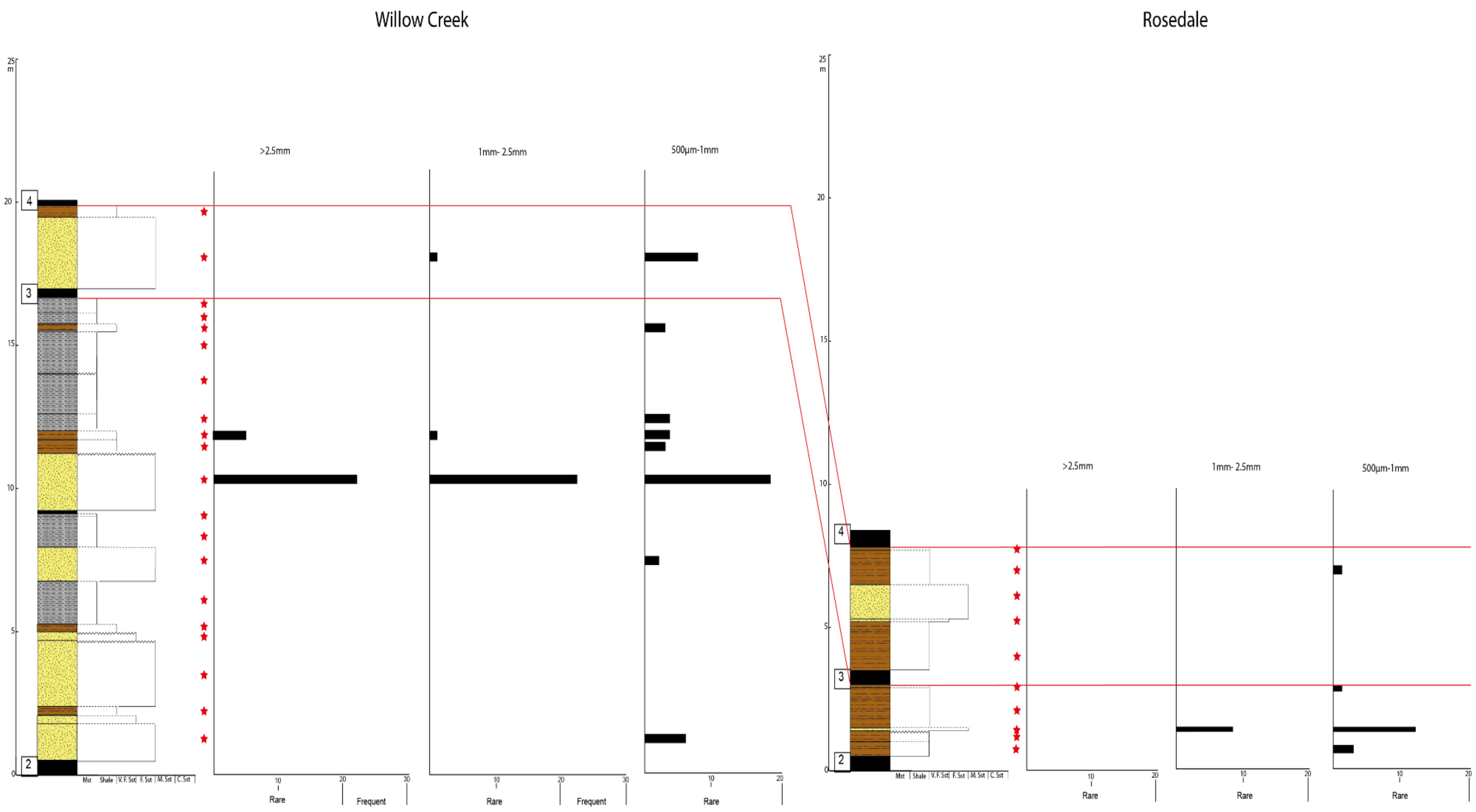


Fig. 6.16 Domin classification and numerical cover value for charcoal in 20g subsamples throughout lateral sections of the Drumheller Member outcropping at Willow Creek and Rosedale. The red stars indicate sampled lithological units. Mined coal seams have industry number located in a box adjacent to each of them. The red lines show correlation based on coal seams.

Outcrops at Willow Creek and Rosedale exhibit different lithologies and palaeoenvironmental conditions for the section coal #2 to coal #4, however the reduction in both charcoal occurrence and relative abundance is recorded at both localities for the interval from coal #3-#4. This may indicate a reduction in wildfire occurrence during the deposition of the succession from coal #3 to coal #4. The trends in charcoal occurrence indicate that wildfires were not localised phenomena, and influenced at least 10km of Maastrichtian landscape.

6.4.3 Temporal distribution of charcoal

The presence of charcoal within the Horseshoe Canyon and Scollard Formations (Table 6.2) indicates that the Maastrichtian landscape was influenced by wildfires, enhancing knowledge of Maastrichtian wildfires globally. There is variation in charcoal distribution and relative abundances throughout the Maastrichtian succession. Temporal distribution of charcoal, with reference to Members and Formations, will be discussed below.

The lower part of the Horseshoe Canyon Formation (Drumheller to Morrin Members) contains charcoal of all size fractions, and contains the greatest relative charcoal abundances within the Maastrichtian succession. Domin classifications of rare dominate the succession, however classifications of frequent and common are recorded in the Drumheller and Morrin Members (Figs. 6.2-6.3, Table 6.2). >2.5mm charcoal is recorded within all Members of the lower Horseshoe Canyon Formation (Table 6.2). There is variation in the proportions of lithological units containing charcoal within and between the Members (Table 6.2), indicating smaller scale variation in charcoal distribution that does not affect the overall trend.

The upper part of the Horseshoe Canyon Formation, including the Tolman, Carbon and Whitemud Members, contains lower relative abundances of charcoal than the upper part, with domin classifications not exceeding rare and low numerical cover values (below 10) (Fig. 6.10). There is an absence of charcoal pieces >2.5mm. Fewer lithological units contain 500μm-1mm charcoal (~26%) when compared with the rest of the Horseshoe Canyon Formation (Table 6.2). Charcoal is absent within the sediments of the Whitemud Formation (Table 6.2).

<table>
<tr><th></th><th></th><th>Member/ Formation</th><th>Environment</th><th>Climate</th><th>No. of units containing charcoal >2.5mm</th><th>No. of units containing charcoal 1mm-2.5mm</th><th>No. of units containing charcoal 500µm-1mm</th></tr>
<tr><td></td><td></td><td>Upper Scollard Formation</td><td>Fluvially influenced alluvial plain</td><td>Warmer, wetter</td><td>0/7</td><td>1/7</td><td>2/7</td></tr>
<tr><td></td><td></td><td>Lower Scollard Formation</td><td>Fluvially influenced alluvial plain</td><td>Warmer, wetter</td><td>0/5</td><td>0/5</td><td>1/5</td></tr>
<tr><td></td><td></td><td>Battle Formation</td><td>Lacustrine</td><td>Cooler</td><td>0/2</td><td>0/2</td><td>0/2</td></tr>
<tr><td rowspan="10">HORSESHOE CANYON FORMATION</td><td rowspan="4">UPPER</td><td>Whitemud Member</td><td>Fluvially influenced alluvial plain</td><td>Warmer, wetter</td><td>0/1</td><td>0/1</td><td>0/1</td></tr>
<tr><td>Carbon Member</td><td>Fluvially influenced alluvial plain</td><td>Warmer, wetter</td><td>0/4</td><td>1/4</td><td>2/4</td></tr>
<tr><td>Upper Tolman Member</td><td>Fluvially influenced alluvial plain</td><td>Cool and dry</td><td>0/4</td><td>0/4</td><td>0/4</td></tr>
<tr><td>Lower Tolman Member</td><td>Fluvially influenced alluvial plain</td><td>Cool and dry</td><td>0/6</td><td>1/6</td><td>2/6</td></tr>
<tr><td rowspan="6">LOWER</td><td>Upper Morin Member</td><td>Fluvially influenced coastal plain</td><td>Cool and dry</td><td>1/4*</td><td>1/4</td><td>2/4</td></tr>
<tr><td>Lower Morin Member</td><td>Fluvially influenced coastal plain</td><td>Cool and dry</td><td>1/3</td><td>2/3*</td><td>2/3*</td></tr>
<tr><td>Upper Horsethief Member</td><td>Fluvially influenced alluvial plain</td><td>Warmer, wetter</td><td>0/5</td><td>1/5</td><td>0/5</td></tr>
<tr><td>Lower Horsetheif Member</td><td>Fluvially influenced coastal to alluvial plain</td><td>Warmer, wetter</td><td>2/5</td><td>2/5</td><td>4/5</td></tr>
<tr><td>Upper Drumheller Member</td><td>Fluvially influenced coastal plain</td><td>Warmer, wetter</td><td>0/4</td><td>3/4</td><td>2/10</td></tr>
<tr><td>Lower Drumheller Member</td><td>Fluvially influenced coastal plain</td><td>Warmer, wetter</td><td>1/10*</td><td>3/10*</td><td>7/10</td></tr>
</table>

*Table 6.2- Summary of Members and Formations along with palaeoenvironmental, climatic conditions (refer to section 6.2.2) and charcoal data. This excludes the lateral sample. Key: x/y- x= number of lithological sample containing charcoal, y= total number of lithological samples. The * indicates a domin classification of frequent or common for at least one sample.*

There is an absence of charcoal in the Battle Formation and the lower part of the Scollard Formation (Table 6.2). Very low relative abundances of charcoal are recorded for the upper part of the exposed Scollard Formation, and there is an absence of charcoal >2.5mm. A low proportion of lithological units containing charcoal has been recorded (~33%).

There is variation in both proportions of lithological units containing charcoal and relative charcoal abundances through the 9.5 million year succession outcropping in Drumheller. The lower part of the Horseshoe Canyon Formation contains greater occurrences and relative abundances of charcoal than the rest of the succession. In addition >2.5mm charcoal is only present within the lower part of the Horseshoe Canyon Formation. There is a major change in charcoal distribution from the lower to the upper part of the Horseshoe Canyon Formation, potentially indicating a reduction in wildfire activity. However, in order to understand whether this variation is due to temporal variation in wildfire activity the climatic variation needs to be considered with respect to charcoal occurrence.

6.4.4 Climatic influences on the distribution of charcoal

The Maastrichtian climate of Alberta was variable with alternating warm and wet and cooler and drier conditions throughout the deposition of the Horseshoe Canyon, Battle and Scollard Formations. Climate can be influential in both charcoal occurrence and distribution. Warm climatic conditions with periodic, seasonal rainfall could be favourable for wildfire occurrence and charcoal distribution. The warm, dry periods could be associated with 'dry lightning' events (Chapter 1) that can lead to both wildfire ignition and propagation, resulting in the production of charcoal. Wildfire spread and duration during a warm and wet climatic phase could be impeded by high fuel and litter moisture resultant from seasonal rainfall. Seasonal rainfall may be responsible for increased charcoal transportation into depositional catchments through overland flow, particularly if rainfall occurred shortly after a wildfire event that induced patchy soil hydrophobicity (Chapters 1- section 1.4; further discussion in Chapter 8- section 8.2 regarding mechanisms of charcoal transportation).

Cool and dry climatic phases can also be favourable for wildfire occurrence. Reduced fuel moisture levels and drier litter layers could lead to extensive wildfire spread after an initial ignition event. However, lightning storms are often associated with warm climatic conditions, with lightning activity less likely during cooler climates. The lower abundances of rainfall may mean that charcoal is less readily transported after a wildfire event, as there is significantly less overland flow. This may result in lower charcoal abundances in lithological units.

Variation in both charcoal occurrence and relative abundances has been recorded throughout the Maastrichtian. A warm and wet climatic phase corresponds with the deposition of the Drumheller and Horsethief Members (section 6.2.1, Table 6.2). These Members contain the greatest proportions of lithological units containing charcoal for all Members and Formations in the Maastrichtian succession (Table 6.2). Domin classifications of frequent have been recorded for the Drumheller Member, with only two Members recording domin classification exceeding rare within the succession (Fig. 6.3, Table 6.2). There are, however, variations in both charcoal occurrence and abundance within these Members and these cannot be linked to climatic conditions.

The Morrin Member also contains a high proportion of lithological units containing charcoal, with charcoal domin classifications of frequent and common recorded (Table 6.2). This is the only Member/Formation to contain common charcoal. The Morrin Member was deposited under cool and dry climatic conditions (section 6.2.1, Table 6.2), indicating a change in climatic conditions has not influenced charcoal occurrence.

The charcoal distribution within the upper part of the Horseshoe Canyon Formation and the Battle and Scollard Formations gives further evidence that changing climatic conditions exerted little or no influence on the temporal distribution of charcoal. Very low domin classifications are recorded for both the upper part of the Horseshoe Canyon Formation and Scollard Formation, along with low proportions of lithological units containing charcoal. There is no charcoal recorded for the Battle Formation. Deposition occurred under warm and wet climatic conditions, similar to the Drumheller and Horsethief Members. If climate was controlling charcoal distribution similar occurrences and abundances of charcoal would be expected in sediments deposited under similar climatic conditions.

6.5 CONCLUSIONS

Charcoal occurs sporadically throughout the Horseshoe Canyon and Scollard Formations, but is absent from the Battle Formation. The lower part of the Horseshoe Canyon Formation (Drumheller to Morrin Members) contains the greater proportions of lithological units containing charcoal, and greater relative charcoal abundances when compared with the rest of the Maastrichtian succession. There is temporal variation in charcoal distribution throughout the sedimentary succession, with a decline in charcoal abundances and occurrence towards the top of the succession. Changing climatic conditions exerted little or no influence on the temporal distribution of charcoal.

Wildfires were influential in all depositional environments and catchments within the Maastrichtian succession, with the exception of the lacustrine Battle Formation. Lower relative abundances of charcoal in shales and mudstones within some Members/Formations may be due to waterlogged conditions during deposition resulting in damp litter layers that were less susceptible to wildfire ignition and spread. The spatial distribution of charcoal between coal #2 and coal #4 at two localities recorded similar trends in charcoal occurrence and abundances, despite different lithologies and palaeoenvironments present. This indicates that wildfire occurrence was not a localised phenomenon, influencing at least 10km of the landscapes.

This is the first detailed temporal and spatial investigation of charcoal distribution within the Maastrichtian, with 60 lithological samples studied for the presence of charcoal within a 9.5Ma interval. This study has highlighted the occurrence of wildfire activity during this time, extending the record of wildfire occurrence within Alberta. The very small number of units containing charcoal >2.5mm (5/60 lithological samples) may mean that charcoal is usually not visible in sediments (Table 6.2). Some charcoal was visible to the naked eye in the Horseshoe Canyon Formation, but was easily missed. Therefore, the presence of charcoal is likely to be overlooked by researchers whose focus is not on the charcoal. This may explain the low number of recorded Maastrichtian charcoal localities (discussed in Chapter 2). Sieving Cretaceous sediment samples for charcoal occurrence would help increase the knowledge of global Cretaceous fire activity, and environmental controls influencing wildfire occurrence.

Chapter 7:

Modern Charcoal Assemblages

7.1 INTRODUCTION

The factors which affect the composition of wildfire derived plant debris assemblages are not fully understood. Thirteen samples, from three modern wildfires (Rodeo-Chediski fire, 2002; Medano fire, 2010; Schultz fire, 2010) have been studied to determine the presence/absence of charred, uncharred and partially charred plant debris, along with the range of plant tissues, organs and taxa present. Samples from channel sands were selected, and identical study methods were used to allow comparison with Late Cretaceous channel sand deposits (Chapters 4-6).

The modern samples vary in their proximity to the wildfire boundary, channel size, vegetation stands and flow type so the influence of these factors on the resultant plant debris assemblages can be considered. The information on factors influencing charcoal assemblages obtained from the modern samples, along with that from other charcoal taphonomic studies (Abu Hamad et al., 2012; Scott, 2010; Uhl et al., 2008), will be used to help interpret Late Cretaceous assemblages and will be discussed in Chapter 8 (section 8.4).

7.2 MATERIALS AND METHODS

7.2.1 The fire events

In order to document the composition of plant debris assemblages within sands collected from known wildfire impacted landscapes, three recently burnt localities have been investigated (Fig. 7.1). Samples from the Rodeo-Chediski fire were provided by Chris Roos, with samples from the Medano and Schultz fire collected by myself.

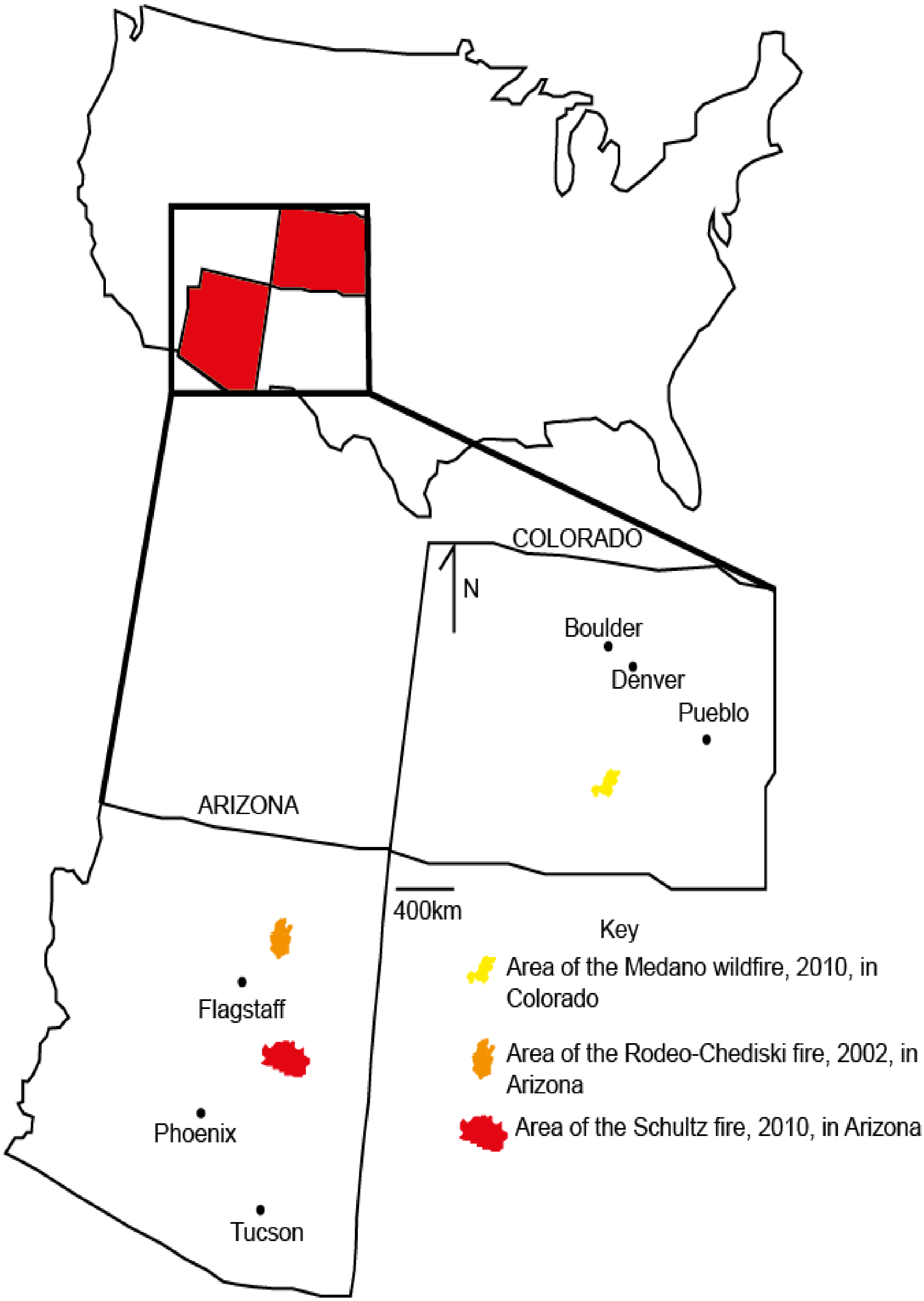


Fig. 7.1 Map of the USA with an enlargement of Colorado and Arizona highlighting the areas affected by the three sampled wildfires.

7.2.1.1 Background to the Rodeo-Chediski wildfire

The Rodeo-Chediski wildfire is the largest of the three investigated wildfires, with approximately 468,635 acres burnt within northeast Arizona (Fig. 7.1), occurring partly within the Apache-Sitgreaves National Forest (Kuenzi et al., 2008; van Leeuwen, 2008). The wildfire started on the June 18th 2002, ignited through arson, and was extinguished on July 7th 2002 representing the second largest wildfire in Arizona's history after the Wallow fire of 2011.

