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TABLE OF CONTENTS

ABSTRACT

Sedimentology and organic petrology-geochemistry from a 160-metre core have been integrated to study the characteristics of an isolated pocket of fine-grained, siliciclastic Eocene sediments deposited within a small kimberlite crater basin, Lac de Gras, Northwest Territories, Canada. These sediments overlie the "Giraffe Pipe", a kimberlite occurrence located at about 65°N/110°W, 25 km northeast of the Ekati Diamond Mine. The strata recovered in the studied core represent an overall shallowing-upward succession of lacustrine-peat mire basin-fill, interpreted to portray the deposits of a maar lake, one of the first identified in Canada (and one of the few maars anywhere to be associated with a kimberlitic pipe). Previously-published palynological data suggest a late Early Eocene to early Middle Eocene age, approximately congruent with a previous radiometric date of 47.4 +/- 0>5 Ma. These deposits include three stratal units: a) a Lower Lacustrine Zone dominated by dark, freshwater, organic-rich mudstone and thick occurrences of oil shale (% total organic carbon: TOC = 15-50 %), interpreted as recording low energy, shallow sub-lacustrine deposition within the crater basin; b) a thin Middle Transitional Zone with evidence of very shallow subaqueous deposition and subaerial exposure (TOC = 2-12 %); and c) an Upper Mire Zone characterized by thick subaerial peat deposits (TOC = 39-55 %), with minor sublacustrine mudstones, interpreted to represent accumulation in a primarily continental setting filling the crater basin. Both lower and upper portions of the succession are characterized by shallowing-upward, higher order sequences whose boundaries correspond with marked changes in TOC, and Rock Eval hydrogen and oxygen indices. These are interpreted to represent either cyclic climatic wet/dry phases or episodic kimberlite/diatreme collapse (downward stoping) subsidence/fill phases. The distribution and type of microscopic organic matter reflects the sedimentological observations: the lower, lacustrine-dominated zone includes abundant freshwater diatoms, chrysophytes and liptinites (e.g. sporinite, alginite), whereas the upper, peat mire zone consists predominantly of woody/peat macerals with well-preserved plant macrofossils. Huminites through the section have reflectance values averaging 0.23 %Ro, indicating that the thermal maturity of these ~47 M.Y.-old sediments, remarkably, is only slightly greater than modern peats, and that post-kimberlite burial and thermal alteration have been insignificant, with temperatures no greater than ~ 30°C. An abrupt cooling and the presence of bentonites during the rapid transitional conversion from lacustrine to mire facies, may indicate a previously-unrecognized regional, post-eruptive, uplift phase, which is recorded in both geochemical and sedimentological indicators.

INTRODUCTION

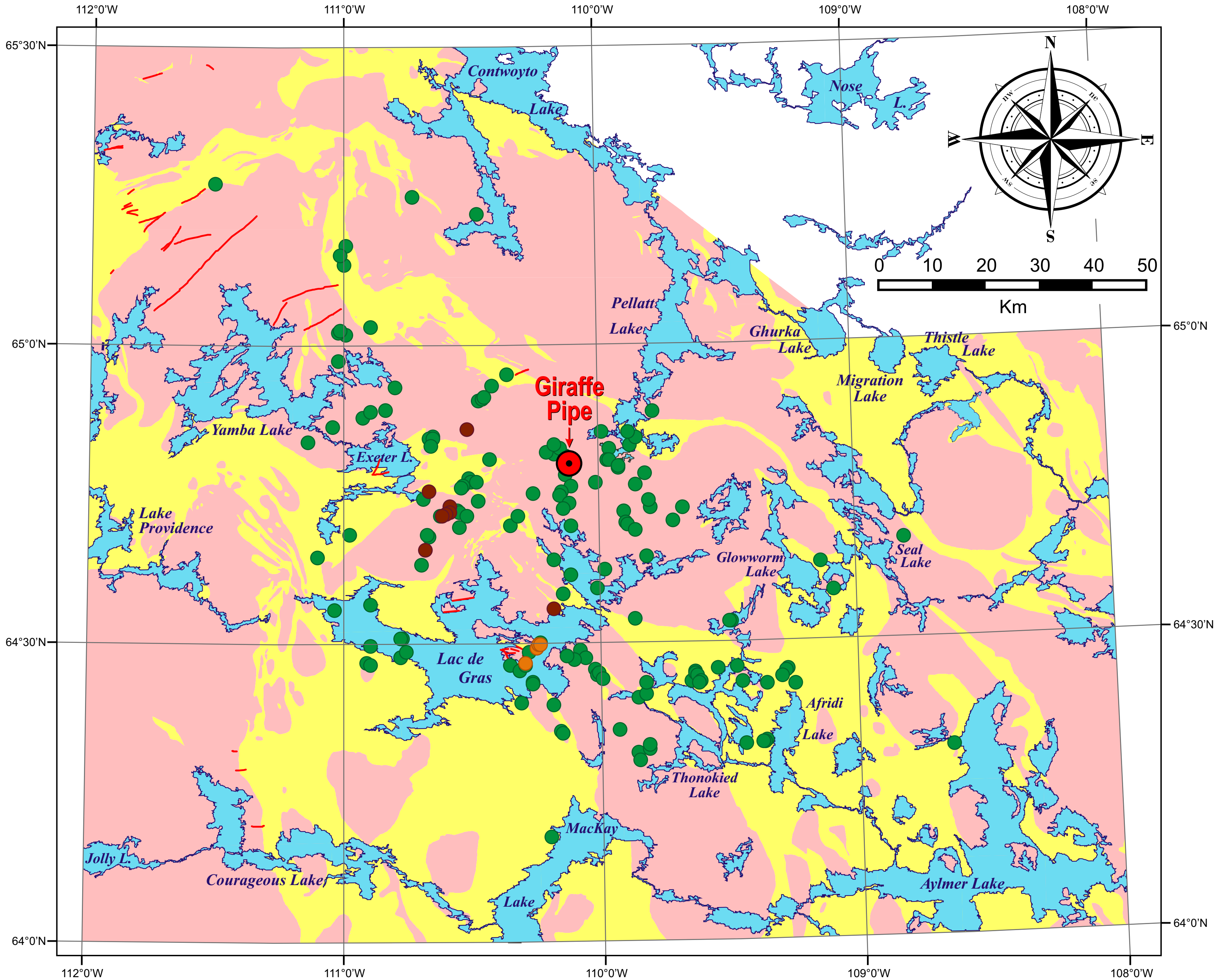
Study Area Location, Objectives and Methods

The “Giraffe Pipe” is a kimberlite occurrence, located 25 km northeast of the Ekati Diamond Mine™, within the Lac de Gras kimberlite field, Northwest Territories, Canada (Figure 1). It is located at about 65° 20’ N, 110° 10’ W, in the Slave Province of the Canadian Shield. The kimberlitic material within this pipe has an emplacement model age of 47.4 +/- 0.5 Ma (Middle Eocene), based on a Rb-Sr age of kimberlitic phlogopite (Creaser et al., 2003; see also Heaman et al., 2004). The Lac de Gras kimberlites are among the youngest, freshest, and most completely-preserved examples on earth, and so offer the possibility of better refining the emplacement and evolution models developed from other diamondiferous occurrences.