There were three years of drought prior to the wildfire, with 2002 recorded as one of the driest on record with the driest May since 1896 (Kuenzi et al., 2008). This wildfire was a crown fire that burnt a forest dominated by ponderosa pine, with mixed conifers at high elevations and pinyon pine, juniper and chaparral vegetation present at lower elevations (Kuenzi et al., 2008).

High burn severities were recorded for 48% of the burned area which is an unprecedented extent of burning in low elevation, dry ponderosa pine forests. The combination of dry fuel, steep topography and plume-driven fire dynamics, whereby a convective cloud of hot gasses and soot cools and collapses into the centre of the fire activity creating extreme surface winds, is believed to be responsible for the fast spread and high burn severity of this fire (Crimmins, 2007). Within the areas of high severity fire approximately 50% of ponderosa pine were killed compared with 17% within low severity areas (Ffolliot et al., 2008, 2011).

Heavy rainfall that followed the wildfire event caused a significant increase in flow rates and erosion levels (Gottfried et al., 2013). Water flow was recorded to be ninety times higher than average in the high severity burnt area, with higher than normal flow rates also recorded in low-medium severity areas (Gottfried et al., 2013). The Salt River was turned black due to the charcoal and ash carried in slope runoff, with large amounts of sediment collected in channels (Gottfried et al., 2013).

7.2.1.2 Background to the Medano wildfire

The Medano wildfire is the smallest of the three investigated wildfires, with 6249 acres burnt within the Great Sand Dunes National Park, Colorado (Fig. 7.1). The wildfire was ignited by a lightning strike at 11:30am on the 6th June 2010, and continued to burn into August 2010. By the 3rd of August, when sampling was carried out, the wildfire had almost burnt out with fires confined to stumpholes and very steep hill slopes (pers. com. Great Sand Dunes Park Authority). The wildfire was comprised of ground and spot fires, influencing the slopes of the Sagre de Cristo Mountains (pers. com. Great Sand Dunes Park Authority).

The scattered open woodland/ low density forest is dominated by mixed conifers (dominated by ponderosa pine) with *Populus* species (poplar or cottonwood, a flowering plant species) also present in this ecosystem (Fig. 7.2). There was variable burn severity within the National Park, with the wildfire burning a mosaic pattern. *Populus* species had a very high burn severity, with high levels of ash coverage and little visible charcoal. The ponderosa pines had variable burn severities, with the death of some trees and the restricted burning of trunks of others. Heavy rainfall and associated thunderstorms occurred episodically throughout the burning of the forest, leading to flooding events and the transportation of charcoal. The Medano Creek ran black during the wildfire. 'Sooty' water was still present in Castle Creek, a tributary of Medano Creek, in 2013 due to summer thunderstorms causing runoff after the 2010 wildfire event (National Park Authority, 2013).

7.2.1.3 Background to the Schultz wildfire

The Schultz wildfire burnt a large area (15,073 acres) of central Arizona, near Flagstaff, from the 20th-30th June 2010 (Neary et al., 2012) (Fig. 7.1). The wildfire occurred within the Cocanino National Forest, on the steep eastern slopes of the San Francisco Peaks (Neary et al., 2013). The fire burnt through a mixed conifer forest, with ponderosa pine being the dominant vegetation consumed by the fire (Neary et al., 2013) (Fig. 7.3). At the time of the wildfire there was substantial ground cover (>60% coverage) of litter and grasses. Severe thunderstorms in July 2010 led to debris flows, hyperconcentrated flows and hill slope erosion (Koestner et al., 2011; Neary et al., 2012), with the flooding events recorded to be larger than pre-fire rainfall events.

The hyperconcentrated flow deposits were fine grained and covered large areas, appearing to fan out into sheets (Koestner et al., 2011) (Fig. 7.4). These appeared black in colour, however no charcoal pieces were visible on the surface.

Fig. 7.2 Burned vegetation within Great Sand Dunes National Park after the Medano wildfire.

Fig. 7.3 Burned vegetation after the Schultz fire.

Fig. 7.4 Hyperconcentrated flow deposited after the Schultz fire.

7.2.2 Field sampling methodology

7.2.2.1 Rodeo-Chediski wildfire

Nine samples (RD101-103, RD105-110) were collected in 2005 by Chris Roos from the high severity burn area of the Rodeo-Chediski fire in 2002 (Fig. 7.5, Table 7.1). Samples were collected from the upper 2-3cm of medium-coarse sand from a sand bar within a channel of a discontinuous ephemeral stream, and from within an overflow channel to the east (Figs. 7.6-7.7, Table 7.1). Collection was undertaken with a small folding shovel with sediment placed into labelled plastic bags. The samples were allowed to air dry, before a subsample (approximately 100g) was taken and posted to the UK.

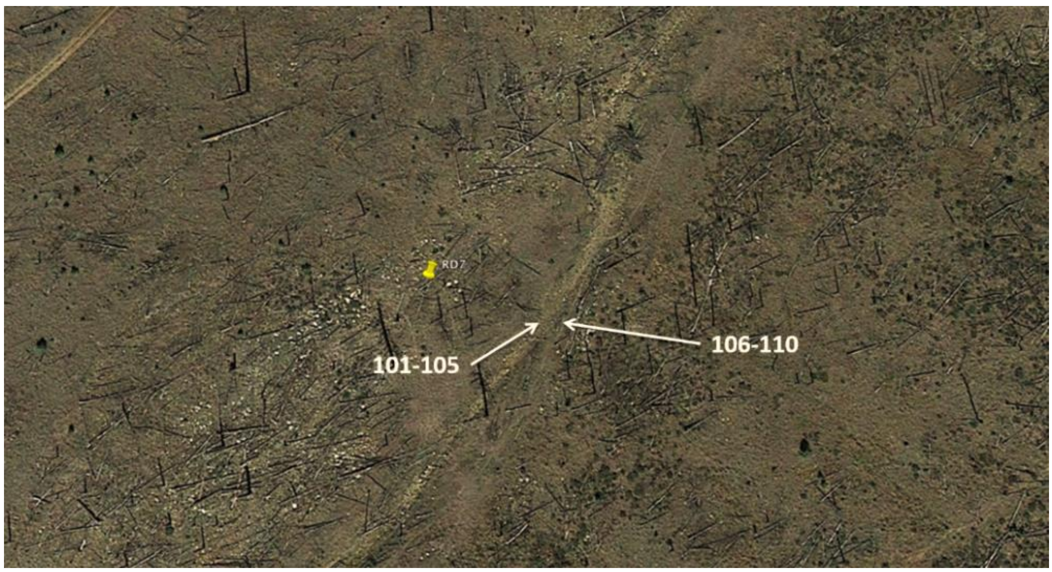


Fig. 7.5 Aerial photograph of an area burnt by the Rodeo-Chediski wildfire, showing the position of the samples. Image supplied by Chris Roos.

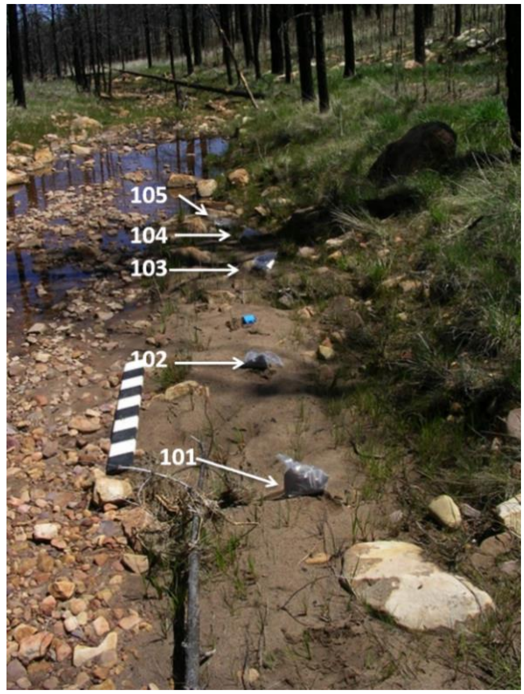


Fig. 7.6 Sampling locations for RD101-RD105. Photograph supplied by Chris Roos.

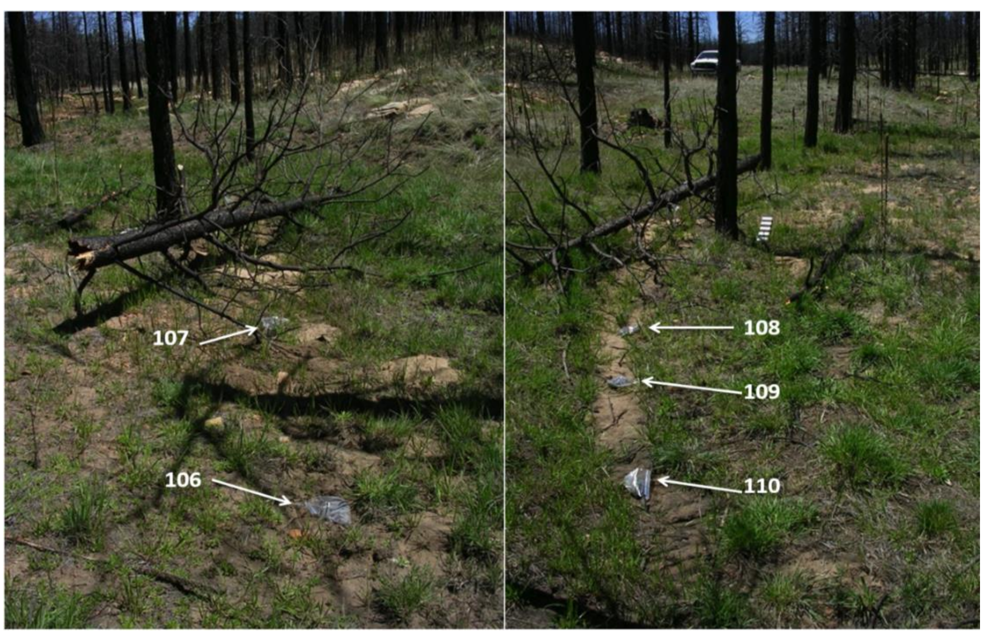


Fig. 7.7 Sampling locations for RD106-RD110. Photographs supplied by Chris Roos.

7.2.2.2 Medano fire

Sample collection was undertaken on the 2nd-3rd of August 2010, whilst the Medano fire was still burning. Three samples were collected, two sand deposits (GSD-01 and GSD-02) and a suspension sample (GSD-W) (Fig. 7.8). GSD-01 and GSD-02 were collected on the 3rd August from small scale sandy channels from within the burned area, and outside it (Fig. 7.8, Table 7.1). A small trowel was used to collect a bulk sediment sample from the upper 2-3cm of the sand. The samples were allowed to air dry before being shipped to the UK.

The suspension sample GSD-W was collected from Medano Creek, an ephemeral river. On the evening of the 2nd of August a large thunderstorm occurred over the Great Sand Dunes National Park, with heavy rainfall lasting for approximately one hour. After the rainfall had ceased the Medano Creek was investigated, which was dry upon arrival. A pulse of charcoal and sediment rich water flowed along this ephemeral river approximately half an hour after the rainfall event, and a sample of this was taken. A plastic sample bag was placed into the flow of water and was filled. This was subsequently allowed to air dry, leaving a sediment residue, before being shipped to the UK.

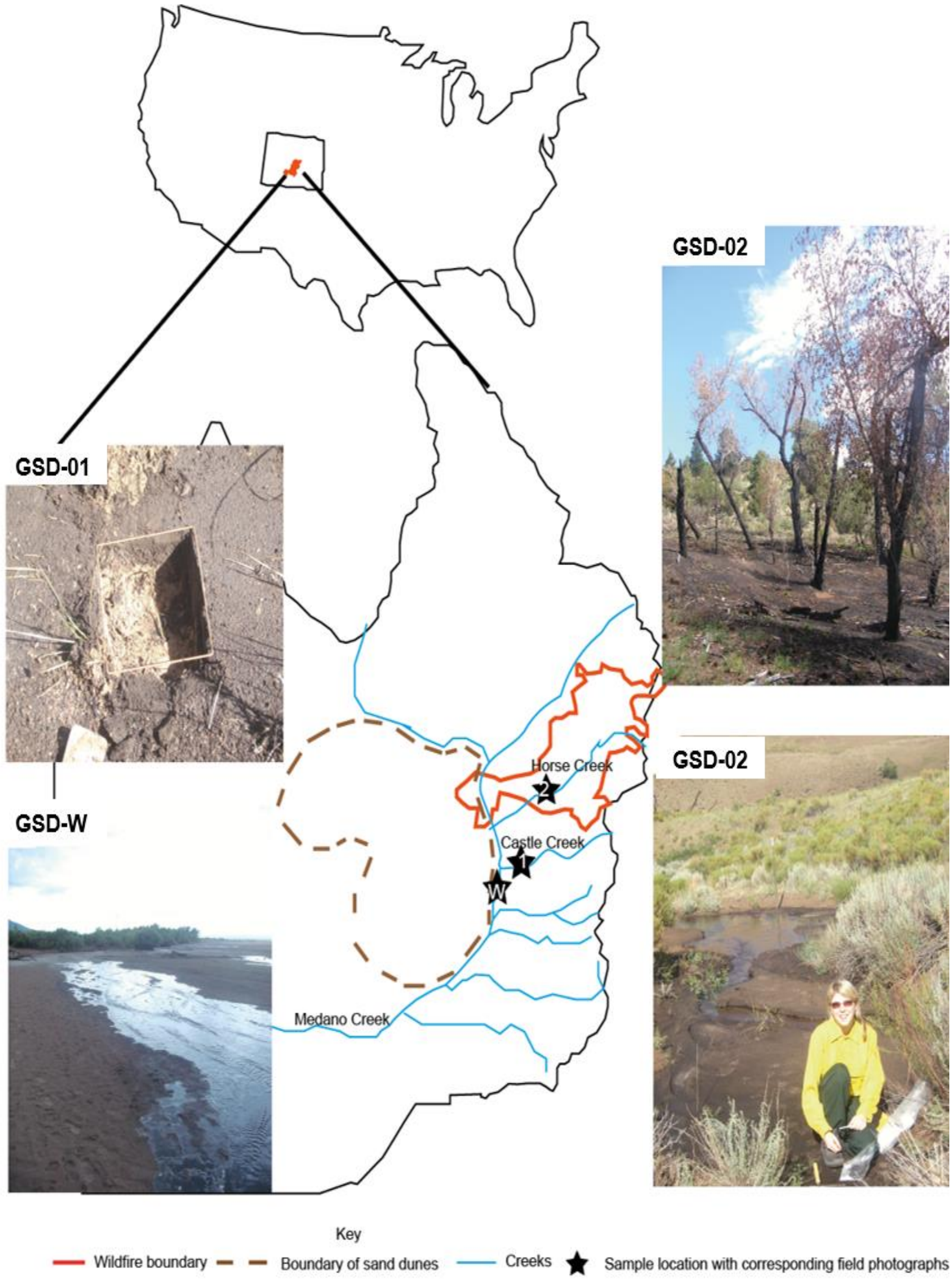


Fig. 7.8 Outline of Great Sand Dunes National Park, Colorado, with the outline of the area affected by the Medano wildfire shown in orange. Field photographs are shown for the three sampled localities and surrounding woodland.

7.2.2.3 Schultz fire

A hyperconcentrated flow deposit, comprised of very fine sand, was selected for sampling (Figs. 7.4, 7.9, Table 7.1). Hyperconcentrated flow events are considered as a mechanism of formation for a Campanian vertebrate deposit (for further discussion refer to Chapter 8- section 8.2.3.1). A small trowel was used to collect a bulk sample from the upper 2-3 cm of sediment. The sample was allowed to air dry before being shipped to the UK.

Fig. 7.9 Hyperconcentrated flow deposit sampled within the Schultz fire burned area.

7.2.3 Laboratory methodology

For each deposit and the dried suspension sample, a 20g subsample was randomly taken. The subsample was disaggregated in warm water. Each diluted residue was wet sieved into three size fractions (>2.5mm, 1mm-2.5mm, 500µm-1mm) in order to allow observations to be made on the relative abundances of different sizes of charcoal and other plant debris. Sieving and charcoal quantification was carried out according to the methodology outlined in Chapter 3 (section 3.3). Partially charred

Sample Number	Wildfire	Wildfire Size (acres	Within Burned Area?	Sediment Type	Vegetation Stands	Forest vs open woodland	Dominant vegetation burnt	Geomorphic Context	Depositional event	Suspension vs deposit
RD-101	Rodeo-Chedisk	468,635	Inside	Medium sand	Monotypic and mixed conifer	Forest	Ponderosa Pine	Small ephemeral	Water flow	Deposit
RD-102	' '	' '	' '	' '	' '	' '	' '	' '	' '	' '
RD-103	' '	' '	' '	' '	' '	' '	' '	' '	' '	' '
RD-105	' '	' '	' '	' '	' '	' '	' '	' '	' '	' '
RD-106	' '	' '	' '	' '	' '	' '	' '	Small overflow channel of stream channel	Water flow	Deposit
RD-107	' '	' '	' '	' '	' '	' '	' '	' '	' '	' '
RD-108	' '	' '	' '	' '	' '	' '	' '	' '	' '	' '
RD-109	' '	' '	' '	' '	' '	' '	' '	' '	' '	' '
RD-110	' '	' '	' '	' '	' '	' '	' '	' '	' '	' '
GSD-01	Medano	6,249	Outside	Fine sand	Monotypic and mixed conifers, *Populus*	Open woodland	Ponderosa Pine and *Populus*	Small ephemeral river channel	Water flow	Deposit
GSD-02	' '	' '	Inside	' '	' '	' '	' '	' '	' '	' '
GSD-W	' '	' '	Outside	' '	' '	' '	' '	' '	' '	Suspension
ARI-1	Schultz	15,073	Inside	Very fine sand	Monotypic and mixed conifer	Forest	Ponderosa Pine	Large channel	Hyper-concentrated	Deposit

Table 7.1 Comparison of the three modern wildfire localities.

7.3 PLANT DEBRIS DERIVED FROM MODERN WILDFIRE EVENTS

7.3.1 Charred plant debris derived from modern wildfires

The thirteen sediment samples from all three modern wildfire localities contained charcoal (Fig. 7.10). The charcoal assemblages were dominated by the <2.5mm size fractions. Nine samples contain charcoal >2.5mm, including samples from both forests and open woodlands within, and outside of, the burned area. However the domin classifications do not exceed rare, with the majority having low numerical cover values (below 10). Samples from within the wildfire boundary and outside of it contain charcoal, however greater relative abundances are recorded for samples within the burnt area, particularly for the 1mm-2.5mm size fraction.

Domin classifications of rare, along with low numerical cover values (below 10), are recorded for the majority of charcoal assemblages in the 1mm-2.5mm size fraction, with a single sample having a classification of frequent (ARI-1). The 500µm-1mm size fractions have the greatest relative abundances of charcoal from the modern wildfire localities. Within the domin classification of rare, the majority of samples have high numerical cover values (above 10). Frequent and common domin classifications are also recorded (RD-106 and ARI-1).

Similar charcoal abundances are recorded for both the ephemeral stream (RD-101-110) and ephemeral river (GSD-1-2, GSD-W) channel deposits. The larger scale channel deposit (ARI-1) contains the greatest relative abundance of charcoal for both the 1mm-2.5mm and 500µm-1mm size fractions, with domin classifications of frequent and common recorded.

The two samples collected from outside the wildfire boundaries contain lower relative abundances of charcoal than the majority of samples collected from within the burned areas. The suspension sample (GSD-W) is dominated by the 500µm-1mm size fraction, with no charcoal >2.5mm recorded and a low numerical cover value (below 10) for the 1mm-2.5mm size fraction. The suspension sample contains greater relative abundances of the finest charcoal fraction when compared to the deposit sample (GSD-01) also collected from outside the burned area.

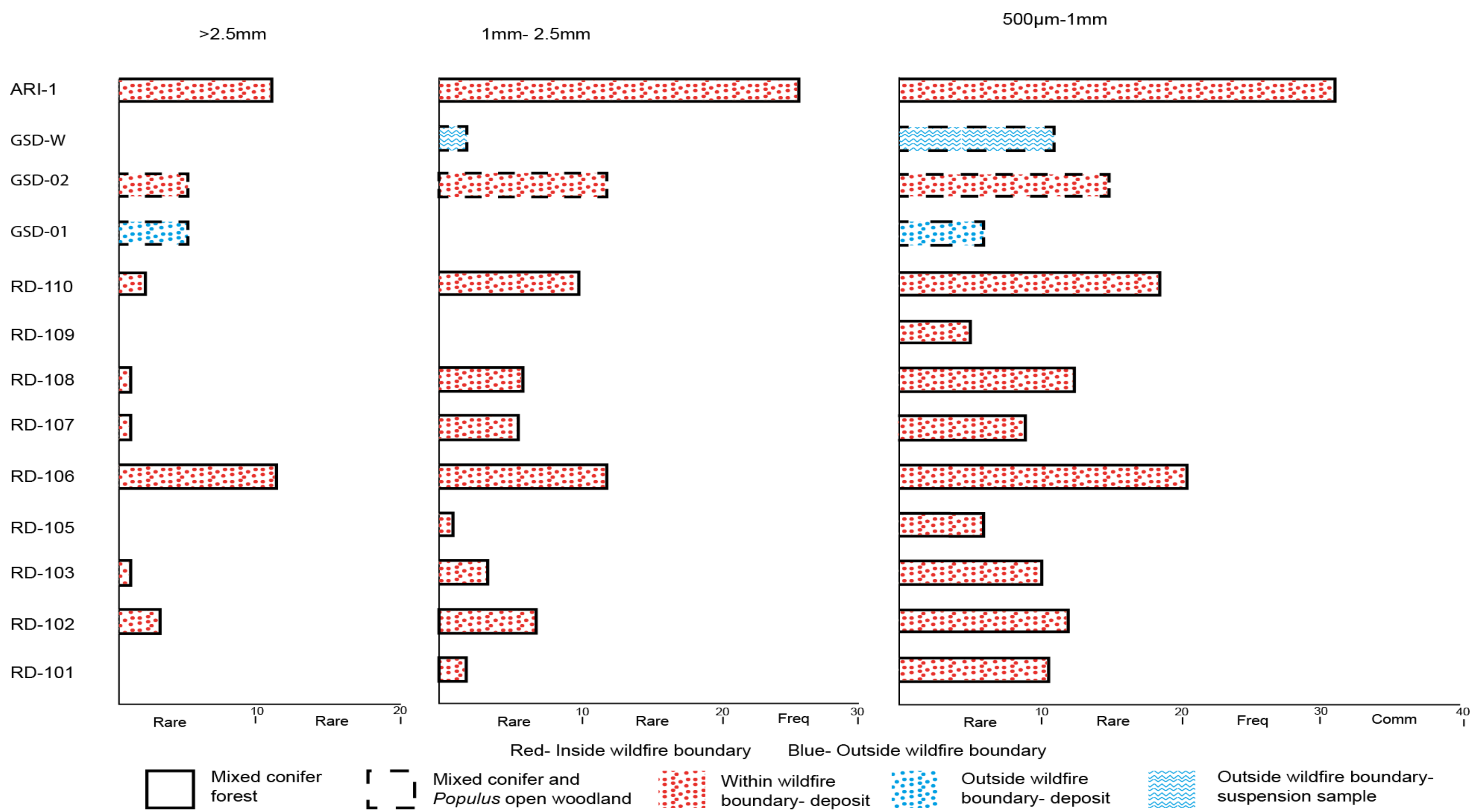


Fig. 7.10 Domin classification and numerical cover value in 20g subsamples from three modern wildfire localities

When comparing mixed conifer forest and mixed conifer and *Populus* open woodland samples collected from inside the burned areas of the modern wildfires, similar charcoal abundances are recorded. However the samples with the greatest relative abundances of charcoal are from within burned mixed conifer forest localities.

7.3.1.1 Plant organs and particle shapes

Twelve charcoal fragments were analysed using SEM (Chapter 3- section 3.3.5). The thirteen sediment samples from all three modern wildfire localities contained a range of charred plant organs (including wood, twigs, needles, leaves and reproductive structures), exhibiting a range of particle shapes (Figs. 7.11-7.12). The particle shapes were varied and included cubic pieces along with twigs with leaf attachments visible under the binocular microscope for some particles. Lath shaped charcoal pieces were also recorded but these were not the dominant shape in any of the plant debris assemblages.

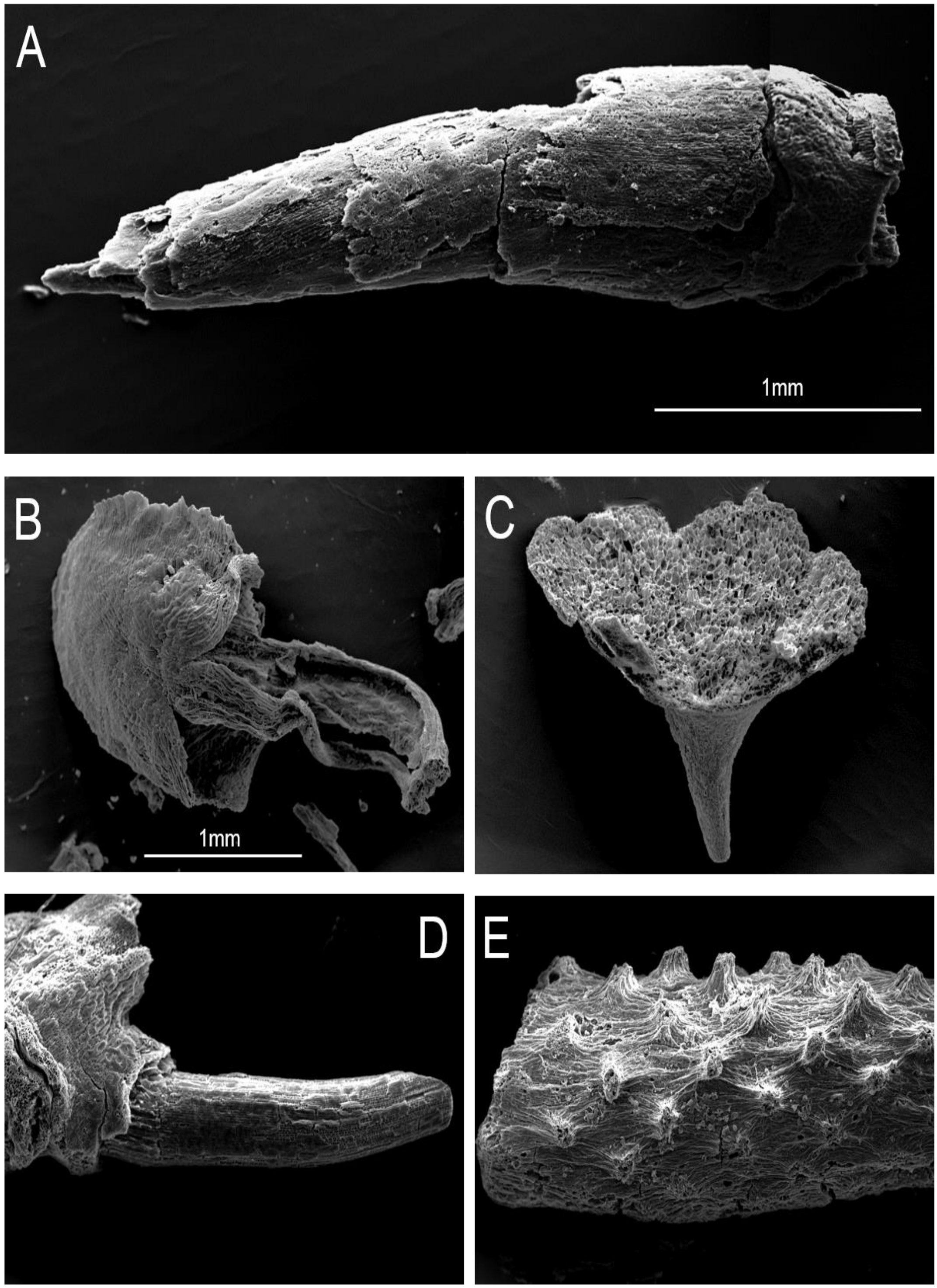


Fig. 7.11 Examples of the range of charred particle shapes and organs from the Schultz fire. A, D- probable twig or short shoot bases; B- probable pollen cone scale; C- probable thorn; E- unidentified particle showing well-preserved ornamentation. All examples have a 1mm scale.

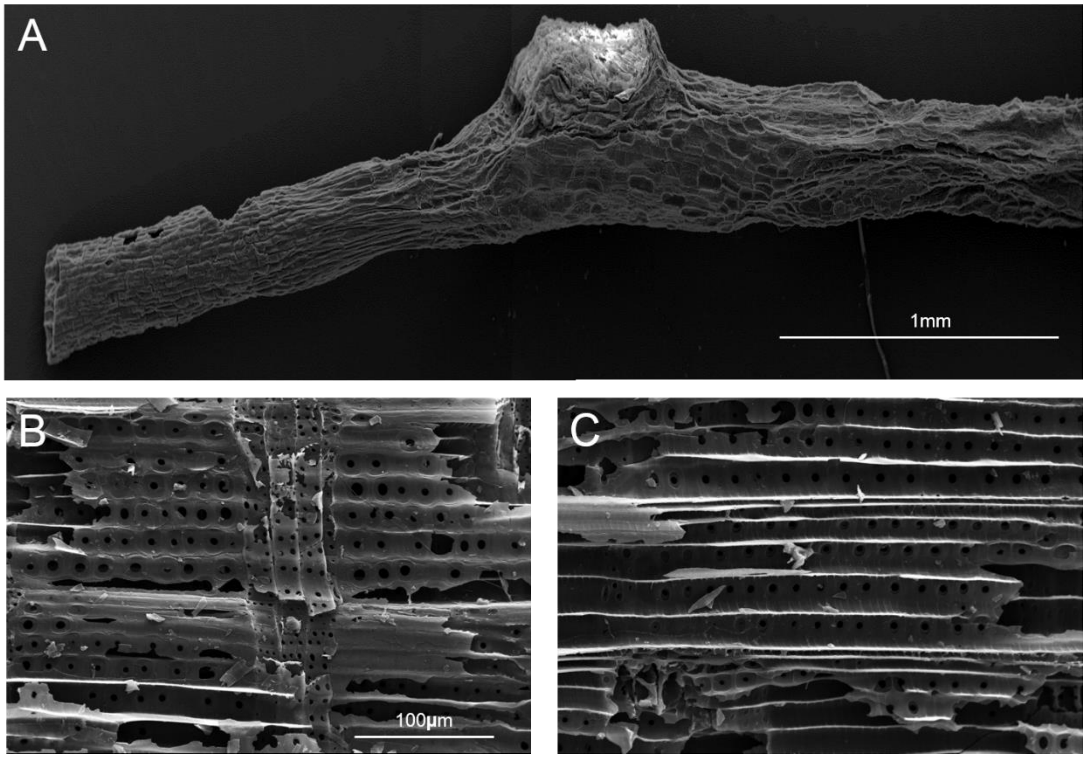


Fig. 7.12 Elongate particle and gymnosperm wood from the Medano and Schultz fires. A- elongate small stem from the Schultz fire, B- radial longitudinal section of conifer wood with bordered pits and cross field pits where the rays cross the tracheids from the Medano fire; C- longitudinal section of conifer wood with bordered pits and spiral thickenings on the tracheids from the Schultz fire. A has a 1mm scale, B-C have a 100µm scale.

7.3.2 Partially charred plant debris derived from modern wildfires

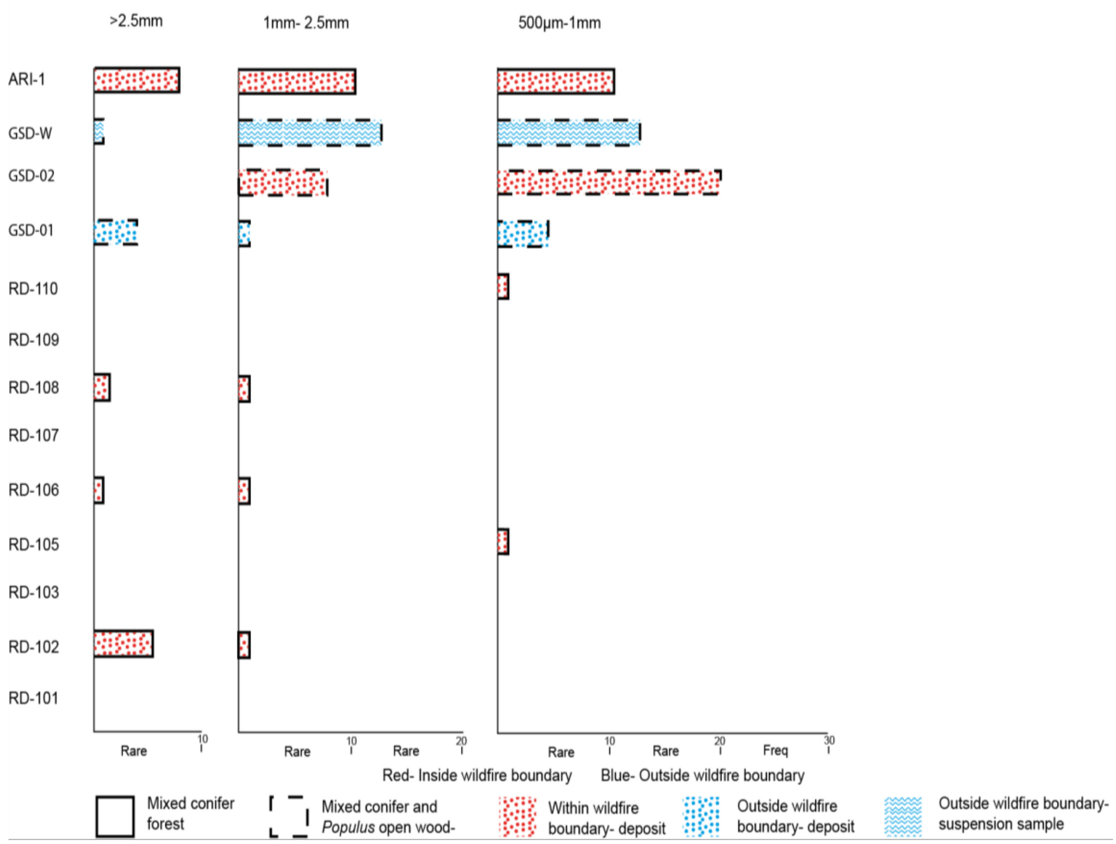


Fig. 7.13 Domin classification and numerical cover value for partially charred debris in 20g subsamples from three modern wildfire localities.

Partially charred plant debris is present in eight samples from all three modern wildfire localities (Fig. 7.13). There are low abundances of partially charred debris >2.5mm with domin classifications of rare and low numerical cover values (below 10). This size fraction is recorded within both forest and woodland deposits both within and outside the wildfire boundary, along with the suspension sample (GSD-W).

Lower relative abundances of partially charred debris (not exceeding the domin classification of rare) are recorded for the 1mm-2.5mm size fraction, with particularly low relative abundances recorded in the Rodeo-Chediski samples. Domin classifications of rare with low numerical cover values (below 10) are also recorded for the 500µm- 1mm size fraction in the Rodeo-Chediski samples. Only four (out of nine) Rodeo-Chediski samples have partially charred material.

Greater abundances of 500µm-1mm partially charred debris are recorded for deposits within, compared to outside, the wildfire boundary in Great Sand Dunes samples, with a domin classification of frequent (GSD-2). The suspension sample contains the greatest relative abundances of partially charred plant debris for the 1mm-2.5mm size fraction, despite collection outside the wildfire boundary.

7.3.3 Uncharred plant debris derived from modern wildfires

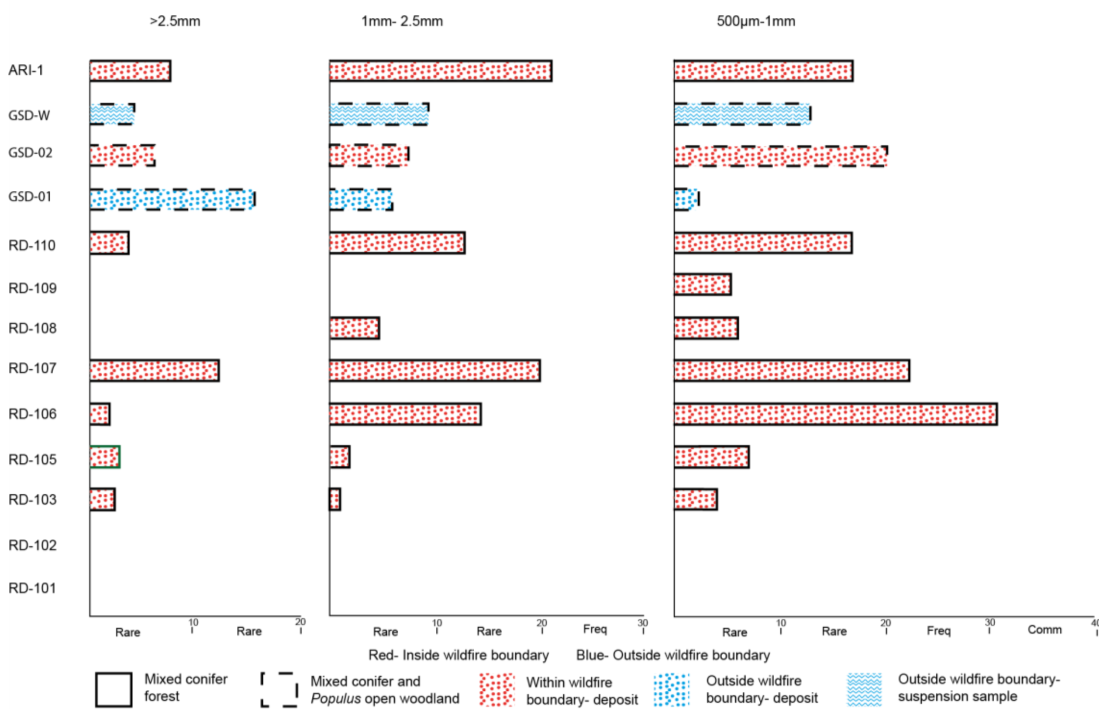


Fig. 7.14 Domin classification and numerical cover value for uncharred plant debris in 20g subsamples from three modern wildfire localities.

Uncharred plant debris occurs in all samples except two from the Rodeo-Chediski fire (Fig 7.14). There are low abundances of >2.5mm uncharred debris (not exceeding the domin classification of rare) within woodland and forest deposit and suspension samples collected from both within and outside of the wildfire boundary.

The greatest abundance of >2.5mm uncharred plant debris is recorded outside of the burned area (GSD-01), with a numerical cover value greater than 10.

There are greater relative abundances of uncharred plant debris in samples collected from within the wildfire boundaries for the 1mm-2.5mm and 500μm-1mm size fractions, with domin classifications of frequent and common recorded.

7.4 DISCUSSION AND IMPLICATIONS FOR LATE CRETACEOUS EXAMPLES

7.4.1 Occurrence of charred plant debris

All thirteen samples collected from modern wildfire localities contain charcoal. Given the recent occurrence of wildfires prior to sample collection, charcoal occurrence was to be expected. Relatively low abundances of >2.5mm charcoal were recorded across all sample settings. This is very similar to the Late Cretaceous charcoal deposits (Chapter 4- section 4.3; Chapter 6- section 6.3). Charcoal fragments easily (Belcher et al., 2013; Abu Hamad et al., 2012; Scott, 2001; Scott, 2010). The low abundances of >2.5mm charcoal two months after wildfire events (GSD and ARI) may be because this size fraction is highly susceptible to fragmentation and hence has a low preservation potential. Therefore an abundance of this size fraction of charcoal should not be routinely expected in wildfire derived plant debris assemblages. The modern charcoal assemblages have their greatest relative abundances in the 500μm-1mm size fractions, a pattern also observed in the Late Cretaceous sediments (Chapter 4- section 4.3; Chapter 6- section 6.3). These modern charcoal assemblages indicate that wildfire deposits, at least in fine-medium sands, are often characterised by fine charcoal pieces.

7.4.2 Potential controls on charcoal distribution and abundances

7.4.2.1 Occurrence/distribution with regard to wildfire boundaries

Charcoal is recorded in samples collected within and outside of the wildfire boundaries, indicating that charcoal is not restricted to burnt areas and is subject to transportation. However greater relative abundances of charcoal have been recorded in samples collected within the wildfire boundaries across all size fractions and localities. The presence of this pattern is particularly important within the Rodeo-Chediski samples as it demonstrates that burnt areas contain relatively abundant charcoal assemblages several years after the fire event, even after enduring numerous storm events. Further evidence that all charcoal is not removed from a wildfire impacted landscape immediately through rainfall induced overland flow is shown by Castle Creek still turning black in the summer of 2013, three years after the wildfire event.

7.4.2.2 Size of channel

The modern wildfire derived charcoal deposits encompass a range of sandy channel settings including ephemeral streams, ephemeral rivers and a larger scale channel. Similar charcoal abundances are recorded for the ephemeral river and stream channels for all size fractions. Greater abundances of the 1mm-2.5mm and 500μm-1mm size fractions are recorded in the ARI-1 sample hinting that a larger channel setting exhibits a control over charcoal abundance. However, similar abundances of >2.5mm charcoal in all three channel settings do not support this. There is only a single large channel sample, therefore the role channel size plays in influencing charcoal abundance cannot really be addressed.