The studied Giraffe BHP drill hole 99-01 encountered post-kimberlite/pre-Quaternary sedimentary strata over an interval of core at depths of 50 to 160 metres (Hamblin et al., 2003). Drilled at an angle of -47°, the core clearly extended through a partial thickness of the post-kimberlite crater-fill, and exited the crater through the side wall at a depth of about 120 m below surface (Figure 2). The encountered strata were, apparently, deposited in a crater lake setting (less than about 250 m diameter) within the open vent of the pipe (as discussed below), following kimberlite emplacement. They, therefore, represent a small isolated pocket of poorly-consolidated sediment, nested within the surrounding metamorphosed basement country rock.

This exceptional-quality core was examined and sampled in detail for the purpose of assessing the paleodepositional environment, sedimentary processes, age, surrounding vegetation, level of coalification and thermal maturity, and bulk organic chemical properties of the sediments. The prime objective was to document the post-emplacement sedimentological processes and paleoenvironment by describing and interpreting the sedimentary facies and depositional processes. By documenting and interpreting the wholly continental environment which developed after these Eocene kimberlites were intruded, this report may contribute toward refining/modifying the current hypotheses for near-surface kimberlite volcanism and crater formation, and help to assess the regional post-emplacement thermal alteration and burial history affecting these diamondiferous deposits. At the same time, these deposits can add to our knowledge of the sedimentary processes and depositional extent of Eocene post-kimberlitic strata on the craton, which are not yet well-known locally or regionally, but which may be more common than previously recognized. Similarly, the understanding of lacustrine deposition within small open craters is currently at a modest level.

Immediately following coring of the BHP Drillhole 99-01 (“Giraffe Pipe”), Lac de Gras region, N.W.T., the core was sealed and frozen until initial description, photography and sampling could be accomplished. The recovered core of post-kimberlite strata was examined, described and sampled in detail at the core facility of Geological Survey of Canada (Calgary) (Hamblin et al., 2003) (Figure 3). The core is in good condition, although it is somewhat disturbed near the base. Preservation of organic components, in particular, is outstanding. The present work was conducted with emphasis on identifying the subtle lithological and sedimentological variations and sequences present and their overall interpretation, as a framework for interpretation of the organic matter present. In addition to palynological sampling, a series of 110 samples were collected for organic petrological and geochemical study (Stasiuk et al., 2003; Hamblin et al., 2003).



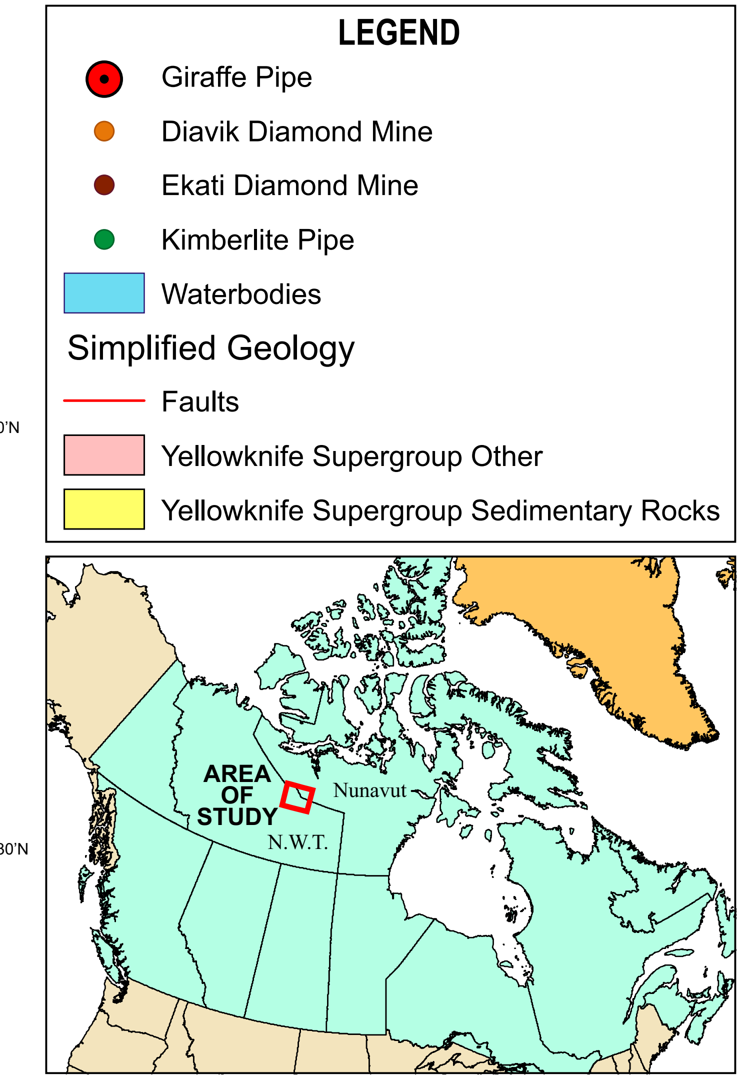


Figure 1. Simplified geological map of the Lac de Gras region showing the location of studied core (simplified from Kjarsgaard et al., 2002).

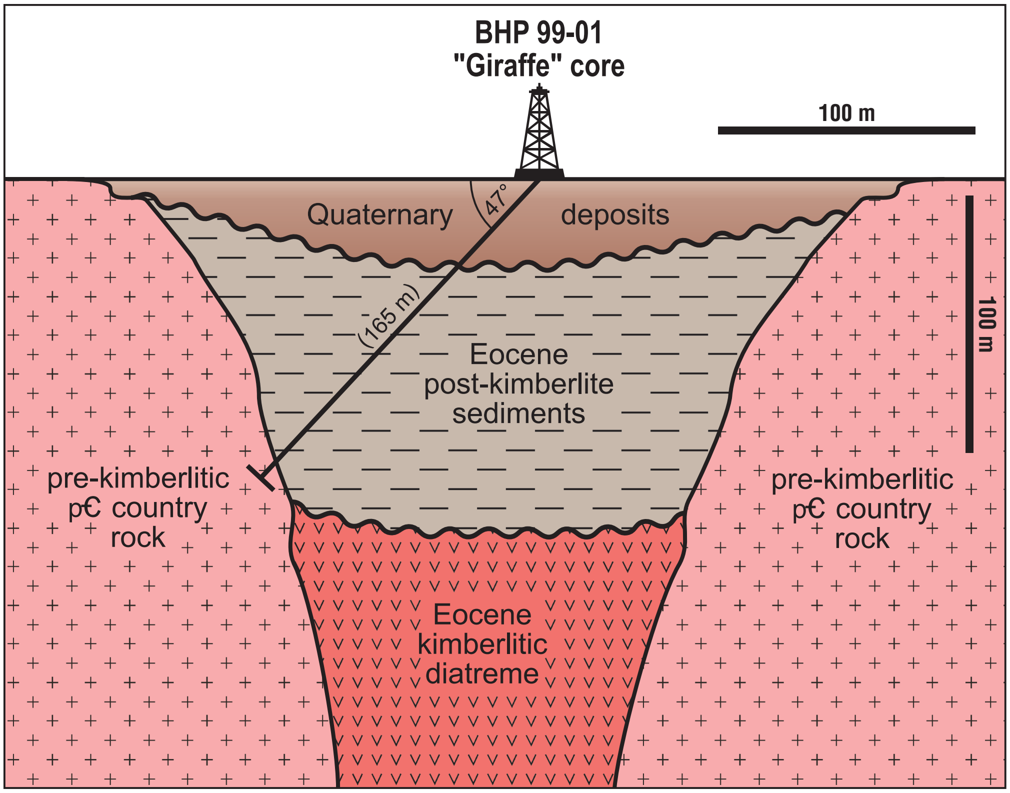


Figure 2. Cartoon cross section sketch of Giraffe crater and core orientation.