7.4.2.3 Vegetation stands

The presence of charcoal in forest and open woodland samples indicates that the different vegetation stands are similarly affected by wildfires. The greatest relative charcoal abundances are found within mixed conifer forest samples (from both Rodeo-Chediski and Schultz fire samples). The charcoal within the woodland sample is relatively abundant, and does not contain the lowest abundances of charcoal within the modern samples across any of the size fractions. However there is only a single woodland sample from within a wildfire boundary, therefore the role vegetation stands play in influencing charcoal abundances cannot really be addressed.

7.4.2.4 Suspension vs deposit samples

The suspension and deposit samples from the modern wildfires both contain charcoal. The suspension sample, however, is dominated by the 500µm-1mm size fraction, with no >2.5mm size fraction present. This sample was furthest from the wildfire boundary, however GSD-01 was located nearby. Charcoal is likely to fragment upon transportation which may explain the dominance of small charcoal pieces (for further discussion on charcoal transportation refer to Chapter 8- section 8.4.5.2). Larger charcoal pieces (if created by the original wildfire) may have been deposited closer to the wildfire boundary. Sample type may exhibit a taphonomic control over charcoal size distribution, however the role it plays with regard to relative charcoal abundance cannot be fully determined.

7.4.2.5 Type of flow

The greatest relative abundances of charcoal for the 1mm-2.5mm and 500µm-1mm size fractions occur within the hyperconcentrated flow deposit (ARI-1). Wildfire derived hyperconcentrated flow deposits are characterised by their fine grained composition and are likely to contain charcoal (characteristics of wildfire induced flow deposits are discussed in Chapter 8- section 8.2.2). The sediments and charcoal are entrained within the hyperconcentrated flow and are deposited together when the energy subsides (Chapter 8- section 8.2.2).

The water flow samples (all others) contain lower relative abundances of charcoal when compared to the hyperconcentrated flow deposit. The charcoal and sediment are not entrained together within this flow, and there is a greater chance of staggered deposition of charcoal pieces, potentially resulting in a size separation of charcoal. Hyperconcentrated flow deposits have been observed to contain greater than background charcoal abundances in the Late Cretaceous (bone bed 43- Chapter 8- section 8.2.4). Wildfires need to be considered as a trigger for the occurrence of this flow type. Additional wildfire derived hyperconcentrated flow deposits, both modern and ancient, should be investigated for the presence of charcoal in order to enhance understanding of charcoal transportational processes.

7.4.3 Range of charred plant organs and particle shapes

There is a greater range of plant tissues and organs preserved as charcoal within the samples from the three modern wildfire localities than observed in the Late Cretaceous sediments of Alberta (Chapter 4- section 4.3.4; Chapter 5- section 5.3.3; Chapter 6- section 6.3.7). Whereas the Cretaceous charcoal deposits are dominated almost entirely by wood fragments, the modern deposits contain a range of wood, twigs, needles and reproductive organs (Figs. 7.11-7.12).

There is a range of charcoal particle shapes within all the modern samples (Figs. 7.11-7.12). This differs from the Late Cretaceous assemblages that are comprised predominantly of either cubic or lath-like charcoal pieces (Chapter 4- section 4.3.4; Chapter 5- section 5.3.3; Chapter 6- section 6.3.7). The wider range of plant parts and plant particle shapes is exhibited in all modern samples including the suspension sample (GSD-W) and the hyperconcentrated flow deposit (ARI-1). The presence of this range, particularly in the aforementioned samples, indicates that mode of transportation of charcoal has not led to an organ or shape based sorting of the assemblages. However the transport distances are unknown for the Late Cretaceous deposits, therefore transportation may have led to a limited range of plant parts and plant particle shapes recorded for the Late Cretaceous deposits of Alberta (Chapter 4- section 4.3.4; Chapter 5- section 5.3.3; Chapter 6- section 6.3.7). The composition of the wildfire derived plant debris assemblages indicate that taphonomic processes are likely to have exhibited a control on the formation of Late Cretaceous charcoal deposits (for further discussion of taphonomic processes refer to Chapter 8- section 8.4).

7.4.4 Occurrence of partially charred and uncharred plant debris

Approximately half of the samples taken from both inside and outside the three modern wildfire boundaries contain partially charred debris. There are relatively low abundances of partially charred plant debris, however its presence within these plant debris assemblages highlights its absence from the Cretaceous assemblages (Chapters 4-6). The vegetation stands and geomorphology of the wildfire locality or deposit type of the sample (suspension vs deposit) are not linked to the presence or absence of partially charred debris (Fig. 7.13). All the samples collected shortly after the wildfire events (GSD and ARI) contain partially charred debris and display the greatest relative abundances.

Partially charred debris is only recorded in four (of nine) samples collected from the Rodeo-Chediski wildfire site and it occurs in low abundances. The duration (three years) between sample collection and the wildfire event may have affected the relative abundance of partially charred plant debris within these samples. Partially charred plant debris formed during the Rodeo-Chediski wildfire may have undergone fragmentation into charred and uncharred parts through decomposition and charcoal fragility whilst within these channel settings from 2002 to 2005 (for further discussion refer to Chapter 8- section 8.4.4).

Fig. 7.15 Charcoal rich overland flow following a rainstorm event, 2002, within the burned area of the Rodeo-Chediski wildfire. Source: Scott et al., 2014.

Partially charred plant debris may have also undergone this fragmentation during rainfall events and overland flow transportation (Fig. 7.15), leading to lower relative abundances when compared to both charred and uncharred plant debris. However the suspension sample (GSD-W), which was the result of water flow transportation outside of the wildfire boundary, contains the greatest relative abundance of 1mm-2.5mm partially charred plant debris.

There is an absence of partially charred plant debris within the Late Cretaceous samples. This may be due to the uncharred material decomposing over time leaving the charred debris only (discussed further in Chapter 8- section 8.4.4). From the plant debris assemblages collected from the Rodeo-Chediski wildfire, the duration between wildfire event and collection can be influential on the composition of the plant debris assemblage, and may be responsible for the absence of partially charred debris from the Late Cretaceous assemblages.

Uncharred plant debris is recorded within eleven (of thirteen) samples collected from three modern wildfires. This highlights an absence of this plant debris type within the Late Cretaceous samples and therefore a taphonomic bias. Uncharred plant debris occurs in all the modern wildfire contexts studied (Fig. 7.14). Therefore, the processes of decomposition are most likely to be responsible for the absence of uncharred plant debris within the Late Cretaceous samples (for further discussion refer to Chapter 8- section 8.4.4).

7.5 CONCLUSIONS

There is little charcoal belonging to the >2.5mm size fraction in the modern channel sand samples. A similar low abundance of this size fraction characterises the channel sandstones and also the shales and mudstones of the Late Cretaceous deposits (Chapter 4-6). However larger charcoal pieces have been recorded globally in Cretaceous sediments (Brown et al., 2012). Various factors, including charcoal transportation, may influence charcoal particle size distribution in sediments (discussed further in Chapter 8-section 8.4.5.2).

The plant debris assemblages from the three modern wildfire deposits contain a mixture of charred, uncharred and partially charred plant debris. The latter two are a major component of the modern plant debris assemblages but are not recorded within the Campanian and Maastrichtian deposits from Alberta, Canada, highlighting a taphonomic bias. There is a greater range of plant tissues, organs and particle shapes represented within the modern charcoals when compared with the Late Cretaceous samples. This indicates that there is a taphonomic bias within the Cretaceous assemblages, so they may not be representative of all components remaining after a wildfire (discussed further in Chapter 8- section 8.4).

The relative abundances of charcoal could not be fully shown to have been influenced by proximity to burned area, vegetation stands, forest type or the size of channel. However these factors should be considered by those studying both ancient and modern charcoal deposits, in order to enhance understanding of charcoal controls. The single modern hyperconcentrated flow deposit studied has been shown to contain greater relative abundances of charcoal than the water flow deposits. Therefore this deposit type should be investigated by researchers studying both ancient and modern charcoals.

Chapter 8:

Discussion

8.1 CHARCOAL QUANTIFICATION METRICS

As outlined in Chapter 3 (section 3.3.2) previously used charcoal and palaeobotanical quantification techniques were not deemed suitable for use within this thesis. The limitations of these techniques are discussed in the sections below (sections 8.1.1-8.1.3), along with the suitability of the novel quantification methodology developed within this thesis (section 8.1.4).

8.1.1 Particle counts

Charcoal quantification techniques have been heavily reliant on particle counts, whereby the number of charcoal particles per given weight of sediment is determined. These techniques are widely used within Quaternary research, particularly with reference to Holocene lake sediments, but have also been used within deep time studies (Clark et al., 1998; Whitlock and Millspaugh, 1996; Scott et al., 2000; Belcher et al., 2009; Higuera et al., 2009). Particle counts are versatile and can be applied to both in situ samples, such as coal blocks, and macerated bulk sediment samples.

Charcoal is brittle in nature (Scott, 2010; Glasspool and Scott, 2013) and therefore can easily fragment. Fragmentation can occur naturally during original deposition, with the processes associated with transportation responsible for both the abrasion and fragmentation of charcoal pieces. Differential fragmentation is achieved through differences in transportation, with charcoal transported by overland flow likely to undergo less fragmentation than particles transported fluvially as bedload (Belcher et al., 2013). In addition, the collection and analysis of charcoal can potentially enhance fragmentation, during collection and transportation in the field and during the maceration and sieving processes. This fragmentation potential can lead to a single charcoal piece fragmenting into hundreds of smaller charcoal laths. A trial particle count was undertaken to highlight the problems of fragmentation (Fig. 8.1, Table 8.1).

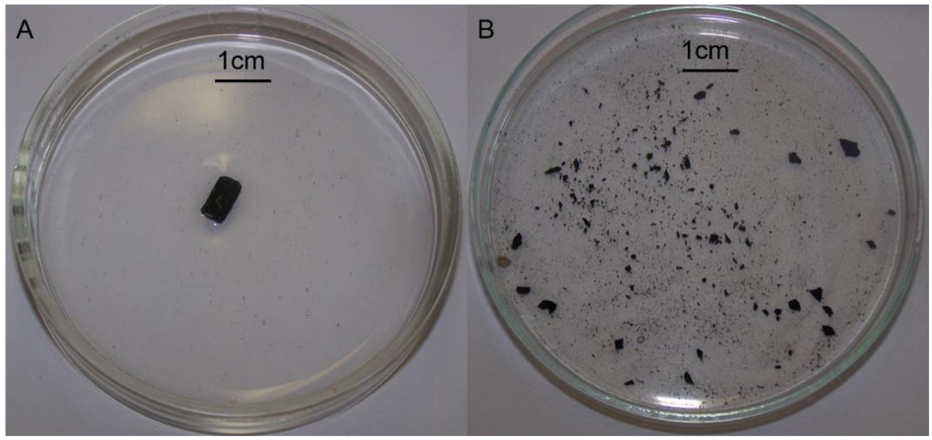


Fig. 8.1 Petri dishes containing charcoal from a trial charcoal sample, highlighting the role fragmentation can play in influencing relative charcoal abundances determined through particle counts. A- single charcoal particle, B- residue after A is subjected to fragmentation.

	Particle count
Whole charcoal	**1**
Fragmented charcoal	**96**

Table 8.1 Particle counts of trial charcoal sample, indicating the role fragmentation can play on determining relative charcoal abundance when calculated through particle counts.

The trial particle counts highlight the discrepancy in recorded charcoal abundances when analysing the same sample using a particle count methodology. The fragmented sample recorded 96 particles that were easily counted, with abundant smaller particles that could not be easily counted under light microscopy. Relative abundances of charcoal will be heavily influenced by the degree of fragmentation that has occurred, and therefore not reflect variations in wildfire activity. Despite widespread use, particle counts are likely to give both overestimations and underestimations (particle counts do not take into account the size of charcoal pieces) of relative charcoal abundances and thus lead to the misidentification of high and low fire activity.

8.1.2 Weight percentage

Weight percentage techniques, whereby the weight of charcoal within a known weight of rock is calculated, have been used within archaeology to quantify charcoal abundances (Sass and Kloss, 2014). Charcoal weight percentages are not influenced by the fragmentation potential of charcoal, so were considered for use within this thesis.

Trials were undertaken, whereby 20g of a lithological unit was weighed prior to maceration and sieving (methodology outlined in Chapter 3- section 3.3.1). Once sieved the residues were oven dried at 50°C for three hours. The dried residues were observed under a binocular microscope, and all charcoal fragments were picked. The picked fragments for each size fraction were weighed, determining relative charcoal abundances per 20g of sediment.

Whilst this technique allowed relative charcoal abundances to be determined, this did not prove to be a feasible methodology when applied on a large scale. The picking of all charcoal particles within each residue was highly time consuming, and therefore not practical when applied to 217 samples. In addition, the picking of charcoal pieces within the 500µm-1mm size fraction proved problematic, with some particles unable to be picked without fragmentation, thus potentially leading to underestimations of charcoal.

The main limitations associated with this technique were the use of oven drying and the picking of the charcoal, which has implications for the use of SEM. As outlined in Chapter 3 (section 3.3.4), charcoal fragments need to be cleaned in hydrofluoric acid prior to SEM analysis. Charcoal pieces have an increased chance of fragmentation if re-wetted once dried. Therefore this technique may have greatly reduced the number of charcoal pieces remaining large enough for SEM analysis. The combination of feasibility and fragmentation issues led to this technique being rejected for charcoal quantification within this thesis.

8.1.3 Charcoal volume

Palaeobotanical research has derived relative abundances from volumetric displacement experiments (Collinson, 1983). This technique was trialled to determine suitability for charcoal quantification. Similar to the weight percentage technique, charcoal volume is not influenced by fragmentation. 100ml of distilled water was placed into a 250ml measuring cylinder with 2ml subdivisions. A subsample of the lithological unit was placed into the measuring cylinder until the water was displaced by 20ml. The subsample was subsequently macerated and sieved according to the methodology outlined in Chapter 3 (section 3.3.1). The residues were oven dried at 50°C for three hours. Charcoal was picked under a binocular microscope and placed into a measuring cylinder filled with 100ml of distilled water and left to settle. Displacement was measured once all charcoal fragments had become waterlogged. However charcoal is very light, and noticeable displacement could not be observed.

This technique had many of the problems associated with weight percentage determination, including time consuming charcoal picking, along with potential implications for SEM through the re-wetting of the charcoal. In addition, the charcoal fragments took variable lengths of time to waterlog, again making the process time consuming. A major associated problem was the light weight of charcoal, which resulted in variations in displacement unable to be measured.

8.1.4 Newly developed charcoal quantification technique

As outlined in section 8.1.1, charcoal fragmentation is a major problem for establishing relative charcoal abundances through quantification techniques, and is often not taken into account by researchers (Belcher et al., 2013). The new quantification method used throughout this thesis (Chapter 3- section 3.3.3) addresses the problem of charcoal fragmentation, developing a strategy to reduce the impact of fragmentation on relative abundances of charcoal. The use of area coverage to determine relative charcoal abundances negates some of the problem of fragmentation, along with other issues raised during the trial methodologies (section 8.1.2-8.1.3).

This methodology has allowed both temporal and spatial distribution of charcoal within the Late Cretaceous to be recorded, with the data unlikely to be skewed by fragmentation. The calculation of numerical cover values in addition to an overall domin classification allowed small variations in relative abundances to be documented for both Late Cretaceous and modern wildfire derived plant debris.

Whilst this methodology offers a more representative measure of relative charcoal abundances throughout the Late Cretaceous than other techniques (section 8.1.1), the use of a domin scale is subjective, with variation expected in results when used by multiple researchers. However all domin classifications are internally consistent within this thesis. Repeatability tests were undertaken (Chapter 3- section 3.3.3) which showed the same domin classifications being recorded for each of the three subsamples.

The use of an area coverage methodology goes some way to addressing the problems of charcoal fragmentation (Belcher et al., 2013), however this new technique does not take into consideration the three-dimensional aspect of the charcoal particles (Weng, 2005; Belcher et al., 2013). It is therefore likely that, for some of the lithological units containing larger charcoal particles, >2.5mm, an underestimation of relative charcoal abundances has resulted from not assessing the volume of charcoal.

The domin classification and numerical cover values were calculated for both the whole and fragmented trial pieces of charcoal (Fig. 8.1, Table 8.2), in addition to the particle counts discussed above. The numerical cover value is lower for the whole piece of charcoal, with greater values recorded once fragmented. This is to be expected as volume is not taken into account. The length and width are recorded within an area coverage, however the height is not. The trial classifications indicate that an underestimation of relative charcoal abundances is occurring, and is therefore likely within both the Late Cretaceous and modern results (Chapters 4-7).

	Numerical Cover Value	**Domin classification**
Whole charcoal	10	Rare
Fragmented charcoal	17	Rare

Table 8.2 Domin classifications and numerical cover values for whole and fragmented charcoal (as shown in Fig. 8.1)

However, despite differences in numerical cover values between the whole and fragmented charcoal, the overall domin classification remains the same (Table 8.2). Potential underestimations of charcoal relative abundances due to the methodology are unlikely to have influenced overall domin classifications and therefore will not have impacted on the overall patterns of Late Cretaceous charcoal distribution documented within Chapters 4 and 6.

Image analysis techniques, such as Image J, have previously been used to quantify charcoal within lithological samples (Thevenon and Anselmetti, 2007). The use of these techniques can potentially improve the repeatability of results by other researchers, as the quantification technique can minimise subjectivity. However, the suitability of these techniques is dependent on the composition of the organic components of the sample. Whilst image analysis techniques can record the size and area covered by charcoal, this identification is based on colour. Image analysis techniques cannot distinguish between charcoal and coaly fragments, as they are both opaque and black in colour. For samples with a high proportion of coaly fragments this technique is not appropriate as each charcoal fragment has to be manually selected for the computer to be able to calculate an area coverage. Light microscopy techniques would be required for the identification of both the charcoal and coaly fragments prior to image analysis techniques being undertaken (Chapter 3- section 3.3.4).

Many of the lithological samples, particularly from the Dinosaur Park Formation, contained coaly fragments in varying abundances. All charcoal particles would need to be classified by eye, therefore the use of image analysis techniques would be equally as subjective as the novel method outlined within this thesis. However imaging techniques could provide a numerical value of area covered, instead of an estimate, increasing the repeatability of charcoal coverage values. This thesis focuses on analysing a large number of samples for relative charcoal abundance, rather than precise charcoal area measurements, therefore image analysis techniques were not included within this thesis.

Confocal laser scanning microscopy has been applied to charcoal research in order to determine three-dimensional volumes of charcoal, representing the first quantification technique incorporating charcoal volume (Belcher et al., 2013). Experiments were carried out using Cretaceous and modern charcoal samples. Whilst this technique mitigates the differential problems of fragmentation, it is not accessible to the majority of researchers due to high associated costs. Research is currently being undertaken to predict charcoal volumes from the surface area charcoal images (Weng, 2005; Belcher et al., 2013). Estimation of volume for numerous charcoal fragments is highly time consuming (Weng, 2005), therefore making it unsuitable for use within this thesis. In addition area measurements do not necessarily have a simple relationship to the 3-D volume, and variability in fuel characteristics may influence overall charcoal volume (Weng, 2005; Ali et al., 2009). Further development is necessary, investigating both modern and ancient charcoal, before this technique can be widely adopted.

Alternative quantification methods could have been applied within my novel methodology regarding the determination of a percentage cover value. Charcoal quantification could have been obtained through the determination of a percentage charcoal coverage, either for a sub-sample as a whole or for each of the twenty centimetre squares within a sub-sample.

Identification of an overall percentage cover value for each sub-sample would be highly problematic. The magnification required to view the sample as a whole would not be sufficient to identify charcoal. This technique could lead to inaccuracies in the determination of charcoal coverage, and determinations of percentages are likely to vary between researchers.

Percentage coverage could have been determined for all twenty squares within a sub-sample, and then averaged to give an overall percentage cover value for the lithological unit. This would have been a possible alternative method and would record more subtle variations in charcoal abundances than the proposed and adopted method used within this thesis (refer to Chapter 3- section 3.3.3 for identification of numerical cover values).

The novel methodology developed within this thesis only requires the classification of charcoal in broad categories of cover; up to a quarter coverage, quarter-third, third-half and greater than a half (Chapter 3- section 3.3.3). Determinations of charcoal coverage within these broader categories are considered likely to be repeatable between multiple researchers. Estimates of percentage coverage are considered less-likely to be repeatable, both between researches and by the same researcher at different times, and therefore the percentage cover per square technique was not adopted during this thesis.