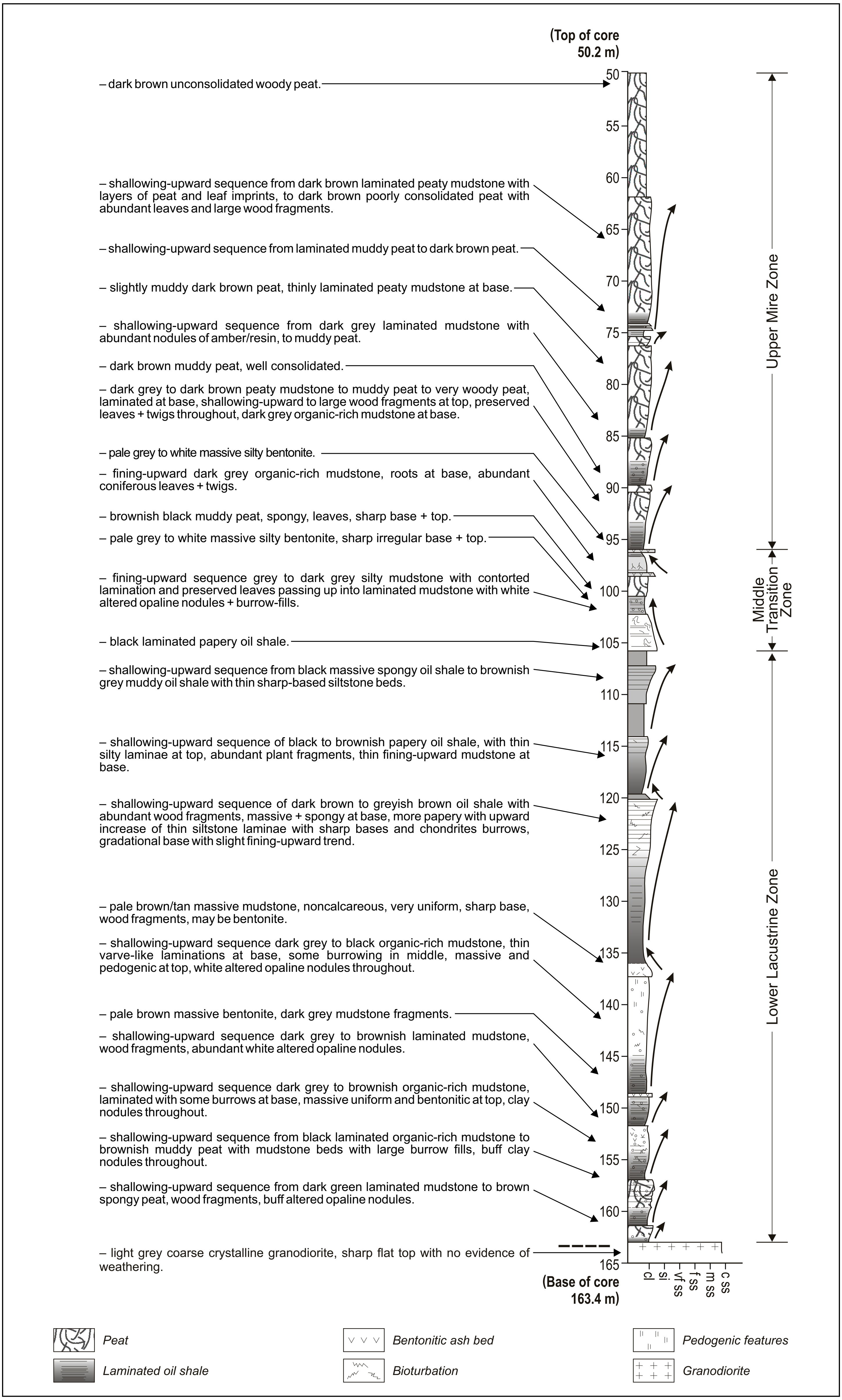


Figure 3. Description and detailed sedimentological column.

Regional Geological Setting

The Slave Province, in Northwest Territories, Canada, is an Archean craton composed primarily of granitoid intrusives and migmatitic gneisses with greenstone belts of mafic to intermediate volcanics and micaceous metasedimentary schists, assembled in the period 4.0 to 2.6 Ga (Carlson et al., 1998; Doyle et al., 1998). The region oscillated between erosive and depositional regimes during the Phanerozoic and likely was thinly covered at various times by Devonian platform carbonates, Cretaceous marine mudstones and Tertiary nonmarine sandstones and shales (Doyle et al., 1998). During the Late Cretaceous-Early Tertiary (between 75 and 47 M.Y. ago), more than 300 kimberlite pipes were intruded into the Slave Province and its overlying cover sequence, along linear trends correlated with local (east-west) and regional (northwest-oriented) structural trends (Wright, 1999; Levinson and Cook, 2000; Kjarsgaard et al., 2002). Most pipes erupted within two separate time periods: Late Cretaceous (73-75 Ma), or Middle Eocene (47-52 Ma) (Kjarsgaard, 1996b). Subsequent regionally-pervasive erosion, primarily during Pleistocene glaciation, has removed all Phanerozoic strata except for locally-protected minor accumulations.

Kimberlites are the products of deep-seated continental intraplate alkaline volcanism, representing magmas derived from 200-400 km depths where the crystalline, high temperature and pressure form of carbon (i.e. diamond) is formed (Dufresne et al, 1994). They tend to occur within old, stable cratons with thick crusts and low geothermal gradients (Kjarsgaard, 1996a). The pipes form through highly explosive surface eruption of CO_2- and H_2O-rich magmas, which speed up to 100 km/hr as they approach the surface due to rapid degassing, forming a crater and surrounding tuff ring (Kjarsgaard, 1996a; Cookenboo, 2000; Head and Wilson, 2003; Wilson and Head, 2003). The kimberlitic magma ablates and mixes unrelated crystals and fragments along its path of ascent, ultimately combining them all with near-surface material upon eruption, in a pastiche of geological components.

Lac de Gras Kimberlites

The Lac de Gras kimberlites occur as small (<2 Ha), sub-circular (150-250 m diameter) inverted-cone shaped volcanic bodies with steeply inclined walls (Field and Scott Smith, 1998; Graham et al., 1998). They are unusual in their small size, but great depth, and in the presence of fill successions dominated by crater facies volcaniclastics, resedimented deposits and pyroclastics (Doyle et al., 1998), rather than primary diatreme and hypabyssal volcanics, as is typical of the classic South African examples (Carlson et al., 1998; Graham et al., 1998). The lack of typical deep diatreme facies, the presence of common xenoliths of shale/siltstone/wood from the sedimentary cover, and the dominance of debris flow resedimented material deposited by sedimentary processes all indicate the dominance of preserved crater facies material. This implies a different emplacement history from the classical diatreme facies-dominated South African kimberlites (Field and Scott Smith, 1998), because pipe morphology appears to be partly controlled by the cover thickness and competence of the country rock at the time of eruption (Field and Scott Smith, 1998). Pipes at Lac de Gras tend to occur in groups of up to 50, as small steep-sided bodies with very small diameters of 100-300 m. These factors suggest large numbers of less powerful and shorter-lived eruptions, with the lack of a discrete, hard confining layer near the surface allowing easy breakthrough of lesser magma plumes and a limited amount of subsurface volatile buildup (Field and Scott Smith, 1998).