Therefore, the new quantification methodology developed within this thesis may be a useful tool for charcoal researchers to mitigate the effects of differential fragmentation, due to its accessibility and repeatability. However, it should be noted that this methodology can be modified as ability to calculate charcoal volume increases.

8.1.2 Identification of charcoal

Selected charcoal pieces were viewed using SEM in order to confirm charcoalification through the presence of homogenised cell walls. The classification of charcoal under light microscopy adhered to the guidelines for charcoal recognition outlined by Scott (1989, 2000, 2010) (Chapter 3- section 3.3.1). Any particles that could not be reliably classified as charcoal under light microscopy were not included within the domin classifications or numerical cover values for the determination of the relative abundances of charcoal, in order to prevent an overestimation of charcoal.

Therefore, it is possible that some low temperature charcoal may have been overlooked within this thesis, due to the difficulty of observing the necessary characteristics for identification. Some particles did not display the same obvious lustre as other charcoal fragments, and cellular detail was difficult to observe. In order to address potential underestimation of charcoal abundances, reflectance measurements of a small sample of charcoal (n=3) were obtained, with all particles greater than 1mm in size. Three particles, taken from the same lithological unit within transect DPP-10-1 (Chapter 4), were selected. Two had been identified as charcoal under light microscopy (1-22a, 1-22b), whilst for one particle (1-22q) it was uncertain if this was or was not charcoal, and therefore it had been excluded from the charcoal quantification. Reflectance measurements were obtained to determine if particle 1-22q represented low temperature charcoal.

The charcoal pieces were embedded in polished blocks and studied (using standard coal petrography techniques, as outlined by Scott and Jones, 1991, 1994; Scott and Glasspool, 2005; McParland, 2007) under a Nikon microphot microscope connected to Leica Qwin image analysis systems (Leica Image Systems Ltd., 1997). Reflectance was measured under oil (Cargill immersion oil, refractive index 1.518) using a x40 objective lens. The microscope was calibrated against five standards: Spinel (Ro- 0.393), YAG (Ro- 0.929), GGG (Ro- 1.7486), cubic zirconium (Ro- 3.188) and silicon carbide (Ro- 7.506). Fifty random points were analysed per charcoal sample. Mean random reflectance data is shown in Table 8.3.

The relationship between increasing charring temperature and higher associated mean reflectance is well established (Jones et al., 1991; Scott and Jones, 1991, 1994; Scott, 2000; Scott and Glasspool, 2005, 2007; McParland et al., 2007; Braadbaart and Poole, 2008; McParland et al., 2009b; Ascough et al., 2011). McParland et al., (2009b) generated a calibration curve for charring at a known temperature (y-axis) against the resulting mean random reflection results (x-axis). Temperatures were inferred for a 1hour and 24hour duration of charring (McParland et al., 2009b). Therefore reflectance values can be used to determine the temperature of charring through extrapolation of the calibration curve (McParland et al., 2009b). For example, a mean random reflectance of 3%Ro indicates a charring temperature of between 575°C-650°C.

	1-22a	**1-22b**	**1-22q**
Mean	0.88	2.05	0.68
Variance	0.02	0.01	0.1
Maximum	1.11	2.22	1.57
Minimum	0.48	1.71	0.28
Standard Deviation	0.14	0.1	0.32

Table 8.3 Mean random reflectance data derived from three charcoal fragments from DPP-10-1

The mean random reflectance data for the Cretaceous charcoal particles (Table 8.3) indicate that all samples were charcoal, with temperatures in excess of 300°C. The mean random reflectance of 1-22a was 0.88%Ro indicating charring temperatures of around 350-425°C, and for 1-22b (2.05%Ro) temperatures of 450-550°C. Particle 1-22q, for which the identification of charcoal was uncertain under light microscopy, has a mean random reflectance of 0.67%Ro. This indicates a charring temperature of 300-350°C, i.e. a charcoal formed at low temperatures. Therefore charcoal formed at low temperatures could not be reliably distinguished under light microscope and has been excluded from the charcoal counts. This will have resulted in an under representation of Cretaceous charcoal abundances. However, there were a low number of these unclassifiable particles overall, therefore it is unlikely that the addition of these would have influenced the domin classification.

8.2 FORMATION OF CHARCOAL-CONTAINING DEPOSITS

8.2.1 Impacts of modern wildfires on landscapes

The impact of a surface fire upon the landscape may be severe (Chapter 1-section 1.4). This will depend on three principle factors: the amount of fuel built-up on the land surface; the intensity and severity of the fire; and the interval between the fire and the first rainstorm (Shakesby and Doerr, 2006). The removal of vegetation can lower erosion thresholds, thus increasing runoff rates (Goode et al., 2012). The combination of lower erosion thresholds and increased runoff can result in large sediment transportation from slopes into fluvial systems via mechanisms such as landslides and debris flows (Goode et al., 2012). Fires can enhance the water repellency of soils and can result in the binding of soil particles through the modification of their organic content (Shakesby and Doerr, 2006) (Chapter 1). The combined effect is that the uppermost layer of the soil becomes more porous but a more water impenetrable layer forms beneath (Shakesby and Doerr, 2006).

Storm characteristics and timing of rainfall occurrence are key factors in sediment transportation after a fire event (Moody et al., 2008; Goode et al., 2012). Two watersheds were examined by Moody et al., (2008) and showed that the proximity of rainfall to a wildfire event greatly influenced the amount of eroded, transported and deposited sediment. Intense rainfall occurring shortly after a wildfire can be responsible for the erosion, transportation and deposition of large volumes of sediment (Moody et al., 2008). By contrast, if the landscape has recovered prior to intense rainfall then the erosive response may be less, as significant vegetation regrowth may increase interception, and other rainfall events may have removed some of the available sediment (Moody et al., 2008).

Sediment containing charcoal is released into the depositional system and may be fluvially transported (Moody et al., 2008; Moody and Martin, 2009). Sediments known to have been deposited after wildfire occurrences are known to contain charcoal (Wohl and Pearthree, 1991; Jones, 1993; Cannon and Reneau, 2000; Wolfe et al., 2006). The occurrence of charcoal may, therefore, provide a significant clue to the recognition of deposits that have formed as a result of wildfire events (Wohl and Pearthree, 1991; Meyer et al., 1992; Cannon and Reneau, 2000). Therefore more sediments, particularly in deep time, should be analysed for the presence of charcoal to determine whether wildfire events may have played a role in their formation.

8.2.2 Mechanisms of sediment transportation during wildfire induced flow events

Flooding events (water flow and hyperconcentrated flow) and debris flow events can result from rainfall following modern wildfires (Meyer and Wells, 1997; Cannon and Reneau, 2000: Moody et al., 2008; Moody and Martin, 2009; Jenkins et al., 2011). These flow events can be classified based on the entrained sediment composition of the flow (Pierson, 2005a).

The flow behaviour of floods (water flow and hyperconcentrated flow) is controlled by the water, typically with fine grained sediment being transported, whereas the flow of debris flows is controlled by the entrained sediment, often with a coarser composition (Pierson, 2005a). The two can be interlinked with both floods and debris flows occurring within the same flow event (Pierson, 2005a).

Debris flow deposits can be characterised by being matrix supported with variation in clast sizes, along with angular sand grains (Pierson, 2005a). Some classifications require 50% of particles being greater than sand size to recognise a debris flow (Varnes, 1984; Pierson, 2005b). They can rapidly infill channels and often display normal grading (Pierson, 2005a). Modern debris flows typically occur in steep watersheds (Cannon and Reneau, 2000); however, Lovelace (2006) noted that slopes only need to be 1-2° for debris flows to occur, though these are likely to travel shorter distances.

Hyperconcentrated flows contain levels of suspended sediment which can alter their transportation properties, can be highly erosive and are often responsible for the transportation of large volumes of sand in dynamic suspension (Meyer and Wells, 1997; Pierson, 2005b). Deposits are typically consolidated and characterised by faint horizontal to massive bedding, poor sorting and rounded grains (Pierson, 2005a).

Water flows contain suspended sediment, but the quantities are not sufficient to alter their transportation properties (Pierson, 2005a). The majority of sediment is transported near the bed, and the bedload can contain material up to boulder size (Pierson, 2005a). Deposits are typically friable and characterised by the presence of cross-bedding, ripple laminations, good sorting and rounded grains (Pierson, 2005a). Water flow and debris flow deposits should be investigated for the presence or absence of charcoal to establish the role wildfires played, if any, in the formation of these deposits.

8.2.3 Formation of Campanian vertebrate deposits in the Dinosaur Park Formation

The presence of charcoal within the studied vertebrate deposits and sediments of the Dinosaur Park Formation indicates that the environment was routinely influenced by wildfire (Chapter 5- section 5.3.1). The vertebrate deposits have greater overall charcoal abundance across all three size fractions when compared with the sediment with isolated bone, particularly for the finest charcoal size of 500μm-1mm (Fig. 5.7). Palaeochannel sandstones in nearby sediments of similar age without any bone material do contain charcoal. However, they have lower domin charcoal abundances across all three size fractions when compared with the vertebrate deposits. This indicates that the presence of charcoal within the vertebrate deposits is not merely a consequence of normal ‘background’ fluvial transport and deposition. There is no orientation of the bones to indicate directional flow associated with fluvial transportation. The bone taphonomy (Ryan et al., 2001) indicates that the bones were moved after death and decomposition rather than remaining stationary, and two of the vertebrate deposits lack microvertebrates. For these reasons, it does not appear that the dinosaur bones within the vertebrate deposits acted as traps for charcoal. Overall, therefore, the formation of vertebrate deposits is most likely to be the result of flow events.

The vertebrate deposits in the Dinosaur Park Formation are formed from fine- to medium-grained sandstones, lack large grain size variation and have rounded grains (Chapter 5- section 5.2.3). Trough cross bedding is documented in bone beds 43 and

50. Therefore these deposits are likely to have resulted from water flow and not debris flows (section 8.2.2).

In the seasonal palaeoclimate (Chapter 4- section 4.2.1) post-fire destabilisation of the landscape, coupled with heavy or prolonged rainfall shortly after the wildfire event, could have resulted in water flow flooding entraining both bone and charcoal prior to deposition. The flow events would have been short lived, with the vertebrate deposits formed close to the area of destabilisation, as energy reduced due to the low gradient river system during deposition of the Dinosaur Park Formation (Chapter 4- section 4.2.1).

The other nearby palaeochannel sandstones of similar age lacking bone and with lower abundances of charcoal may result from deposition after lower intensity rainfall events. Alternatively, rainfall occurring significantly after a wildfire event would result in reduced overland water flow due to regrowth of vegetation stabilising the surface and impeding flow.

8.2.3.1 The specific case of bone bed 43 (Dinosaur Park Formation)

Bone bed 43 in the Dinosaur Park Formation is distinct within the studied bone beds owing to the high number of dinosaur specimens (57 *Centrosaurus apertus)* (Ryan et al., 2001). Post-mortem analysis of the dinosaur bones indicates the presence of fractures, mostly concentrated on the ends of bones. Because of the lack of publications dealing with the other bone beds in the Dinosaur Park Formation it is unknown whether similar bone fracture patterns occur elsewhere. In addition mudclasts are present within the fine-grained sandstone body containing the dinosaur bones (Ryan et al., 2001).

A large flooding event has previously been suggested as a hypothesis for the origin of formation of this bone bed (Currie and Dodson, 1984; Ryan et al., 2001; Eberth and Getty, 2005). Charcoal has now been identified within this bone bed (Chapter 5- section 5.3.1), something that has been previously overlooked. In addition, of all samples in this study, the stratigraphic horizon of bone bed 43 contains the most charcoal wherever it has been sampled (Fig. 5.7). The relative abundance of charcoal within this bone bed indicates that post-fire erosional flooding may have been responsible for the formation of this vertebrate deposit.

The dinosaur bones and charcoal are concentrated at the bottom of the uppermost stacked palaeochannel sandstone. This lower part is massive, well consolidated and comprised of rounded sand grains (Chapter 5- section 5.2.3.5), indicating that this may have been deposited by a hyperconcentrated flow flooding event which entrained dinosaur bones from the surrounding landscape prior to deposition. The upper part of the palaeochannel sandstone contains ripples and cross bedding, along with a fining upwards sequence (Chapter 5- section 5.2.3.5), and these characteristics are indicative of a water flow flooding event. Once the deposition of the lower part of the bone bed had occurred, there would have been reduced suspended sediment, altering the nature of the flow from hyperconcentrated to water flow dominated. The evidence indicates that a flooding event caused by intense rainfall shortly after a wildfire event was responsible for the erosion, transportation and deposition of both bone and charcoal into this vertebrate deposit.

However, alternative fire-induced mechanisms need to be considered for the formation of bone bed 43. The majority of hyperconcentrated flow examples, both modern and in deep time, occur on slopes greater than a few degrees (Meyer and Wells, 1997; Pierson, 2005b; Lovelace, 2006). The depositional environment of the Dinosaur Park Formation has been interpreted as a low relief alluvial plain with shallow gradients (Chapter 4- section 4.2.1). Therefore, it is possible that the low gradients were not sufficiently steep to allow the development of a hyperconcentrated flow event, and thus may have prevented a flooding event entraining dinosaur bones across the floodplain.

It is possible that dinosaur bones were present on the overbank facies at the edge of an abandoned river channel. Flood waters, caused by intense rainfall on a burnt landscape, may have flowed into the channel resulting in the destabilisation of the river bank. The process of the floodwater undercutting the bank of the river may have resulted in the dinosaur carcasses falling into the channel leading to the formation of bone bed 43. However, if the flow still had sufficient energy this may have resulted in the separation of dinosaur bones, a feature not observed within bone bed 43. Whilst the low gradient may pose a problem for the development of a hyperconcetrated flow event, the sedimentary indicators present within the bone bed do support that mechanism for the formation of bone bed 43.

8.2.4 Formation of the majority of the Campanian/Maastrichtian charcoal-containing deposits

The presence of charcoal within the Campanian and Maastrichtian sediments of southern Alberta indicates that the environments were influenced by wildfire events (Chapters 4-6). Unlike the Campanian vertebrate deposits where both water flow and hyperconcentrated flow events were instrumental in charcoal deposition (section 8.2.3), the sedimentological indicators of these mechanisms of formation are not present in the majority of Campanian/Maaastrichtian charcoal bearing deposits.

The products of these flow events were large palaeochannel sandstone units. The evidence of charcoal distributed within all lithologies for the Late Cretaceous (Chapter 4- section 4.3, Chapter 6- section 6.3) suggests that these charcoal deposits may be the result of ‘normal’ background overland flow and/or fluvial transportation and deposition.

It can be hypothesised that the combination of a wildfire’s impact on the landscape (Chapter 1- section 1.4, section 8.2.1), coupled with rainfall, played a major role in the formation of the majority of investigated Campanian/Maastrichtian charcoal-bearing deposits. There is a ‘window of disturbance’ during which landscapes can be altered (Prosser and Williams, 1998; Doerr and Shakesby, 2013). This encompasses the direct changes made by a fire, such as removal of vegetation and litter, and indirect changes, such as infiltration and overland flow, altered stream flows and vegetation recovery (Doerr and Shakesby, 2013). This disturbance window has variable timescales from a few months to numerous years (Chapter 7- section 7.4.2.1).

As outlined in Chapter 1 (section 1.2) the occurrence of charcoal within sedimentary successions can be influenced by numerous processes. Since this thesis focuses on charcoal >500µm, it is likely that the majority of the charcoal was deposited on the surface during a wildfire and not incorporated into a smoke plume (refer to section 8.4.5.1 for discussion of windblown charcoal). Therefore it can be assumed that these charcoal deposits represent localised fire activity, however it is likely that transportation processes acted on the charcoal.

In modern ecosystems the surface storage of rainfall, held within vegetation coverage and litter, is instrumental in governing the amount of overland flow affecting a landscape. Surface storage of rainfall varies globally with up to 3mm being held within the litter layer alone (Shakesby and Doerr, 2006). The expanse of ground covered by vegetation and/or litter is strongly linked to overland flow amounts after a rainfall event (Shakesby and Doerr, 2006). For ground coverage of 37% only 14% of rainfall contributes to overland flow, however for 10% ground coverage approximately 73% of rainfall contributes to overland flow (Robichaud et al., 2000; Shakesby and Doerr, 2006; Doerr and Shakesby, 2013). Ground coverage exhibits a significant control over overland flow amounts, therefore wildfire occurrence can greatly enhance overland flow through vegetation and litter removal.

Soil hydrophobicity (Chapter 1- section 1.4; section 8.2.2) is acknowledged as one of the dominant factors influencing accelerated slope runoff and erosional levels after a fire event (Doerr et al., 2009; Finley and Glenn, 2009; Beatty and Smith, 2010). Soil infiltration experiments in modern burnt forest stands indicate that infiltration is reduced 16-fold for hydrophobic soils compared to non-hydrophobic soils in the same environment (Leighton-Boyce et al., 2007; Doerr and Shakesby, 2013). The impact of soil hydrophobicity is enhanced if there is a period of dry conditions between the wildfire and a rainfall event (Doerr and Shakesby, 2013).

Reductions in surface storage and infiltration lead to enhanced overland flow after rainfall events. Surface charcoal fragments produced by a wildfire event are likely to be transported through enhanced overland flow rates. Rainsplash on soils during prolonged rainfall events can be responsible for significant downslope soil transfer, with soils being entrained by overland flows (Doerr and Shakesby, 2013).

This mechanism may also be responsible for the transportation and deposition of charcoal deposits in the Late Cretaceous of Alberta.

The climatic information for all studied Formations indicates seasonally wet environments, with significant rainfall levels during deposition of the Maastrichtian Formations (Chapter 4- section 4.2.1; Chapter 6- section 6.2.2). This indicates that rainfall would have been occurring regularly, therefore giving a high likelihood of charcoal transportation via this mechanism.

The depositional environments for all studied Late Cretaceous Formations, with the exception of the Battle Formation, occurred on low sinuosity, fluvially influenced coastal to alluvial plains. The responses of river channels to the destruction and alteration of vegetation, litter and soil layers as a result of wildfires are complex (Doerr and Shakesby, 2013). This can lead to channel aggradation, braiding and the creation of alluvial fans after large scale disturbances (Meyer and Wells, 1997; Leighton-Boyce et al, 2003; Doerr and Shakesby, 2013). Surface charcoal deposits could be washed into rivers as a result of overland flow, and transported large distances in the fluvial system. Flooding events may be responsible for the transportation and deposition of charcoal on floodplains. The occurrence of charcoal in overbank shale and mudstone units may be indicative of this mode of transportation and deposition.

8.3 CLIMATIC INFLUENCES ON LATE CRETACEOUS CHARCOAL DISTRIBUTION

Climatic factors can be influential in determining wildfire occurrence and propagation, particularly with regard to fuel availability and distribution (Chapter 1- section 1.6). Climatic influences are complex, with often conflicting opinions on the control exerted on wildfire occurrence. It is unclear what magnitude of climatic change should be evident from sedimentary records of wildfire history (Gavin et al., 2006). Little research has been carried out into long-term fire histories, where a good record of climatic variability is known (Gavin et al., 2006). Wetter conditions are considered to enhance primary production of vegetation, and thus increase fire activity

(Nelson et al., 2012). However rainfall above 800mm has been shown to impede wildfire occurrence in African savannahs (Nelson et al., 2012). Elevated charcoal abundances have been associated with decadal drought observable in Holocene lake sediments (Whitlock et al., 1997). However, this research relies upon particle counts of charcoal and therefore, may be influenced by the fragmentation potential of charcoal (section 8.1.1).

The role climate may have played cannot be considered for the Campanian due to a lack of detailed palaeoclimatic information (Chapter 4- section 4.2.1). Whilst the Campanian of southern Alberta is considered to be seasonally warm and wet, rainfall amounts and small scale climatic variations in time have not been documented (Chapter 4- section 4.2.1). Palaeoclimatic data are available for the Maastrichtian of southern Alberta, derived from palynology and palaeosols along with turtle, crocodilian and amphibian abundances (Chapter 6- section 6.2.2).

The palaeoclimate alternated from warm and wet to cool and dry during the Maastrichtian (Chapter 6- section 6.2.2, Table 6.2). Charcoal was recorded within both climatic phases with similar relative abundances. The temporal distribution of relative charcoal abundances did not correlate with specific climatic phases, therefore climate exerted little or no influence on Maastrichtian wildfire occurrence. Further research needs to be undertaken, as suggested by Gavin et al., (2006), in order to determine the magnitude of climatic change that may result in observable variation in charcoal abundances.

Whilst relative charcoal abundances did not show a correlation with the Maastrichtian climatic phases, variation associated with waterlogged conditions was recorded. The degree of standing water soil profiles contain may influence wildfire occurrence. Shale units close stratigraphically to coal units and palaeosols indicating waterlogged conditions, did not contain any charcoal (Chapter 6- section 6.4.1). Waterlogged conditions may result in litter layers being too damp to ignite, thus preventing the propagation of wildfires.

8.4 TAPHONOMIC BIASES IN LATE CRETACEOUS CHARCOAL ASSEMBLAGES

8.4.1 Taphonomic controls on plant organs within Late Cretaceous charcoal assemblages

The plant debris assemblages from the modern wildfires (Chapter 7- section 7.3) contain a greater range of plant organs than those of Late Cretaceous origin (Chapters 4-6). The modern samples contain charred wood along with probable twigs, pollen cone scales, thorns and unidentifiabled particles (Chapter 7- Fig. 7.11). The Late Cretaceous charcoal assemblages are comprised almost entirely of wood, with a single leaf fragment recorded from the Maastrichtian of Drumheller (Chapter 4- section 4.3.4, Fig. 4.9; Chapter 6- section 6.3.7, Figs. 6.13-6.14). This limited range of organs is not related to the age of deposits, because charred plant debris assemblages with diverse organs are recorded at numerous Cretaceous localities (Chapter 2- section 2.1, Tables 2.1-2.3).

The influence of fluvial activity on charcoal transportation is likely to result in the separation of plant organs due to differences in waterlogging behaviour (Nichols et al., 2000). Charcoal fragments initially float upon water, with agitation of the surface water responsible for increases in waterlogging rates (Nichols et al., 2000). Agitation causes charcoal fragments to be immersed in water, with repeated submersion leading to overall waterlogging (Vaughan and Nichols, 1995).

Waterlogging experiments indicated that *Pinus sylvestris* showed great waterlogging variation between organs, with charred needles waterlogging at twice the rate of charred wood and leaves (Nichols et al., 2000). The experimental research highlighted a much slower rate of waterlogging for charred cones, and potentially for charred flowers (Nichols et al., 2000). Different degrees of transportation would occur with faster waterlogging organs, such as wood, being transported shorter distances.

Therefore, wood and other plant organs are likely to be deposited in separate events, thus resulting in separate assemblages.

Deposition of charcoal via fluvial processes may, therefore, be a contributing factor leading to Late Cretaceous assemblages dominated almost entirely by wood (Chapter 4- section 4.3.4; Chapter 6- section 6.3.7). The low occurrences of charred leaves within these assemblages (single fragment only, Chapter 6- section 6.3.7) may be the result of differences in the waterlogging potential of leaves. Leaf shape can be influential in determining the rate of waterlogging. However leaf shapes have been shown to have different degrees of flammability, with narrow-leaf forms exhibiting greater flammability than broad-leaf forms (Belcher et al., 2010). Therefore the low leaf abundance within the Late Cretaceous sediments may be a function of flammability.

Leaf charcoal is preserved in other Cretaceous sediments, with evidence recorded in Japan, Portugal, Antarctica and New Zealand (Chapter 2- Tables 2.1-2.3 and references therein). However there are only four documented occurrences in the whole of the Cretaceous to date, indicating that charred leaves may not be prevalent within plant debris assemblages. Charred leaves have been recorded in modern plant debris assemblages derived from the Frensham Common fire, 1995, with percentage abundances ranging from 25%-45% (Scott et al., 2000). Charred leaves were not, however, recorded in the three modern wildfire assemblages reported within this thesis.

The presence of charcoalified leaves in some examples of both Cretaceous and modern plant debris assemblages indicates that some types of charcoalified leaf can be preserved within sediments (Scott et al., 2000; Chapter 2- Tables 2.1-2.3 and references therein). It is unlikely that fluvial processes are responsible for this taphonomic bias within the Late Cretaceous plant debris assemblages of southern Alberta, and that other factors, such as being fully consumed by wildfires or fragmentation into unidentifiable pieces, are likely have been responsible for the low recorded abundance.

8.4.2 Charcoal assemblages as a reflection of local vegetation

There is a detailed palynological record for the Late Cretaceous of southern Alberta, indicating highly diverse vegetation communities (Braman and Koppelhus, 2005; Eberth and Braman, 2012). Over five hundred different palynomorphs have been identified from the Oldman and Dinosaur Park Formations (not including dinoflagellates, megaspores or fungal spores) however the affinity of many of these remains unknown (Braman and Koppelhus, 2005). The Late Cretaceous charcoal assemblages do not reflect the diverse vegetation community, being comprised almost entirely of gymnosperm wood (Chapter 4- section 4.3.4, Chapter 6- section 6.3.7).

The palaeobotanical mesofossil record is sparse throughout all Formations studied with little published research (Braman and Koppelhus, 2005; Koppelhus, 2005; Tweet et al., 2008). Some carbonised compressions and impressions have been recorded within the sediments of the Oldman and Dinosaur Park Formations, predominantly composed of bark, cones and seeds (Koppelhus, 2005). Twenty types of leaf, twig and cone fossils have been identified, but these have never been fully described or published (Koppelhus, 2005). One hundred permineralised gymnosperm cones were recorded within the Horseshoe Canyon Formation, all recorded in a single horizon (Serbet and Stockey, 1991), along with a single angiosperm infructescence and silicified Cupresaceae conifers (Mclver and Aulenbach, 1994; Bogner et al., 2005).

Palynological data indicates the presence of a range of ferns, including Schizaeaceae and Gleicheniaceae, and tree ferns, comprising 40% of the total record within the Dinosaur Park Formation (Jarzen, 1982; Braman and Koppelhus, 2005). Fern prairies have been hypothesised to have occupied open areas (Coe et al., 1987; Mallon et al., 2013), however evidence for fern-communities in southern Alberta is lacking (Tiffney, 1992; Mallon et al., 2013).

Diverse ferns have also been recorded within the Horseshoe Canyon Formation, occurring as permineralisations (Serbet and Rothwell, 1999, 2003, 2006). These have all been observed in stratigraphic units close to coal #7, and originate from the Kent's Knoll locality (Fig. 8.2; Serbet and Rothwell, 1999, 2003, 2006). Therefore it is possible that ferns covered a restricted area during the Maastrichtian of southern Alberta, and were not widespread.

Charred ferns are not recorded within any of the sampled Formations in the Late Cretaceous of Alberta. Charred fern communities have been recorded within the Wealden of Europe during the Early Cretaceous (Chapter 2- Table 2.1), therefore it is clear that these can readily be charcoalified. The absence within the Campanian and Maastrichtian Formations may be indicative of an absence of widespread fern prairies at those times, or may indicate that wildfires were not occurring readily within open areas.

Gymnospermous pollen is recorded in large abundances within the Campanian and lower Maastrichtian Formations, representing over half the palynological record (Eberth and Braman, 2012; Chapter 6- section 6.2.2). Vegetation reconstructions indicate that conifer forests dominated the Campanian landscape of southern Alberta (Ramanujam, 1972; Braman and Koppelhus, 2005; Koppelhus, 2005; Mallon et al., 2013). Therefore the gymnosperm dominated charcoal assemblages are likely to reflect the local vegetation at the time of the wildfires.

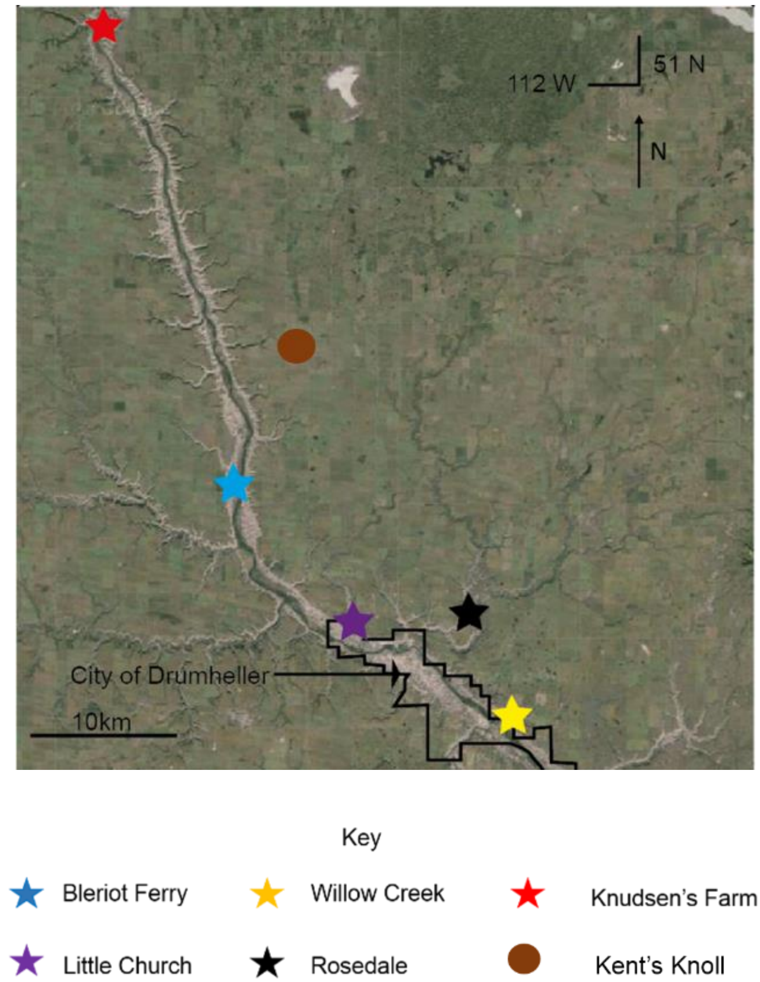


Fig. 8.2 Map of Drumheller showing Maastrichtian sampling localities (Chapter 6- Fig. 6.1), and the geographical position of Kent's Knoll, where permineralised ferns have previously been documented.

Palynological data indicate a range of different angiosperm types, however affinity and stature cannot be determined (Braman and Koppelhus, 2005). Angiosperm trees are not considered likely within the depositional environments of the Oldman and Dinosaur Park Formations, as angiosperm wood was unknown prior to this thesis (Wolfe and Upchurch, 1987; Braman and Koppelhus, 2005; Mallon et al., 2013). The charred angiosperm wood recorded in Chapter 4 (section 4.3.4) represents the first documented occurrence within the Dinosaur Park Formation. There are very low relative abundances of angiosperm charcoal recorded in the Late Cretaceous of southern Alberta, with only three fragments recorded, out of seventy-nine fragments analysed using SEM. (Chapter 4- section 4.3.4; Chapter 6- section 6.3.7, Fig. 6.14E-F).

The presence of charred angiosperm wood indicates possible angiosperm trees or shrubs, but the low occurrences within the charred assemblages may indicate that these were not prevalent within these Late Cretaceous landscapes. Angiosperm trees extended up to 80°N globally in the Campanian and Maastrichtian (Peralta-Medina and Falcon-Lang, 2012), therefore geographical constraints on distribution are not responsible for the low recorded charred angiosperm abundances.

There is an excellent Cretaceous record of angiosperm charcoal, particularly with regard to floral structures and wood (Chapter 2- Tables 2.1-2.3 and references therein). Therefore the low abundances recorded within this thesis are not representative of a lack of charcoalification potential. The palynology and single permineralised infructescence (Bogner et al., 2005; Braman and Koppelhus, 2005; Koppelhus, 2005; Eberth and Braman, 2012), coupled with the rare occurrences of charred angiosperm wood and single angiosperm leaf fragment documented within this thesis, indicates that angiosperms were present within the Late Cretaceous landscapes of southern Alberta. However there is a taphonomic bias within the charcoal assemblages, with gymnospermous wood dominating all assemblages. This may be a taphonomic bias caused by transportation leading to assemblages with both low taxonomic diversity and low diversity of plant organs.

However the composition of local vegetation needs to be considered. The abundance and stature of angiosperms within the Late Cretaceous of Alberta is unknown, due to a lack of palaeobotanical research. Angiosperms may have represented low stature, herbaceous, sparsely distributed vegetation. This may have been entirely consumed by wildfires, leaving no charcoal residue, or wildfires may not have influenced these environments. Therefore the low abundances of charcoal may be a reflection of wildfires preferentially influencing gymnosperm dominated environments.

The fluvial depositional environment of all Late Cretaceous Formations (with the exception of the Battle Formation) indicates that transportation is likely to have played a major role in the formation of the charcoal assemblages (section 8.3.1). Therefore it is possible that fluvial transportation may have led to the potential fragmentation of charred flowers. As outlined in section 8.3.1, charred flowers may remain buoyant longer than wood fragments, therefore may be deposited in separate assemblages. The investigations of charcoal within all lithologies indicate that these organs did not remain anywhere within the catchment of the depositional environments of the Late Cretaceous of southern Alberta. Therefore fluvial transportation is unlikely to be responsible for the absence of charred flowers.

The sample size used within this thesis may have exhibited a control on the range of plant organs present. Whilst there is evidence of numerous Cretaceous localities with charred flowers (Chapter 2- Tables 2.2-2.3 and references therein), those plant organs were still rarer within those sedimentary units than wood charcoal. The absence of charred flowers and other plant organs may be the result of the small sub-sample size of 20g used throughout this thesis. 20kg sediment samples were investigated by Herendeen et al (1999) for the presence of Cretaceous flowers. This larger sample size resulted in 250 floral specimens being recorded (Herendeen et al., 1999). Therefore, larger sediment samples, within the kilogram range rather than the gram range, may have yielded a greater range of plant organs and botanical affinities. Further investigation into specific lithological units could yield a greater range of plant organs. However, multiple lithological samples containing charcoal (n= 97) were analysed within this thesis and no floral organs were identified. This may indicate that sample size was not a controlling factor on botanical diversity of charcoal in these assemblages from Late Cretaceous of Alberta.

8.4.3 Taphonomic controls on taxa within Late Cretaceous charcoal assemblages

Fluvial process may be responsible for low diversities of taxa represented by wood charcoal, with wildfire derived plant debris assemblages not reflecting the full range of tree species burnt (Nichols et al., 2000). Only one type of gymnosperm and angiosperm wood has been recorded within the Campanian charcoal assemblages (Chapter 4- section 4.9). Four types of gymnosperm wood and a single type of angiosperm wood have been documented within the Maastrichtian charcoal assemblages (Chapter 6- Fig. 6.14). Palynology shows a diverse range of gymnosperms and angiosperms within both the Campanian and Maastrichtian landscapes of southern Alberta, therefore it is clear that the charcoal assemblages are not fully representative of the Late Cretaceous vegetation.

Charred wood fragments from different taxa have different waterlogging potentials, with those waterlogging first likely to be deposited first, and those remaining buoyant being transported further (Nichols et al., 2000). This phenomenon has been hypothesised to be responsible for limited wood taxa recorded in charcoal assemblages of the Jurassic Scalby Formation (Cope, 1993; Nichols et al., 2000).

Potential fluvial transportation during the Late Cretaceous may have led to a sorting of wood fragments based on waterlogging potential of different taxa, leading to low wood charcoal diversities. However spatial sampling across Dinosaur Provincial Park did not indicate any variations in observable wood taxa. Therefore either fluvial transportation was not responsible for the low diversity taxa recorded or some charred wood fragments were transported outside the boundaries of the modern day Dinosaur Provincial Park.

8.4.4 Taphonomic controls on the presence of partially charred and uncharred debris within wildfire derived assemblages

A major taphonomic bias within the Late Cretaceous plant debris assemblages is the absence of both partially charred and uncharred plant debris. Investigations into the composition of modern wildfire derived plant debris assemblages (Chapter 7- section 7.3.2-7.3.3) highlight the presence of both partially charred and uncharred material, thus indicating that these are components of wildfire derived plant debris assemblages.

Partially charred plant debris is often associated with modern wildfires (Jones et al., 1993). Dead logs and tree trunks are often observed partially charred, with an absence of charring on the lower surface where this debris is partially buried in soil profiles, and a charred upper surface (Jones et al., 1993). Living fuel, such as twigs and tree trunks in growth position, may be partially charred during a wildfire, resulting in fuel with a charred exterior and an uncharred centre (Jones et al., 1993). Partially charred plant debris has been recorded within wildfire derived plant debris assemblages for the Rodeo-Chediski, Medano and Shultz fires (Chapter 7- section 7.3.2).

Partially charred debris occurred in low abundances (with all but one sample not exceeding the domin classification of rare) at all three localities (Chapter 7- section 7.3.2). The low relative abundances indicate that partially charred material is not a major component of modern wildfire derived plant debris assemblages. This is supported by data collected by Scott et al., (2000) after the Frensham Common fire in 1995. Partially charred fragments did not exceed 32% of the plant debris assemblages, with the majority of sample sites recording less than 20% (Scott et al., 2000). Therefore it is likely that partially charred plant debris is produced in lower abundances than charcoal during a wildfire event. This may reduce the likelihood of partially charred plant debris being recorded within the 20g subsamples of Late Cretaceous lithological units.

Very little partially charred plant debris was recorded at the edge of the burnt area during the Frensham Common fire, with a single sample site recording 1% (Scott et al., 2000). Partially charred plant debris was not recorded outside of the burnt area, despite charcoal assemblages being present (Scott et al., 2000). Partially charred material may not withstand transportation. Fragmentation may occur upon transportation, with the charred and uncharred parts being affected differently. Therefore the fluvial environment of the Late Cretaceous during the formation of the charcoal assemblages may have been a contributing factor to the removal of partially charred plant debris.

As outlined in Chapter 7 (section 7.3.2) there are fewer recorded occurrences of partially charred plant debris within the area affected by the Rodeo-Chediski wildfire when compared with the other two modern wildfire events. A duration of three years occurred between the fire and subsequent collection, which may have been responsible for fragmentation and/or decomposition of parts of the partially charred debris resulting in only charcoal residues remaining. The duration of exposure of the plant debris assemblages derived from Late Cretaceous wildfires is unknown, therefore decomposition of the uncharred plant parts may have occurred prior to burial thus resulting in a lower preservation potential.

There are instances of partially charred plant debris being recorded within the geological record (Jones et al., 1993; Kruge et al., 1994; Scott and Jones, 1994; Falcon-Lang et al., 2001; Falcon-Lang, 2004), however these are few in nature. Partially charred woody axes and unidentified plant debris have been recorded in the Carboniferous of Scotland and Nova Scotia, Canada, however all the partially charred plant debris has been found as permineralisations (Jones et al., 1993; Scott and Jones, 1994; Falcon-Lang, 2004). Whilst some permineralisations have been recorded within the Dinosaur Park and Horseshoe Canyon Formations (Serbet and Stockey, 1991; Koppelhus, 2005), no permineralisations were observed or recorded within the Late Cretaceous sediments sampled within this thesis.

There are two Cretaceous records of partially charred plant debris; 17cm wood laths from the Cenomanian of the Czech Republic, and unidentified plant debris from a K-T boundary section in Mexico (Kruge et al., 1994; Falcon-Lang et al., 2001). No details are given regarding the K-T boundary assemblage. The size of the Cenomanian wood fragments may have aided preservation during transportation, with fragmentation less likely to destroy it. The small size of the material within the Late Cretaceous plant debris assemblages (Chapter 4- section 4.3; Chapter 6- section 6.3) may contribute to the absence of partially charred material. In addition if a rapid burial occurred after the wildfire, this may have enhanced preservation potential.

Uncharred plant debris is a substantial component within the modern wildfire derived plant debris assemblages, occurring within eleven out of thirteen samples (Chapter 7- section 7.3.3). Uncharred plant debris is recorded in variable levels of abundance, with domin classifications of frequent and common recorded (Chapter 7-

section 7.3.3; samples RD106, RD107 and ARI-1). Greater relative abundances are recorded than for partially charred debris.

There is a considerable record of Cretaceous uncharred plant debris within wildfire derived assemblages (Chapter 2- Tables 2.1-2.3 and references therein). Therefore uncharred components would be expected within the wildfire derived plant debris assemblages of the Late Cretaceous of southern Alberta. There is limited evidence of Campanian and Maastrichtian uncharred vegetation in southern Alberta, with diverse assemblages not recorded (section 8.4.2). Therefore depositional conditions may not have been conducive to their preservation, leading to an apparent taphonomic bias within the Late Cretaceous recorded plant debris assemblages (Chapters 4-6). Uncharred plant debris may have decayed and decomposed prior to burial, thus resulting in an absence within the assemblages.

The state of wood (living versus decaying) prior to wildfire activity is influential in determining the preservation potential of charcoal (Théry-Parisot et al., 2010). Charcoal derived from decayed wood is typically more porous than that derived from living wood, and has a greater fragmentation potential, which occurs at a faster rate (Théry-Parisot et al., 2010). For living or non-decayed wood, fragmentation is typically concentrated around the edges resulting in a charred core remaining (Théry-Parisot et al., 2010). These properties make charcoal derived from living/non-decayed wood three to five times more resistant than that of decayed wood (Théry-Parisot et al., 2010).