Important for this study, and in contrast to those of South Africa, Lac de Gras pipes include abundant xenoliths of sedimentary cover rocks and fossils, suggesting the complete explosive excavation and expulsion of the host rock, leaving behind an open crater (Kirkley et al., 1998; Doyle et al., 1998; Graham et al., 1998; Field and Scott Smith, 1998; Nowicki et al., 2003). Near-surface breakthrough allowed catastrophic pressure drop and explosive exsolution, fragmenting the magma and country rock and possibly creating a tephra cone which later supplied material to refill the crater (Skinner and Marsh, 2003; Kjarsgaard, 2003). The volcaniclastic infill material includes some primary magmatic kimberlite, but most pipes are dominated by resedimented, massive or bedded, fragmented pyroclastics. The common occurrence of well-preserved wood and fossils, of Cretaceous and Tertiary age, attests to the abruptness of the emplacement event, but also suggests little post-depositional thermal alteration and, therefore, burial by only a thin cover sequence (Kirkley et al., 1998), estimated as 250-500 m by Stasiuk et al. (2003). Apparently, the lack of a hard confining layer, and a thin cover sequence of water-charged Phanerozoic sediments created the conditions ideal for complete excavation of numerous small, closely-spaced craters which could then accumulate post-emplacement, unconsolidated sedimentary debris from the rim and steep walls (Doyle et al., 1998; Field and Scott Smith, 1998; Kirkley et al., 1998). In addition, any open topographic depression in a non-arid setting normally becomes filled with water and, therefore, the site of subsequent subaqueous sedimentary deposition. Lac de Gras pipes are younger and less eroded than their counterparts in South Africa or Russia, and are typically overlain by small, Holocene-Modern shallow lakes.

Age of Giraffe Kimberlite and Overlying Strata

The Rb/Sr emplacement model age of 47.4 +/- 0.5 Ma (Middle Eocene) derived from kimberlitic material (Creaser et al., 2003) appears to give an approximate maximum age of the overlying intra-crater sedimentary succession. Palynomorphs, recovered from the sampled strata, including *Pistillipollenites mcgregorii* and *Platycaryapollenites swasticoides* ally the Eocene flora of the Lac de Gras area with that of the Middle Eocene fossil forest on Axel Heiberg Island, and suggest that the post-kimberlite sediments are of late Early to early Middle Eocene age (Hamblin et al., 2003; A.R. Sweet, 2005, pers. comm.). The climate of the fossil forest has been interpreted as warm temperate (McIntyre, 1991), and a similar climate would likely be indicated for the Giraffe sediments. This climatic regime argues for the age of the Giraffe Pipe to be closely associated with the late Early Eocene "Cenozoic Thermal Maximum" (~47-55 Ma), an age which is compatible with the 47.4 Ma Rb-Sr age obtained.

LAC DE GRAS POST-KIMBERLITE CRATER-FILL DEPOSITS

Sedimentary Facies Descriptions and Interpretations (Figure 3)

Dark Grey to Brownish Mudstone

Description The lower half of the core, from 163-106 m, is dominated by dark grey to dark brown to black mudstone and oil shale, occurring in units from 1 to 12 m thick. These mudstones are typically uniform, organic-rich, papery, thinly-laminated on a mm-scale, have a petroliferous smell, and pressure-smeared carbon films on slickensided bedding-plane surfaces (Figure 4). Many occurrences are massive, uniform and spongy in texture, with abundant, well-preserved, carbonized, plant fragments on bedding planes. Others have mm-scale alternations of light and dark laminae, which resemble varves. In the lower 20 m of core there are well-preserved delicate chrysophyte skeletons (fresh-water golden algae) and abundant, scattered, opaline clay nodules, which may themselves represent altered chrysophyte skeletons incorporated into the initial sedimentation. No marine fossils were found, although abundant continental plant fragments and palynomorphs are present (Hamblin et al., 2003). In places (e.g. 107-110 m, 114-116 m, 120-135 m), the mudstone becomes siltier upward and thin mm- to cm-scale siltstone laminae, described below, enhance this coarsening-upward trend. These coarsening-upward sequences sharply overlie the preceding deposits, gradually increase in grain size and siltstone content upward to sharp tops, and range from 3-15 m thick. Discrete siltstone beds and small, horizontal burrows are only common in upper, siltier parts of these coarsening-upward sequences.

Figure 4. Dark grey to brownish mudstone facies: massive dark brown oil shale, spongy and light, from lower part of shallowing-upward sequence, 130 m (DSCN 1372). Scale in centimetres.

Interpretation These sediments are interpreted as the low-energy deposits of a small lacustrine body of poorly-oxygenated freshwater. They accumulated beyond the narrow range of clastic input from shoreline processes in this small-diametre basin. Abundant organic matter accumulated and was preserved, with minor fine-grained clastic input, in a quiet, largely dysoxic environment of a few tens of metres depth. In the warm equable Eocene climate, water body stratification would be expected, producing a thick, stagnant, anoxic lower hypolimnion where preservation of organic matter would be prevalent. Alternating varve-like laminae may have recorded seasonal climatic variation. Within this setting, a series of asymmetric coarsening-upward sequences are interpreted to represent shallowing-upward trends which represent progradation of marginal settings over open lacustrine sediments, punctuated by multiple rapid deepening events. The shallowest portions of theses sequences were deposited in more oxygenated and agitated surface waters where a meagre infauna could exist and laminated siltstone beds were deposited. Even in the shallowest nearshore-shoreline environments the energy levels, clastic input and sediment grain size were low, suggesting a small, sediment-starved body of water in a protected setting with low relief margins.

Thin Siltstone

Description The core interval from 107-135 m is dominated by several thick, stacked coarsening-upward sequences of dark grey mudstone. In the upper portions of each of these sequences, thin beds of siltstone increase upward in number and thickness - the prime expression of the coarsening-upward trends. These siltstone beds range up to 5 cm thick, have sharp flat bases and tops, and horizontal lamination (Figure 5). Carbonized wood fragments and well-preserved leaf imprints are common within these beds, and tiny *Chondrites*-like horizontal burrows are present in some.

Figure 5. Thin siltstone facies: thinly interbedded black laminated oil shale and grey siltstone with deciduous leaves and twigs, 108 m (DSCN 1366).

Interpretation These sharp-based beds are interpreted to represent subaqueous density-current deposition of minor clastic sediment in the shallow fresh water which characterized the open lacustrine phase and narrow basin margin areas of the crater fill at these times. The upward increase of thickness and number of siltstone beds at the top of each sequence is interpreted as a shallowing-upward lacustrine-fill trend, repeated several times within the history of the crater. The occurrence of these siltstone beds represents the shallowest and most marginal phases of open lacustrine deposition where minor influx of clastic material due to storms or slumps, and slight elevation of agitation and energy level, were possible. Sediment-laden density current underflows are common in lacustrine settings and can be preserved in the stagnant hypolimnion.

Thick, Dark Brownish Massive Silty Mudstone

Description In the core intervals 102-106 m and 136-145 m, brownish grey silty mudstone to muddy siltstone occurs as thick, massive units, characterized by friable texture and contorted lamination. Wood fragments and possible burrows are present. Both occurrences are at the top of shallowing-upward sequences: the lower is overlain by further shallowing-upward sequences, whereas the upper is overlain by the peat-dominated part of the core.

Interpretation These units are interpreted as the result of either shallow subaqueous deposition and bioturbation, and/or subaerial deposition and pedogenic alteration. Thus, given their context at the tops of shallowing-upward sequences, these sediments are interpreted to represent low-energy, muddy lacustrine nearshore/shoreline facies.

Dark Brown Muddy Peat

Description Dark brown, poorly- to well-consolidated peat and muddy peat occurs in intervals up to 12 m thick in the upper 50 m and lower 10 m of the core. The peat typically is fibrous, spongy, with densely layered and well-preserved needles, leaves, twigs and large wood fragments (Figure 6). The deposits are papery, very light-weight and friable, reminiscent of modern bagged garden peat, despite their age. These intervals gradationally overlie thin units of dark grey laminated mudstones, as the thick caps to shallowing-upward sequences and dominate the upper half of the core. They usually have sharp tops. At the base of the core, where peat closely overlies basement country rock of the crater-wall granodiorite, there are scattered, opaline nodules which represent the skeletons of chrysophytes, incorporated into the vegetative growth. Thicknesses of individual depositional units range from 2 to 12 m, and in several intervals the core recovery is poor.

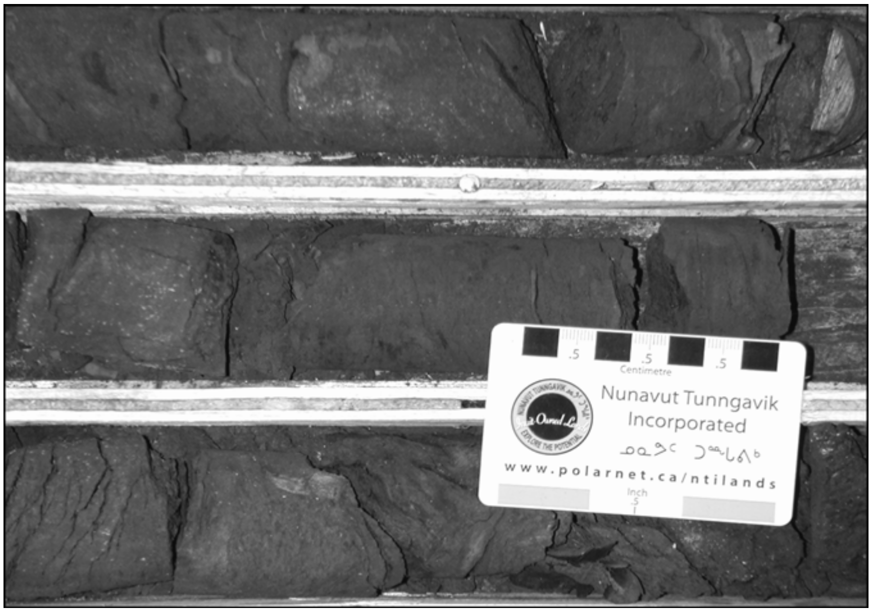


Figure 6. Dark brown muddy peat facies: consolidated, dark brown peat with large branches and wood fragments, 78-79 m (DSCN 1359).

Interpretation The peat facies is interpreted to represent the progressive impingement of subaerial raised mire accumulation from the crater margin, with a mixture of nearby deciduous and coniferous trees and no significant clastic input. This forested mire vegetation dominated the later filling stages of the crater. Several occurrences of peat may represent transported vegetative material (e.g. 99-101 m), but most are interpreted to represent in-place vegetative mire growth.

Thin, Pale Grey to Brown Massive Bentonite

Description Two thin but distinctive, 10-20 cm beds of pale grey to white claystone occur in the interval 96-99 m, within the middle portion of the core (Figure 7). The lower one overlies a minor interval of peat and they are separated by 2 m of rooted dark grey mudstone with coniferous leaves and twigs. These claystones are silty, massive, uniform and have sharp bases and sharp irregular tops. The upper one has carbonaceous partings. An additional, similar, thin pale brownish claystone bed, with dark grey mudstone concretions is present at 149 m of the core.

Figure 7. Thin massive bentonite facies: pale grey, massive silty bentonite with sharp, irregular top and thin charcoal layers, 99 m (DSCN 1362).

Interpretation These beds are interpreted as bentonitic ash-fall layers, deposited and preserved in subaerial shoreline, or very shallow water nearshore, environments as a result of several pulses of nearby volcanism, suggesting minor continued intermittent igneous activity throughout the region after emplacement of this kimberlitic pipe.

Organic Petrology and Thermal Maturity

Based on the general maceral composition, the sediments from the Giraffe pipe can be grossly subdivided into a lower, diatom-rich and liptinite-rich lacustrine oil shale zone (including freshwater *Botryococcus* alginite)(100-160 m), and an upper, huminite-rich lignitic peat zone (50-100 m) (Hamblin et al., 2003). In general, the organic matter throughout this core is still within the peat stage of coalification. Unusually, for deposits ~47 M.Y. old, the mean %Ro (0.23 % Ro, Figure 3) is only slightly greater than "zero" coalification, or the mean %Ro of 0.18 – 0.20 for modern surface peats which have not undergone burial diagenesis (Hamblin et al., 2003; L.D. Stasiuk, 2005, pers. comm.). Thus, organic matter in Middle Eocene sediments overlying the Giraffe Pipe still have not experienced any significant amount of burial since deposition, nor has it been exposed to temperatures any higher than ~ 20 to 30° C (Hamblin et al., 2003). The excellent preservation of the delicate opalline skeletons of chrysophytes in the lower part of the core also attests to the very low level of thermal alteration and lack of compaction of the strata. This lack of compaction, thermal alteration or later burial indicates that there was no appreciable accumulation of sedimentary cover from the mid-Eocene to Quaternary/Recent time in the Lac de Gras region (Hamblin et al., 2003).

STRATIGRAPHIC SUCCESSION

General Giraffe Stratigraphic Succession

The sedimentary succession in the Giraffe core, deposited into a small-diameter open crater after kimberlite emplacement, spans the interval 50-160 m of drilling depth (Figure 3). The strata present in this small basin delineate an overall shallowing-upward succession of lake-basin fill, and are divisible into several stratal units, as described in detail below. The lower interval (160-106 m) is dominated by dark organic-rich subaqueous lacustrine mudstone, the upper portion (97-50 m) is dominated by subaerial accumulations of brown muddy peat, and a thin transition zone between (106-97 m) has the characteristics of a nearshore-shoreline, shallow subaqueous or subaerial setting with abundant roots, thin bentonite beds and vegetative hash layers. Both lower and upper portions of the core are characterized by higher-order, shallowing-upward sequences.