However, experimental research by Nichols et al., (2000) reported no differences in the waterlogging behaviour of fresh, dried or rotten wood tissue, whether charred or uncharred, with 93%-100% waterlogging and sinking within the first twenty-four hours. Therefore it is unlikely that water induced transportation led to the absence of uncharred plant debris within the Late Cretaceous assemblages.

8.4.5 Influences of transportation on size distribution of charcoal

8.4.5.1 Wind induced transportation

During wildfire events, both microcharcoal and macrocharcoal can be injected into the atmosphere by thermally buoyant plumes driven by the fire (Clark, 1988; Clark et al., 1998; Chapter 1- Fig. 1.1, section 1.2). Charcoal is often a large component of wildfire derived smoke plumes, representing 10%-30% of aerosol mass (Andreae et al., 1998). The production and size of charcoal particles influence the transport and subsequent deposition from smoke plumes (Clark et al., 1998).

There is evidence of modern smoke plumes being transported large distances, with potential global charcoal distribution a result of deposition out of plumes (Clark, 1988). Plumes associated with the 2003 Siberian wildfires were recorded in Korea (Lee et al., 2005; Preston and Schmidt, 2006). In addition charcoal derived from tropical wildfires has been recorded in Antarctica, and charcoal originating from Canadian wildfires has been recorded across the U.S.A. (Wolff and Cachier, 1998; Wotawa and Trainer, 2000; Park et al., 2003; Preston and Schmidt, 2006).

Particle motion experiments have indicated that 100µm is the optimum size of mineral particles for entrainment by wind (Clark, 1988). The aerodynamic properties and cohesive forces of smaller particles make them difficult to entrain, with larger pieces often too massive to be lofted into the atmosphere (Clark, 1988). The optimum size of charcoal for entrainment within smoke plumes was calculated to be 120µm-130µm, with this size fraction readily lofted by wind, even at low wind velocities (Clark, 1988). Evidence of 200µm charcoal transported within smoke plumes has also been reported (Clark, 1988). Whilst these are the optimum charcoal sizes for wind transportation, larger pieces can also be transported (Clark, 1988).

Charcoal dispersal distances increase with wind speed, and the height at which charcoal is injected into the atmosphere, with decreasing dispersal distances associated with increasing particle size (Peters and Higuera, 2007). Small charcoal pieces, for example 120µm-130µm, are considered to travel furthest within smoke plumes, and are unlikely to be representative of localised fire activity (Patterson et al., 1987; Clark, 1988; MacDonald et al., 1991; Clark and Royall, 1995; Whitlock and Millspaugh, 1996; Tinner et al., 1998; Ohlson and Tryterud, 2000; Carcaillet et al., 2001b; Gardner and Whitlock, 2001; Lynch et al., 2004a; Higuera et al., 2007; Peters and Higuera, 2007).

Many studies consider larger (>500μm) charcoal pieces to be locally dispersed, even if lofted into a smoke plume (Patterson et al., 1987; Clark, 1988; MacDonald et al., 1991; Clark and Royall, 1995; Whitlock and Millspaugh, 1996; Tinner et al., 1998; Ohlson and Tryterud, 2000; Carcaillet et al., 2001b; Gardner and Whitlock, 2001; Lynch et al., 2004a; Higuera et al., 2007; Peters and Higuera, 2007). Localised deposition can encompass tens to hundreds of metres within a sedimentary basin (Wein et al., 1987; Clark et al., 1998; Blackford, 2000; Ohlson and Tryterud, 2000; Lynch et al., 2004a; Higeura et al., 2007; Peters and Higuera, 2007). However, some recent investigations have indicated that larger charcoal pieces may travel up to ten kilometres away from wildfires during high wind events such as hurricanes (Pisaric, 2002; Tinner et al., 2006; Higuera et al., 2007).

Whilst there is debate regarding charcoal transportation within smoke plumes, the majority of experimental results do indicate a prevalence of transport for charcoal <130μm. Therefore, in order to document localised wildfire activity throughout the Late Cretaceous of southern Alberta (Chapters 4-6), 500μm was selected as a minimum threshold for investigated charcoal size within this thesis (Chapter 3- section 3.3.1). Charcoal sizes at or above this value should be representative of local wildfire events, therefore it is likely that the documented charcoal assemblages (Chapters 4-6) were not derived from fire activity outside of southern Alberta. This minimum threshold value also still allowed the variation in charcoal sizes within plant debris assemblages to be assessed for the Late Cretaceous deposits (Chapters 4-6).

It cannot be categorically stated that all documented charcoal deposits recorded within this thesis are the result of localised wildfire activity, but it is most likely. Further research into smoke plume compositions and global transportation patterns of charcoal are required in order to ascertain the most appropriate charcoal particle sizes for use in analysis to document local or regional fires.

The analysis of the 125µm-500µm size fraction would have added additional information to the temporal record of relative charcoal abundances throughout the Late Cretaceous of Alberta. However, this would have added a significant time component to this thesis, which was not possible. In addition the charcoal data added through the study of this size fraction would have been unlikely to alter the general patterns of relative abundance shown in Chapters 4-7.

Charcoal was observed in the finest size fraction, during sieving, of some samples already containing charcoal belonging to other size fractions. There were no large quantities of charcoal observed within the 125µm-500µm residues. The presence of charcoal within the finest size fraction may indicate the occurrence of regional fires in addition to the localised fires within Alberta.

In addition to the finest size fraction not being representative of localised wildfire activity, a major problem with the potential study of this fraction was the large quantities of sediment retained within the sieve. Abundant retained sediment would prevent the square grid for charcoal quantification being visible (Chapter 3- section 3.2.2), with the determination of domin classifications not possible. The majority of the 125µm-500µm would have had to be treated with HF to remove all sediment, which would have proved highly time consuming given the number of samples (n=217), and may have resulted in enhanced charcoal fragmentation.

8.4.5.2 Water induced transportation

The Late Cretaceous charcoal assemblages of southern Alberta contain very low abundances of charcoal >2.5mm (Chapter 4- section 4.3, Figs. 4.4-4.8, Figs. 4.10-4.11; Chapter 6- section 6.3, Figs. 6.3-6.12, Figs. 6.15-6.16). Within the Campanian sediments charcoal abundances do not exceed rare, with low numerical cover values. Only eight lithological units contained charcoal >2.5mm, out of a total of one hundred and seventeen, for the Oldman and Dinosaur Park Formations (Chapter 4- section 4.3). A similar trend is observed within the Maastrichtian sediments. Only six units contained charcoal >2.5mm, out of a total of eighty-seven, for the Horseshoe Canyon, Battle and Scollard Formations (Chapter 6- section 6.3). However two units recorded frequent and common relative charcoal abundances for the >2.5mm size fraction.

The plant debris assemblages derived from the modern wildfires contained greater occurrences of charcoal >2.5mm, present in nine out of thirteen samples, than the Late Cretaceous assemblages, however these occurred in low relative abundances (Chapter 7- section 7.3.1, Fig. 7.10). Therefore charcoal fragments >2.5mm are unlikely to be a major component in wildfire derived plant debris assemblages. Large charcoal fragments may not be readily produced within wildfire events. In addition the process of transportation may be responsible for the low relative abundances of this size fraction.

Modification of both the size and shape of charcoal fragments is likely during transportation due to abrasion and attrition (Nichols et al., 2000). Experimental work by Nichols et al., (2000) highlighted that individual charcoal fragments exhibit variable amounts of abrasion and fragmentation when transported in water. However, research indicated that short periods of charcoal transportation, as part of bedload, resulted in approximately 25% of abrasion and fragmentation of the charcoal fragments (Nichols et al., 2000). Charcoal fragments quickly into smaller pieces that then remain stable and relatively resistant to further water induced abrasion (Nichols et al., 2000).

It is likely that water induced transportation, either through enhanced overland flow or fluvial transportation, played a role in the low abundances of >2.5mm charcoal in both the modern and Late Cretaceous wildfire derived plant debris assemblages. The absence of >2.5mm in GSD-W (Chapter 7- Fig. 7.10), the suspension sample collected from Medano creek, supports this hypothesis. Extensive or prolonged transportation has been shown to produce little increase in the amount of abrasion and fragmentation, therefore extensive transportation is not responsible for the low relative abundances of >2.5mm charcoal.

8.4.6 Regional verses localised wildfire activity

As outlined in section 8.4.5.1, 500µm was selected as the minimum threshold for charcoal documentation within this thesis to attempt to document localised wildfire events, avoiding the analysis of potentially windblown charcoal that may have been transported hundreds of kilometres. However, the fluvially dominated environments of deposition for the Late Cretaceous of southern Alberta (Fig. 8.3) are likely to have led to the transportation of charcoal. Therefore, this needs to be considered when determining the occurrence of localised or regional wildfires.

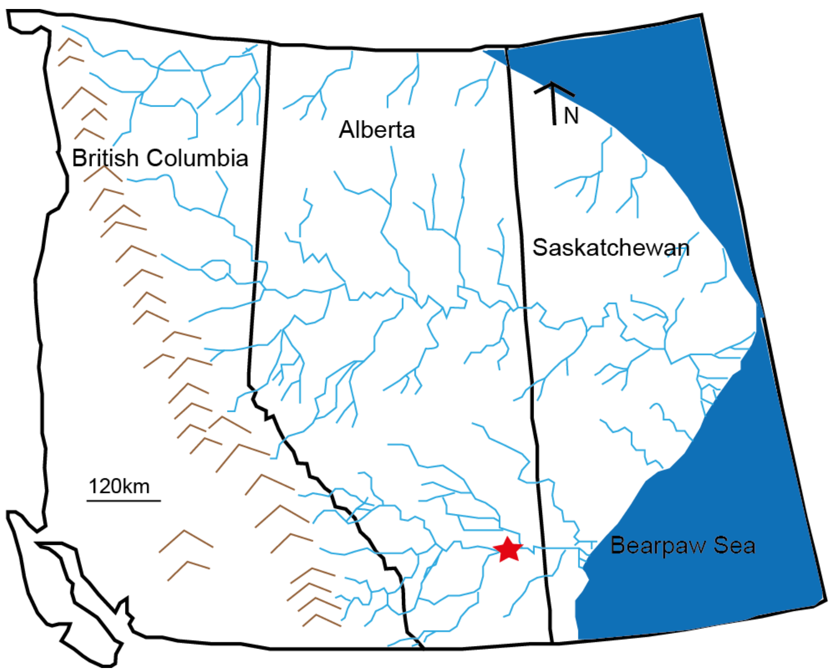


Fig. 8.3 Palaeogeographic map of British Colombia, Alberta and Saskatchewan during the Campanian, highlighting the fluvial systems within southern Canada. Fluvial systems originate typically within the mountainous regions of southern British Colombia, and terminate at the Bearpaw Sea. The location of the Dinosaur Park Formation is shown with a red star (modified after Eberth, 2005).

The Late Cretaceous charcoal assemblages are dominated by 500µm-1mm size fractions, with little charcoal >2.5mm (section 8.4.5.2; Chapter 4- section 4.3, Figs. 4.4-4.8, Figs. 4.10-4.11; Chapter 6- section 6.3, Figs. 6.3-6.12, Figs. 6.15-6.16). The lack of large charcoal particles, which have been recorded in other Cretaceous localities (Chapter 2- Tables 2.1-2.3), may be indicative of fragmentation through water induced transportation. However, fluvially induced abrasion and fragmentation does not increase with increasing distance of transportation (Nichols et al., 2000; section 8.4.5.2). Therefore observations of charcoal shape cannot be used to determine the extent of transportation, and therefore cannot determine whether wildfires are regional or localised.

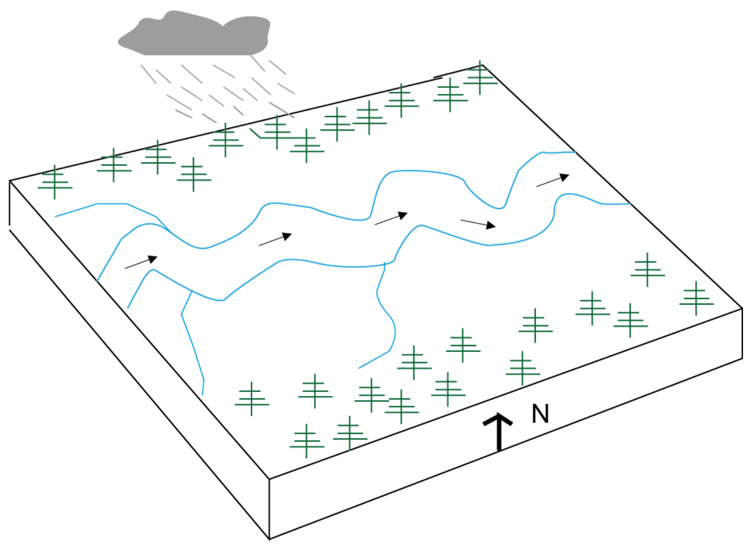


Fig. 8.4 Simplified schematic representation of the Late Cretaceous fluvial environments of southern Alberta with gymnospermous forests. Rainfall induced overland flow may have transported charcoal into the fluvial system.

The deposition of the Dinosaur Park Formation occurred on a low relief, fluvially influenced, coastal to alluvial plain (Chapter 4- section 4.2.1). The fluvial system originated in the mountainous region of present day southern British Colombia and terminated in present day southern Saskatchewan in the Bearpaw Sea, an incursion of the Western Interior Seaway (Fig. 8.3; Eberth, 2005). Prolonged rainfall on burnt landscapes, leading to enhanced overland flow, could have led to the transportation of charcoal into this fluvial system (Fig. 8.4). Therefore it is possible that some Late Cretaceous charcoal was produced by wildfires occurring in present day southern British Colombia, with the charcoal transported and deposited within the Campanian and Maastrichtian Formations of southern Alberta. Other charcoal fragments may have also been transported further, with deposition occurring in the area of present day southern Saskatchewan.

8.4.7 Degradation of charcoal

Charcoalified material is typically able to overcome physical and chemical decompositional processes associated with burial within soils (Braadbaart and Poole, 2008). Whilst charcoal is a relatively inert substance, some charcoal undergoes environmental alteration and degradation, highlighted through carbon loss (Ascough et al., 2011). Oxidative processes are thought to play a role in the alteration of charcoal, with oxidation leading to the partial degradation of charcoal into a substance similar to humic acid (Cohen-Ofri et al., 2006; Ascough et al., 2010; Ascough et al., 2011). However this is a poorly understood field of study, with factors influencing charcoal degradation under natural conditions relatively unknown (Ascough et al., 2011; Kasin and Ohlson, 2013).

What is clear, however, is that diagenetic alteration of charcoal does not necessarily correlate with length of environmental exposure (Liang et al., 2006; Cheng et al., 2008; Ascough et al., 2011). Analysis of relative charcoal abundances within a range of Late Cretaceous lithologies (Chapters 4-6) indicates that the preservation potential of charcoal is not linked to the sedimentary context in which it was found. Similar conclusions have been outlined by Chrzazvez et al., (2014).

Whilst similar proportions of charcoal have been recorded within all Campanian lithologies (Chapters 4-5), there are lower charcoal abundances or an absence of charcoal recorded within many of the Maastrichtian mudstones and shales (Chapter 6). This may be due to limited wildfire activity due to waterlogged conditions as outlined in section 8.3. However, the formation and development of soils may have led to a reduction or absence of charcoal within Maastrichtian overbank facies.

The survival of charcoal within developing soils is thought to be dependent on soil characteristics, rapid burial and the degree of bioturbation (Scott and Damblon, 2010; Kasin and Ohlson, 2013). The interaction of plant roots and burrowing organisms can lead to the alteration of soil profiles, and lead to the fragmentation of charcoal pieces (Prothero and Schwab, 2004). In addition fungal hyphae have been shown to colonise charcoal in modern boreal forests which may lead to further charcoal fragmentation (Kasin and Ohlson, 2013). Therefore, Campanian and Maastrichtian soil formation may have been responsible for the fragmentation of charcoal. This may have resulted in charcoal fragments <500µm, which were below the minimum size threshold analysed within this thesis, resulting in a perceived absence of charcoal from some overbank facies.

Recombustion of charcoal has been hypothesised as a destructive process affecting charcoal remains, with experimental burns undertaken in tropical savanna woodlands, however only small percentages of charcoal were affected (Saiz et al., 2014). Experimental work by McParland et al (2009) on the recharring of charcoal highlighted that charcoal is not destroyed by this process. However experimentally recharred charcoal displayed increased reflectance measurements, increased brittleness and increased weight loss, resulting in more fragile particles (McParland et al., 2009).

It is likely that some Late Cretaceous charcoal underwent some form of degradation prior to burial, however the nature and degree of this cannot be determined. Further research is required into charcoal degradation, as the degree to which it may affect charcoal assemblages in deep time is not understood. However, the abundances of charcoal recorded for the Late Cretaceous assemblages within this thesis (Chapters 4-6) indicate that degradation is unlikely to have played a major role, with preservation of charcoal recorded in all sediment types and environmental settings.

8.4.8 The role of charring temperature in the preservation potential and fragmentation of charcoal

The temperature of wildfires is believed to be influential on the degradation, fragmentation and transportation of charcoal, thus greatly influencing its preservational potential (Ascough et al., 2010; Théry-Parisot et al., 2010; Ascough et al., 2011; Kasin and Ohlson, 2013). It has been stated that fire characteristics may be more important for charcoal fragmentation than erosional processes (Leys et al., 2013). Diagenetic processes can potentially alter charcoal formed at wildfire temperatures <400°C, and may result in a post-depositional loss of charcoal from sediments (Ascough et al., 2010)

Waterlogging experiments by Vaughan and Nichols (1995) indicated that charcoal formed at 300°C takes three times longer to waterlog than material formed at higher temperatures. Extensive fractures are produced by 600°C wildfire temperatures which allow the permeation of water into the charcoal, increasing the rate of waterlogging (Vaughan and Nichols, 1995; Nichols et al., 2000). In addition charcoal formed at low temperatures (<450°C) is more robust than those formed at higher temperatures, withstanding abrasion and attrition (Nichols et al., 2000). Charcoal formed at lower temperatures may also be deposited separately from uncharred wood due to longer waterlogging rates.

The reflectance measurements taken from three charcoal fragments (section 8.1.2) indicate wildfire temperatures ranging from 300-550°C. These charcoal fragments were collected from the same lithological unit. This indicates that differential sorting based on charring temperatures was not influential during the deposition of this lithological unit. Further investigations into the temperature of charring for Late Cretaceous charcoal need to be undertaken to document the range of wildfire temperatures and to investigate whether differential sorting may have occurred elsewhere within the Late Cretaceous succession.

8.4.9 The potential role of dinosaurs in the formation of charcoal assemblages

Herbivore abundance and species richness can have profound impacts on terrestrial ecosystems (Barrett, 2014). Modern herbivorous vertebrates have major effects on plant communities (Barrett, 2014). Herbivorous dinosaurs may have had an impact on the availability of leaves that could be consumed by wildfires, and may therefore have played a role in their absence within Campanian charcoal assemblages, and low abundances within the Maastrichtian assemblages (section 8.4.2). Ecosystems were dominated by dinosaurs during the deposition of both the Oldman and Dinosaur Park Formations (for further information on dinosaur biota refer to Chapter 5- section 5.2.2). The Dinosaur Park Formation preserves the most diverse assemblage of large-bodied herbivorous dinosaurs from Laramida (Ryan and Evans, 2005; Mallon et al., 2013). Therefore their feeding patterns and preferences can be hypothesised to have had an impact on fuel availability for wildfires, removing vegetation and reducing litter layers.

Hadrosaurids formed 40% of the herbivorous dinosaur assemblage within the Dinosaur Park ecosystem (Mallon et al., 2013). Hadrosaurids recovered from contemporaneous sediments in Montana, close to the Canadian/USA border, contained gut contents dominated by leaves, indicating a leaf dominated diet (Tweet et al., 2008). Maximum browsing heights of hadrosaurids have been established to be 4m, with feeding hypothesised to be concentrated below 2m (Mallon et al., 2013). Therefore the minor role herbivorous dinosaurs played in removing leaves and other small stature vegetation should be considered when analysing Late Cretaceous charcoal assemblages.

Bio-pedoturbations have been hypothesised to lead to the fragmentation of charcoal in archaeological sites (Théry-Parisot et al., 2010; Chrzazvez et al., 2014). Therefore it is possible that surface charcoal was trampled by dinosaurs inhabiting the Late Cretaceous landscapes, potentially leading to a reduction in large (>2.5mm) charcoal fragments within the Cretaceous assemblages. There is no way of determining the role, if any, played by dinosaurs, however it should be considered as a potential taphonomic control on Late Cretaceous charcoal assemblages, and may have implications for the Mesozoic as a whole.