Unit A - Lower Lacustrine Zone (160-106 m)

Description The core interval between 160 and 106 m depth is predominantly dark brownish grey to dark brown to black, organic-rich mudstone or oil shale (Figure 3). It sharply overlies granodiorite with no obvious weathering profile, but thin units of brown spongy peat occur near the base. These sediments are very petroliferous, very uniform, non-calcareous, massive to thinly laminated, with common carbonized wood fragments on the bedding planes. Horizontal *Chondrites*-like burrows are present in many units and dark grey concretions are typical near the base of the Zone. Thin siltstone laminae, up to 1 cm thick, with sharp bases and tops are common and these thinly interbedded lithologies are arranged into coarsening-upward sequences 2-15 m thick. In general, this portion of the core is dominated by diatom- and liptinite-enriched lacustrine oil shale. It is characterized by high TOC, high Hydrogen Indices, and higher T_{max}, suggesting abundant oil-prone organic matter (Hamblin et al., 2003). Overall TOC contents in this zone range from 15 to 50 % and are uniformly high in the 107-137 m interval. There is a good correspondence between sedimentological unit boundaries and marked increase-decrease changes in TOC. Hydrogen Indices in the lower zone progressively decrease with decreasing depth whereas Oxygen Indices progressively increase with decreasing depth (Hamblin et al., 2003).

Interpretation This interval is interpreted to represent quiet open lacustrine sedimentation within a collapse crater, with very little clastic input beyond suspended clays, and essentially no wave/current energy. The laminated oil shales present here are similar to those documented in the Eckfeld Maar crater by Pirrung et al. (2003). Clearly, after eruption, the collapsed kimberlitic structure was expressed at surface as a discrete depression with steep sides, and this open crater structure was maintained for some time. The resulting micro-basin would present a local drainage reservoir with a relatively narrow diameter, and would have immediately begun filling with water, creating a sediment-starved lake. The mm- to cm-scale siltstone beds are interpreted as sudden, minor influxes of clastic material from the unvegetated, unstable margins, perhaps in response to storms, or minor seismic slumping events. Depth of subaqueous deposition was likely shallow, a few tens of metres at most, and the lack of higher energy and coarser clastic input suggests deposition near the centre of an areally small body of freshwater. The crater floor was rapidly inundated, with little time for regolith development, and the lower 10 m of the core (positioned near a crater side wall) represent a generally deepening-upward, transgressive tract. The rest of the depositional motif is dominated by stacking of subtle, but discernible, coarsening-upward sequences, interpreted as shallowing-upward lake-basin fill sequences, or progradational tracts, representing either periodic wet/dry climatic phases or episodic kimberlite collapse (downward-stoping) subsidence/fill phases. Abundant, well-preserved organic matter and plant fossils suggest a relatively humid climate and reducing conditions in the lower hypolimnion. Several periods of possible short-lived subaerial exposure are recorded at the tops of some sequences by a) thin 0-2 m bentonite beds, b) thin 1-3 m peat units and c) a possible pedogenically-altered brownish-grey mudstone.

The vertical distribution of TOC, HI and OI are typical of a progressive, water depth shallowing and terrestrialization through time, from a subaqueous lacustrine towards a subaerial mire paleodepositional setting (Hamblin et al., 2003). The maceral and micro-fossil composition of the lower section also reflects a dominantly lacustrine assemblage of organic material near the base of the zone consisting of assemblages of abundant fluorescing amorphous liptinite, sporinites, fresh to brackish water *Botyrococcus* alginites, diatoms and chrysophytes, with varying amounts of huminite (woody-derived matter). The amount of woody huminite increases progressively upward, whereas alginite decreases progressively upward, reflecting progressive terrestrialization from an open water lacustrine to a mire environment.

Unit B - Middle Transition Zone (106-97 m)

Description Between 106 and 97 m core depth, sediments consist of dark grey laminated mudstone with abundant roots, silty mudstone with contorted lamination, thin white bentonite beds, muddy peats, and surfaces covered in well-preserved coniferous twigs and needles (Figure 3).

Rock Eval pyrolysis data defines a similar geochemical transition zone, from lacustrine to mire environments, comparable with sedimentological features (Hamblin et al., 2003). Between 105 and 98 m depth, there is a marked reduction in TOC contents (from ~ 40 % down to 2-12 %) followed by a sharp increase and, then another reduction. Similarly, hydrogen indices show a reduction (from ~ 250 to < 100 mg HC/gTOC) and then a marked increase to values > 800.

Interpretation This heterogeneous unit is interpreted to represent a transition zone between the predominantly subaqueous lacustrine mudstones below and the predominantly subaerial peats above. It thus marks the approximate chrono-stratigraphic point in time where the lake basin ceased to be a body of open water and was converted to a mire setting. It is dominated by indicators of near-exposure: roots, the lowest occurrence of peat, well-preserved very thin bentonite beds and well-preserved higher plant matter. The crater was likely still a subdued negative topographic feature (probably < 50 m deep), but clastic input from the margins was greatly reduced, perhaps because the uppermost reaches of the crater had a wider diameter, or the margins had stabilized and become vegetated.

This likely represents a period of instability in the organic productivity, input and preservation potential of the paleoenvironment related to rapidly alternating sub-aerial exposure and submersion, and perhaps multiple disruptions by volcanic activity as indicated by bentonites. In general, the organic matter at the top of the Giraffe Pipe has never experienced any significant amount of burial since deposition, nor has it been exposed to temperatures any higher than ~ 20 to 30° C (Hamblin et al., 2003). However, within the transition zone, concomitant with rapid shallowing and several bentonite beds, there is also a distinct change in the thermal regime. T_{max} values shifted abruptly to much lower temperatures at that point in the geological history, perhaps indicating a brief, but discernible, uplift/volcanic phase (Hamblin et al., 2003). This previously-unrecognized post-eruptive cooling/uplift event may be recorded in other pipes, and it may prove to be regional in extent.

Unit C - Upper Mire Zone (97-50 m)

Description The core interval 97-50 m is predominantly dark brown to grey to light brown, muddy peat, fairly well consolidated (except at the top of the core), very well-preserved, in places quite woody and with some large leaf imprints, large wood fragments and roots (Figure 3). Abundant tiny nodules of amber or resin are present in some portions. These deposits are also arranged in coarsening-upward sequences 5-13 m thick, passing from thin units of dark grey laminated organic-rich mudstone at their bases to thick peat units.

This portion of the core is dominated by huminite-enriched lignitic peat. It is characterized by high TOC, lower Hydrogen Indices and low T_{max}, suggesting abundant terrestrial organic matter (Hamblin et al., 2003). Changes in TOC and HI values in the upper zone of Giraffe Pipe strata correspond very well with the sedimentologically-defined transition from lower, to upper zone. Overall, the amount of TOC in the upper, mire zone exceeds that of the lower, lacustrine zone (ranging 39 to 55 wt %) (Hamblin et al., 2003).

Interpretation This interval is interpreted to represent subaerial peat mire deposits in a continental setting with little open water and essentially no clastic input beyond minor suspended clay sedimentation. The subdued crater margins must have presented little topographic expression at this point, and/or were completely stabilized and vegetated. These deposits represent the final fill stage of this lake basin where vegetative mats of organic matter extended outward from the margins to cover the surface with a wetland setting. The abundant preservation of organic matter suggests a relatively humid climate. Water depths here were likely never more than a few metres at this stage. Interestingly, the depositional motif was still dominated by subtle coarsening-upward sequences, interpreted as progradational shallowing-upward lake-basin fill sequences, or vegetative clogging sequences. This suggests the continuation of multiple periodic wet/dry climatic phases and/or episodic tectonically-induced (downward-stoping) subsidence/fill phases. Pirrung et al. (2003) noted that, at Eckfeld Maar, the final peat phase was eroded by subsequent fluvial activity. The full preservation of the thick peats here in the Lac de Gras region reinforces the idea that these deposits, nestled within a localized crater in the metamorphosed basement, have been protected from significant later erosion, including Quaternary continental glaciation.