8.5 FUTURE WORK

Specific future work regarding the development of a robust methodology for charcoal quantification, greater research into taphonomic processes influencing charcoal deposits, along with further research into the Late Cretaceous of Alberta have been discussed in the sections above. Research into the Late Cretaceous of southern Alberta has shown that there is extensive evidence of previously unrecorded wildfire activity. Therefore, the perceived paucity of charcoal within the Late Cretaceous, as highlighted in Chapter 2 (Fig. 2.5), should not simply be accepted. Further investigations of Late Cretaceous sediments are necessary to enhance the knowledge of Cretaceous fire activity. The extensive charcoal database (Chapter 2- Figs. 2.3-2.5, Tables 2.1-2.3) also indicated low occurrences of Cretaceous charcoal within sediments from the Southern Hemisphere. Therefore research into these sediments should be considered, with the aim of determining the geographical extent of Cretaceous wildfires. This potential overlooking of charcoal by researchers not only has implications for the Late Cretaceous, but also highlights that other apparent gaps in charcoal within the geological record (such as the Early-Mid Triassic (Chapter 1-section 1.5) should undergo extensive investigation.

Chapter 9:

Conclusions

The development of a novel methodology allowed relative charcoal abundances to be quantified throughout the Late Cretaceous whilst mitigating some of the effects associated with differential fragmentation often overlooked by researchers. The development of techniques to determine the volume of charcoal (e.g. 3-D laser scanning) addresses more of the issues associated with differential fragmentation than area coverage alone. However further development is necessary before 3-D laser scanning can be considered as a methodology for charcoal quantification.

The combined use of a domin scale and numerical cover values, within the novel methodology, allowed small variations in relative abundances to be documented. This novel methodology may be a useful tool for researchers across many fields of charcoal research, due to its accessibility and repeatability, with room for modification as ability to calculate charcoal volume increases. Documenting charcoal abundances by light microscopy has been found to lead to low temperature charcoal being overlooked, potentially indicating that all light microscopy studies underestimate charcoal abundances. Therefore the new methodology should be used in greater conjunction with charcoal reflectance measurement for future research, to ensure that low temperature charcoal is not overlooked.

Charcoal is distributed throughout the Oldman and Dinosaur Park Formations, within lithological units spanning 1.8Ma of the Campanian. This is the first documentation of wildfire occurrence within the Campanian of southern Alberta. Greater wildfire activity is suggested for the lower part of the Dinosaur Park Formation based on higher relative abundances of charcoal. Charcoal distribution is more sporadic throughout the Maastrichtian of southern Alberta, with high relative abundances of charcoal concentrated within the lower part of the Horseshoe Canyon Formation. Wildfire activity is hypothesised to decrease within the upper part of the Maastrichtian based on lower relative charcoal abundances. The extensive distribution of charcoal throughout the Campanian and Maastrichtian of southern Alberta indicates that wildfires were prevalent, and likely to be a major component of these Late Cretaceous ecosystems.

Taphonomic controls, including fluvial transportation, overland flow, decomposition and trampling, are all likely to have influenced the composition of wildfire derived plant debris prior to deposition. Decomposition is hypothesised to have led to the absence of both uncharred and partially charred plant debris within the Cretaceous assemblages, components that are recorded within modern wildfire derived plant debris. Relative abundances of charcoal could not be shown to be influenced by proximity to burnt area, vegetation stands, forest types or the size of channels. Further investigations into taphonomic controls on modern charcoal distribution need to be undertaken, in order to enhance understanding of charcoal assemblages in deep time. The rate of waterlogging, resulting in differential transportation of charcoal particles, is hypothesised to be responsible for both the low taxonomic diversity within the assemblages and the low diversity of plant organs. The rate of waterlogging may have potentially contributed to the low abundances of >2.5mm charcoal particles.

This thesis represents the first detailed temporal and spatial investigation of charcoal distribution within the Late Cretaceous. The extent of the temporal and spatial distribution of charcoal, coupled with its presence in all lithologies, indicates that the previously low numbers of documented occurrences of charcoal globally within the Late Cretaceous may be due to a lack of research. The Oldman and Dinosaur Park Formations have been researched for over a century, with charcoal never recorded prior to this thesis. Therefore, charcoal is being overlooked or not recognised by researchers in the field. As a consequence, the role wildfires may have played as a mechanism of formation for some deposits is not being considered. The low abundance of >2.5mm charcoal is likely to exacerbate the problem of field recognition of charcoal.

High relative abundances of charcoal have been recorded within Campanian vertebrate assemblages. Comparative investigations of lithological units without bone indicate that formation of vertebrate deposits was not simply a function of normal 'background' wildfire activity. Heavy rainfall following wildfire events may have resulted in the destabilisation of the landscape, leading to the formation of water flows entraining both bones and charcoal prior to deposition. The elevated relative abundance of charcoal observed within bone bed 43 is indicative of a wildfire induced hyperconcentrated flow event, responsible for the deposition of charcoal along with the bones of over fifty dinosaurs (*Centrosaurus apertus)*.

The failure to consider post-fire induced flooding as a mechanism for the formation of some vertebrate deposits, bone bed 43 in particular, further supports the view that the role wildfires may have played in vertebrate deposit formation is often overlooked. Flooding events following wildfires need to be considered as a causal mechanism for the formation of other vertebrate deposits. In addition elevated relative charcoal abundances, in both bone bed 43 and the hyperconcentrated flow deposit derived from the Schultz fire, indicate that this type of flow deposit should be investigated for the presence of charcoal. Wildfires may be a major contributing factor in the formation of some hyperconcentrated flow deposits.

The detailed charcoal record provided within this thesis indicates that Cretaceous charcoal occurrences are being overlooked, even within areas that have undergone extensive palaeontological research. The perceived paucity in the Late Cretaceous, as indicated by limited previously documented charcoal occurrences, may be due to a lack of research. Therefore further research into global Late Cretaceous charcoal deposits should be carried out. In addition, research into the occurrence of Cretaceous charcoal in the Southern Hemisphere should be addressed, as little record currently exists. Furthermore greater efforts to recognise and document charcoal within sedimentary successions, throughout deep time, should be undertaken. This would greatly enhance the understanding of wildfires, and their impacts on landscapes, in deep time.

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Appendix 1- Full data for Chapters 4-6

Transect 1

Sample Number	Lithology	Formation	Charcoal >2.5mm	Charcoal 1mm-2.5mm	Charcoal 500μm-1mm
DPP-10-1-1	Mudstone	Oldman Fm	0	0	0
DPP-10-1-2	Mudstone	Oldman Fm	0	0	0
DPP-10-1-3	Shale	Oldman Fm	0	0	0
DPP-10-1-4	Shale	Oldman Fm	0	3	6
DPP-10-1-6	Shale	Oldman Fm	0	0	4
DPP-10-1-7	Mudstone	Oldman Fm	0	0	0
DPP-10-1-8	Shale	Oldman Fm	0	0	1
DPP-10-1-9	Sandstone	Oldman Fm	0	2	1
DPP-10-1-10	Sandstone	Oldman Fm	0	2	3
DPP-10-1-11	Shale	Oldman Fm	0	7	3
DPP-10-1-12	Mudstone	Oldman Fm	0	0	0
DPP-10-1-13	Sandstone	Oldman Fm	0	0	1
DPP-10-1-14	Sandstone	Oldman Fm	0	0	1
DPP-10-1-15	Shale	Oldman Fm	0	0	0
DPP-10-1-16	Shale	Oldman Fm	0	0	2
DPP-10-1-17	Sandstone	Oldman Fm	0	0	0
DPP-10-1-18	Sandstone	Oldman Fm	4	8	0

DPP-10-1-19	Sandstone	Oldman Fm	0	2	0
DPP-10-1-21	Sandstone	Dinosaur Park Fm	0	4	0
DPP-10-1-22	Sandstone	Dinosaur Park Fm	7	20	13
DPP-10-1-23	Mudstone	Dinosaur Park Fm	0	1	6
DPP-10-1-24	Shale	Dinosaur Park Fm	0	0	1
DPP-10-1-25	Sandstone	Dinosaur Park Fm	0	1	1
DPP-10-1-26	Mudstone	Dinosaur Park Fm	0	0	0
DPP-10-1-27	Sandstone	Dinosaur Park Fm	0	0	2
DPP-10-1-28	Mudstone	Dinosaur Park Fm	4	1	3
DPP-10-1-29	Mudstone	Dinosaur Park Fm	0	0	1
DPP-10-1-30	Mudstone	Dinosaur Park Fm	0	0	4
DPP-10-1-31	Shale	Dinosaur Park Fm	0	0	0
DPP-10-1-32	Shale	Dinosaur Park Fm	0	0	2
DPP-10-1-33	Mudstone	Dinosaur Park Fm	0	0	0
DPP-10-1-34	Mudstone	Dinosaur Park Fm	0	0	1
DPP-10-1-35	Mudstone	Dinosaur Park Fm	0	0	0

DPP-10-1-36	Shale	Dinosaur Park Fm	0	0	1
DPP-10-1-37	Sandstone	Dinosaur Park Fm	0	0	0
DPP-10-1-38	Sandstone	Dinosaur Park Fm	0	0	0
DPP-10-1-39	Mudstone	Dinosaur Park Fm	0	0	2
DPP-10-1-40	Sandstone	Dinosaur Park Fm	0	0	1
DPP-10-1-41	Sandstone	Dinosaur Park Fm	0	0	3
DPP-10-1-42	Mudstone	Dinosaur Park Fm	0	0	5

DPP-10-1-5 and DPP-10-1-21 were small surface samples of charcoal. These could not be temporally correlated and were therefore not included within this thesis.

Transect 2

Sample Number	Lithology	Formation	Charcoal >2.5mm	Charcoal 1mm-2.5mm	Charcoal 500µm-1mm
DPP-10-2-1	Sandstone	Oldman Fm	0	0	0
DPP-10-2-2	Sandstone	Dinosaur Park Fm	0	0	0
DPP-10-2-3	Mudstone	Dinosaur Park Fm	0	0	0
DPP-10-2-4	Sandstone	Dinosaur Park Fm	0	2	6
DPP-10-2-5	Sandstone	Dinosaur Park Fm	0	3	11
DPP-10-2-6	Sandstone	Dinosaur Park Fm	0	0	0

DPP-10-2-7	Mudstone	Dinosaur Park Fm	0	0	1
DPP-10-2-8	Mudstone	Dinosaur Park Fm	0	0	0
DPP-10-2-9	Sandstone	Dinosaur Park Fm	0	0	0
DPP-10-2-10	Shale	Dinosaur Park Fm	0	4	0
DPP-10-2-11	Sandstone	Dinosaur Park Fm	0	1	5
DPP-10-2-12	Shale	Dinosaur Park Fm	0	0	0
DPP-10-2-13	Sandstone	Dinosaur Park Fm	0	1	4
DPP-10-2-14	Sandstone	Dinosaur Park Fm	0	6	16
DPP-10-2-15	Sandstone	Dinosaur Park Fm	0	0	0
DPP-10-2-16	Shale	Dinosaur Park Fm	0	0	1
DPP-10-2-17	Mudstone	Dinosaur Park Fm	0	0	0
DPP-10-2-18	Sandstone	Dinosaur Park Fm	0	0	4
DPP-10-2-19	Sandstone	Dinosaur Park Fm	0	0	0
DPP-10-2-20	Shale	Dinosaur Park Fm	0	0	0
DPP-10-2-21	Shale	Dinosaur Park Fm	0	2	2
DPP-10-2-22	Shale	Dinosaur Park Fm	0	0	0

DPP-10-2-23	Shale	Dinosaur Park Fm	0	0	0
DPP-10-2-24	Shale	Dinosaur Park Fm	0	0	0
DPP-10-2-25	Mudstone	Dinosaur Park Fm	0	0	0
DPP-10-2-26	Sandstone	Dinosaur Park Fm	0	0	0
DPP-10-2-27	Sandstone	Dinosaur Park Fm	0	0	0
DPP-10-2-28	Mudstone	Dinosaur Park Fm	0	0	0
DPP-10-2-29	Shale	Dinosaur Park Fm	2	1	1
DPP-10-2-30	Shale	Dinosaur Park Fm	0	0	0
DPP-10-2-31	Shale	Dinosaur Park Fm	0	0	0
DPP-10-2-32	Mudstone	Dinosaur Park Fm	0	0	0
DPP-10-2-33	Mudstone	Dinosaur Park Fm	0	1	0
DPP-10-2-34	Shale	Dinosaur Park Fm	0	0	0
DPP-10-2-35	Shale	Dinosaur Park Fm	0	0	0
DPP-10-2-36	Mudstone	Dinosaur Park Fm	0	0	3
DPP-10-2-37	Mudstone	Dinosaur Park Fm	0	0	0
DPP-10-2-38	Shale	Dinosaur Park Fm	0	1	1

DPP-10-2-39	Shale	Dinosaur Park Fm	0	0	0
DPP-10-2-40	Shale	Dinosaur Park Fm	0	0	0
DPP-10-2-41	Shale	Dinosaur Park Fm	0	0	2
DPP-10-2-42	Sandstone	Dinosaur Park Fm	0	0	0
DPP-10-2-43	Shale	Dinosaur Park Fm	0	0	0

Transect 6

Sample Number	Lithology	Formation	Charcoal >2.5mm	Charcoal 1mm-2.5mm	Charcoal 500µm-1mm
DPP-10-6-1	Sandstone	Oldman Fm	0	0	0
DPP-10-6-2	Sandstone	Dinosaur Park Fm	0	0	0
DPP-10-6-3	Sandstone	Dinosaur Park Fm	7	6	19
DPP-10-6-4	Sandstone	Dinosaur Park Fm	1	18	28
DPP-10-6-5	Mudstone	Dinosaur Park Fm	0	0	0
DPP-10-6-6	Sandstone	Dinosaur Park Fm	0	0	0
DPP-10-6-7	Mudstone	Dinosaur Park Fm	0	0	0
DPP-10-6-8	Mudstone	Dinosaur Park Fm	0	0	0

DPP-10-6-9	Sandstone	Dinosaur Park Fm	0	2	3
DPP-10-6-10	Mudstone	Dinosaur Park Fm	0	0	0
DPP-10-6-11	Mudstone	Dinosaur Park Fm	0	0	0
DPP-10-6-12	Sandstone	Dinosaur Park Fm	0	0	0
DPP-10-6-13	Sandstone	Dinosaur Park Fm	0	0	0
DPP-10-6-14	Sandstone	Dinosaur Park Fm	0	4	2
DPP-10-6-15	Mudstone	Dinosaur Park Fm	0	0	0
DPP-10-6-16	Shale	Dinosaur Park Fm	0	3	2
DPP-10-6-17	Shale	Dinosaur Park Fm	0	10	12
DPP-10-6-18	Shale	Dinosaur Park Fm	0	0	1
DPP-10-6-19	Mudstone	Dinosaur Park Fm	0	0	0
DPP-10-6-20	Mudstone	Dinosaur Park Fm	0	0	0
DPP-10-6-21	Sandstone	Dinosaur Park Fm	0	3	13
DPP-10-6-22	Sandstone	Dinosaur Park Fm	6	11	12
DPP-10-6-23	Sandstone	Dinosaur Park Fm	0	0	1
DPP-10-6-24	Mudstone	Dinosaur Park Fm	0	0	0

DPP-10-6-25	Sandstone	Dinosaur Park Fm	0	0	0
DPP-10-6-26	Mudstone	Dinosaur Park Fm	0	4	3
DPP-10-6-27	Shale	Dinosaur Park Fm	0	0	0
DPP-10-6-28	Shale	Dinosaur Park Fm	0	0	1
DPP-10-6-29	Sandstone	Dinosaur Park Fm	0	0	0
DPP-10-6-30	Sandstone	Dinosaur Park Fm	0	0	0
DPP-10-6-31	Mudstone	Dinosaur Park Fm	8	2	1
DPP-10-6-32	Shale	Dinosaur Park Fm	0	1	3

Chapter 5

Sample Number	Lithology	Formation	Charcoal >2.5mm	Charcoal 1mm-2.5mm	Charcoal 500µm-1mm
BB50-01	Sandstone	Dinosaur Park Fm	7	9	10
BB50-02	Sandstone	Dinosaur Park Fm	0	5	15
BB50-03	Sandstone	Dinosaur Park Fm	9	18	12
Q213	Sandstone	Dinosaur Park Fm	3	20	16

Q11	Mudstone	Dinosaur Park Fm	0	3	1
BB43	Sandstone	Dinosaur Park Fm	0	19	35

Chapter 6

Sample Number	Lithology	Formation	Charcoal >2.5mm	Charcoal 1mm-2.5mm	Charcoal 500µm-1mm
DRH-1	Sandstone	Horseshoe Canyon Fm	0	0	12
DRH-2	Sandstone	Horseshoe Canyon Fm	0	0	1
DRH-3	Mudstone	Horseshoe Canyon Fm	0	0	0
DRH-4	Shale	Horseshoe Canyon Fm	0	0	2
DRH-5	Sandstone	Horseshoe Canyon Fm	0	1	1
DRH-6	Sandstone	Horseshoe Canyon Fm	0	0	0
DRH-7	Mudstone	Horseshoe Canyon Fm	0	0	0
DRH-8	Sandstone	Horseshoe Canyon Fm	14	22	18

DRH-9	Mudstone	Horseshoe Canyon Fm	0	0	3
DRH-10	Sandstone	Horseshoe Canyon Fm	0	1	8
DRH-11	Shale	Horseshoe Canyon Fm	0	1	2
DRH-12	Shale	Horseshoe Canyon Fm	0	1	0
DRH-13	Sandstone	Horseshoe Canyon Fm	0	1	2
DRH-14	Mudstone	Horseshoe Canyon Fm	0	0	0
DRH-15	Mudstone	Horseshoe Canyon Fm	0	0	0
DRH-16	Shale	Horseshoe Canyon Fm	2	6	12
DRH-17	Sandstone	Horseshoe Canyon Fm	2	6	9
DRH-18	Sandstone	Horseshoe Canyon Fm	0	0	3
DRH-19	Mudstone	Horseshoe Canyon Fm	0	0	2
DRH-20	Sandstone	Horseshoe Canyon Fm	0	0	0
DRH-21	Shale	Horseshoe Canyon Fm	0	0	0
DRH-22	Sandstone	Horseshoe Canyon Fm	0	1	0
DRH-23	Sandstone	Horseshoe Canyon Fm	0	0	0
DRH-24	Mudstone	Horseshoe Canyon Fm	5	27	27

DRH-25	Sandstone	Horseshoe Canyon Fm	0	1	5
DRH-26	Shale	Horseshoe Canyon Fm	0	0	0
DRH-27	Mudstone	Horseshoe Canyon Fm	23	0	2
DRH-28	Sandstone	Horseshoe Canyon Fm	0	6	18
DRH-29	Sandstone	Horseshoe Canyon Fm	0	0	0
DRH-30	Sandstone	Horseshoe Canyon Fm	0	0	0
DRH-31	Mudstone	Horseshoe Canyon Fm	0	0	0
DRH-32	Sandstone	Horseshoe Canyon Fm	0	1	1
DRH-33	Mudstone	Horseshoe Canyon Fm	0	0	1
DRH-34	Sandstone	Horseshoe Canyon Fm	0	0	0
DRH-35	Sandstone	Horseshoe Canyon Fm	0	0	0
DRH-36	Sandstone	Horseshoe Canyon Fm	0	0	0
DRH-37	Sandstone	Horseshoe Canyon Fm	0	0	0
DRH-38	Sandstone	Horseshoe Canyon Fm	0	0	0
DRH-39	Sandstone	Horseshoe Canyon Fm	0	0	0
DRH-40	Sandstone	Horseshoe Canyon Fm	0	0	0

DRH-41	Sandstone	Horseshoe Canyon Fm	0	0	0
DRH-42	Sandstone	Horseshoe Canyon Fm	0	1	0
DRH-43	Sandstone	Horseshoe Canyon Fm	0	0	1
DRH-44	Mudstone	Horseshoe Canyon Fm	0	0	2
DRH-45	Sandstone	Horseshoe Canyon Fm	0	0	0
DRH-46	Sandstone	Horseshoe Canyon Fm	0	0	0
DRH-47	Mudstone	Battle Fm	0	0	0
DRH-48	Mudstone	Battle Fm	0	0	0
DRH-49	Mudstone	Scollard Fm	0	0	0
DRH-50	Sandstone	Scollard Fm	0	0	0
DRH-51	Sandstone	Scollard Fm	0	0	0
DRH-52	Sandstone	Scollard Fm	0	0	0
DRH-53	Shale	Scollard Fm	0	0	2
DRH-54	Mudstone	Scollard Fm	0	0	0
DRH-55	Mudstone	Scollard Fm	0	0	0
DRH-56	Mudstone	Scollard Fm	0	0	0