However the vertical profile of TOC against depth in the upper zone is on trend with the lower profile (Hamblin et al., 2003) suggesting a steady progressive increase in productivity and preservation of organic matter with time as the mire was established, combined with a progressive reduction in the amount of external inorganic sediment being fed into the lacustrine-mire system. The lower zone contains more open water, hydrogen- rich liptinite macerals such as amorphinite, sporinite, cutinite, and alginite, whereas the upper zone is dominated almost exclusively by carbon- and oxygen-enriched, wood-derived macerals such as huminite (Hamblin et al., 2003).

INTEGRATED INTERPRETATION OF THE GIRAFFE EOCENE DEPOSITS

Giraffe Crater Depositional Setting

The Giraffe kimberlite pipe was emplaced in Early to Middle Eocene time within the surrounding Archean granitoids and gneisses of the Slave Province that were originally overlain by a thin veneer of Cretaceous-Tertiary sedimentary strata (there is no evidence of Paleozoic cover, which might have been eroded prior to Late Cretaceous deposition). The rapid and highly explosive surface eruption of volatile-rich, diamond-bearing magma into a subaerial setting, with only a thin, water-charged, incompetent sedimentary cover, created a circular topographic depression of small diametre, which remained for some time as an open crater. It is evident that the Lac de Gras area was not subsequently inundated by a marine seaway after the emplacement of the kimberlite body which underlies the succession described here, but remained in a continental setting. Neither was there a great thickness of post-eruption cover strata deposited over the region during the 40 + M.Y. time-span between Middle Eocene and Quaternary times. The nonmarine setting continued, positioned above sea level, and the crater itself was retained as an open negative topographic feature after kimberlite collapse, which could accumulate lacustrine and mire deposits. This crater was infilled over the immediately following few million years. The relatively deep, steep-sided pocket of Eocene strata was then protected and preserved from later Tertiary or Quaternary erosion by virtue of being nestled within the surrounding Precambrian granodioritic country rock.

Origin of, and Deposition in, Maar Craters

Maars are low relief volcanic craters (below general ground level) formed by multiple shallow explosive eruptions which form in any subaerial environment where intrusions encounter hydrogeological potential (Lorenz, 1973; Lorenz, 1987). The type occurrence is in the Eifel area of Germany (e.g. the Middle Eocene Ekfeld Maar discussed by Mingram, 1998 and Pirrung et al., 2003). The craters are typically circular topographic depressions less than 1 km in diametre, underlain by a funnel-shaped diatreme, contain coarse volcanic debris, and are often surrounded by a crater ring of pyroclastic debris (Lorenz, 1973; Pirrung et al., 2003). They typically form by phreatomagmatic eruption: a volcanic explosion extruding magmatic gases and steam, caused by contact and interaction of magma with groundwater or shallow surface water (Lorenz, 1973; Lorenz, 1987), such as that interpreted for the post-Pliocene Hopi Butte maars in Arizona (White, 1991). These eruptions involve rapid mixing of the magma with external water and instantaneous transfer of heat from the magma to the water which becomes pressurized and explodes, forcibly ejecting all juvenile and host rock pyroclastic material (Lorenz, 1987). With successive eruptions, water vapour explosions occur at deeper levels, resulting in progressive downward subsidence of the crater and downward penetration of the diatreme, with concomitant growth in diameter (Lorenz, 1986; White, 1991). The emplacement characteristics of rapid phreatomagmatic eruption into water-saturated, noncompetent surface deposits, creating small volcanic craters above deep-seated diatremes is comparable to the emplacement mechanism postulated for kimberlites. Maars are essentially collapse craters, resulting from the catastrophic ejection of wallrocks fragmented by phreatomagmatic water vapour explosions in the near-surface environment (Lorenz, 1986). As a consequence of this open topographic depression, maars are commonly filled with water, forming small, deep, sediment-starved lakes with restricted catchment areas (Mingram, 1998), nested within surrounding bedrock. As a result, thick hypolimnions develop, characterized by a reducing environment where fine grained sediment, varves and abundant organic matter can accumulate and be well-preserved (e.g. Mid-Eocene Messel oil shale, Germany; Goth et al., 1988). Thus, they provide ideal archives for high resolution studies of paleoenvironmental and climate change, protected from erosion for millions of years (Lorenz, 1987). The following example provides details which may aid in interpretation of the Eocene strata overlying the Giraffe kimberlite pipe.

Mingram (1998) and Pirrung et al. (2003) described the Eckfeld Maar, an Eifel area Eocene maar lake deposit. It is about 100 m thick, dated as mid-Eocene by palynology and mammal-age stratigraphy and with a $^{40}Ar/^{39}Ar$ date of 44.3$\pm$0.4 Ma. The Ekfeld Maar was about 800-1000 m in diameter, with a water depth of less than 170 m (Mingram, 1998). Bituminous laminites characterize the basin central area, whereas the margins include coarser clastics derived from the blasted host rocks and syn-eruptive volcaniclastic debris (Mingram, 1998). This deposit includes post-eruptive basal collapse breccias and debris flows, followed by a shallowing-upward succession of laminated oil shales, bituminous siltstones, graded turbidite siltstones, and final gyttja and peat (Pirrung et al., 2003). TOC averaged up to 8.5%, derived from detrital terrestrial plant and aquatic green algal material (Mingram, 1998; Pirrung et al., 2003). Deposition occurred in a subtropical climate at a paleolatitudinal position of about 42-44° N (Mingram, 1998). The mid-latitude position allowed the development of strong seasonality, and therefore seasonal mixing and layered algal enrichments, in spite of the overall warmer Eocene climate. Therefore, the oil shale laminations were interpreted as varves, deposited in a permanently stratified lake, delineating maar lifetime of about 80 - 100 thousand years (Mingram, 1998). This succession is similar to that recorded in the Giraffe core, and may provide a model for interpretation.

GIRAFFE PIPE STRATA AS A MAAR DEPOSIT

The kimberlite crater and post-kimberlitic Eocene strata exhibited in the Giraffe core display many of the unique characteristics of the classic examples of maar deposits. Immediately after kimberlite emplacement, the Giraffe crater must have been a small, but relatively deep and steep-sided, topographic depression in the cratonic setting, underlain by a funnel-shaped kimberlitic diatreme. It appears to have formed by rapid explosive phreatomagmatic eruption, probably through interaction with a thin layer of wet Cretaceous-Tertiary cover rocks, whose existence is indicated by the numerous xenoliths of unaltered sandstone, mudstone and fossil fragments preserved in the kimberlite. This explosive excavation and ejection of the wallrocks apparently created an open maar crater, as described from Hopi Buttes (White, 1991). The position of the maar deposit as a negative topographic feature encased in much older and harder metamorphic country rock (typical of maars) allowed excellent preservation of the sedimentary body, despite later extensive glacial erosion. The enclosed, well-preserved sedimentary strata record the deposits of a small, relatively deep, sediment-starved lake dominated by mudstone sufficiently organic-rich to be classed as oil shale, comparable to the classic Messel and Eckfeld examples of the Eifel area (Goth et al., 1988; Mingram, 1998; Pirrung et al., 2003). The oil shales preserved here are also approximately coeval with those of the well-known maars of the Eifel area of Germany (Mingram, 1998; Pirrung et al., 2003). The small areal extent, relative depth and sediment-starved nature of an isolated maar basin in a prevailing subtropical Eocene climate would encourage water column stratification, a reducing hypolimnion and excellent preservation of organic matter in laminated oil shale, as recorded at Giraffe, Messel and Eckfeld. Even the overall shallowing-upward succession of crater-fill is similar to that described by Pirrung et al. (2003) at the Eckfeld Maar, beginning with lacustrine oil shale and culminating in subaerial peat mire deposits. The succession recorded in the Giraffe core is therefore interpreted as the record of deposition in a late Early to early Middle Eocene, post-kimberlite maar.

Depositional Summary for the Giraffe Maar

The overall setting is interpreted as a small, low-energy maar lake basin of Early to early Middle Eocene age, initially with considerable topographic expression and steep sides, which was filled by a single complex sublacustrine to subaerial succession with minimal clastic input or carbonate precipitation (Figure 8). This succession is characterized by multiple stacked higher-order shallowing-upward sequences, which likely correlate over the entire micro-basin. These sequences are interpreted to represent either 1) periodic, short-duration wet/dry climatic phases, or 2) episodic, downward-stoping subsidence/fill tectonic phases. However, there was a continuous upward increase in shallowing and exposure periods from dominantly subaqueous suspended sediments to dominantly subaerial vegetative mat sediments as the basin filled and the marginal vegetative mats grew outward to clog the surface. This is a common process in modern, small freshwater basins present in humid climates.

This sequence of deposition occurred toward the end of the “Cenozoic Thermal Maximum”, when the crater was surrounded by a mixed deciduous-coniferous forest growing in a warm temperate humid climate, approximately coeval with the famous fossil forest of the Arctic Islands (McIntyre, 1991). During deposition, there was a concomitant upward change from thermally immature lacustrine organic-rich mud and oil shale, to thermally immature terrestrial mire deposits. Although we have data from only a single core, the abrupt reflectance (temperature) shift and presence of bentonite beds marking the transition from lacustrine-dominated to peat mire-dominated deposition may indicate a regional uplift event which occurred after initial kimberlite emplacement. The record of this event may be discernible in the post-eruptive deposits of other pipes.

Whereas this paper presents a brief description of one maar lake succession, much further work is necessary to properly understand this unique depositional setting. To my knowledge, this is one of the first descriptions of a maar lake deposit, and one of only two possible maar deposits of any kind, currently known in Canada (see Zonneveld et al., 2004, for another sedimentary style), but I postulate that more occurrences await discovery. In the current climate of active kimberlite exploration in many regions of the country, I anticipate further identifications of these interesting deposits of a variety of ages. They have great potential for helping to elucidate younger regional tectonic, depositional, climatic and biotic histories in areas of the Canadian Shield with little or no preserved Phanerozoic cover. Furthermore, as Pirrung et al. (2003) suggested, the unusually good preservation of organic matter in maar lake deposits makes them extraordinary archives of delicate fossils, paleoecological data and paleoclimatic indicators.

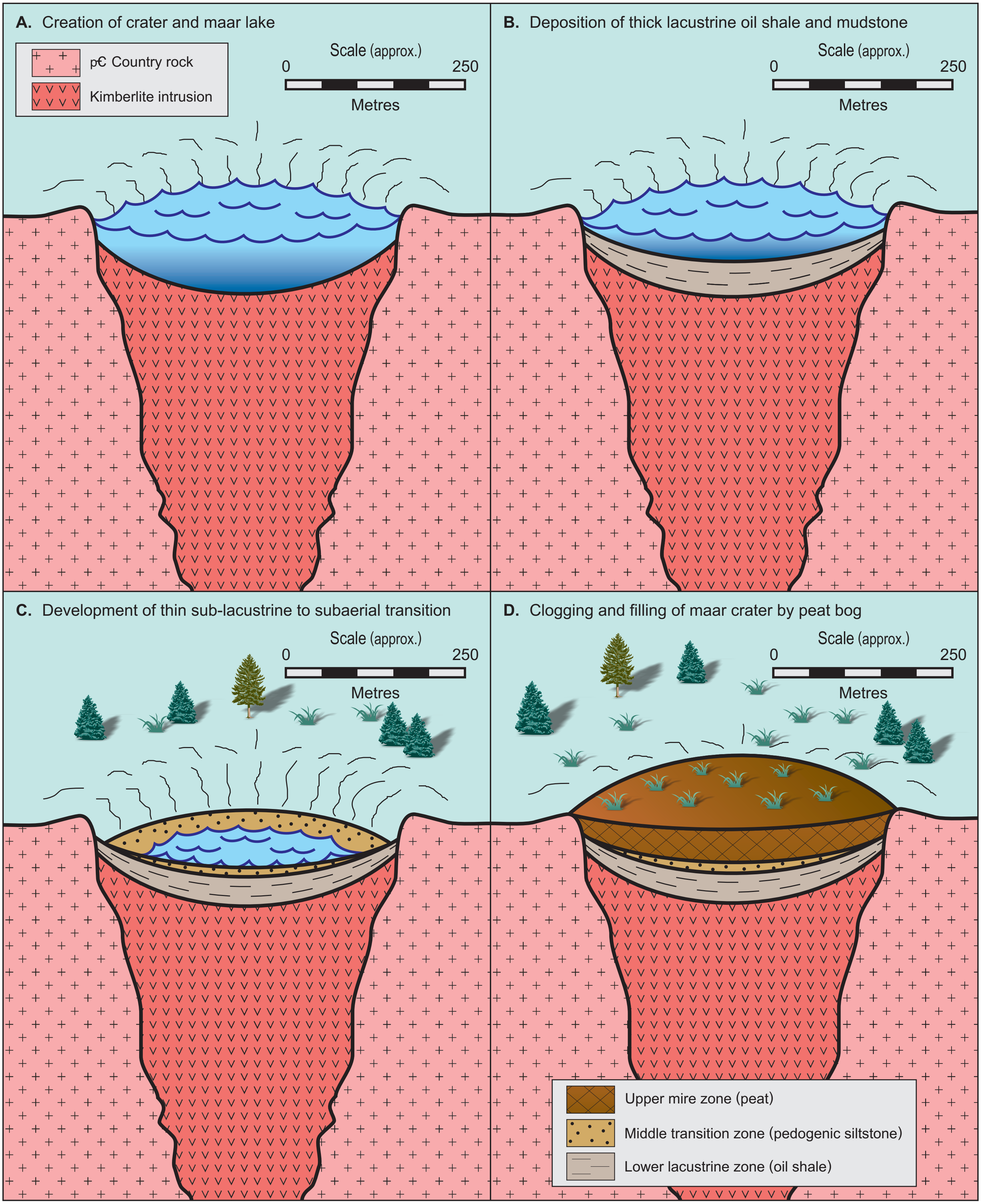


Figure 8. Cartoon cross section depicting Giraffe post-kimberlite maar lake basin in Early to Middle Eocene.

CONCLUSIONS AND IMPLICATIONS

1. A well-preserved section of post-kimberlite, pre-Quaternary sedimentary strata is displayed in the BHP Drillhole 99-01 "Giraffe Pipe" core, which provides an opportunity to study the post-emplacement geological history and paleoenvironment in the immediate crater area. The 110 m succession recorded in the core is of late Early to early Middle Eocene age, was deposited into a small-diametre open maar crater in a subaerial setting and records an overall shallowing-upward succession of maar lake basin-fill. This is one of the first ancient maar lakes identified in Canada, and one of the first in the world to be associated with emplacement of a kimberlite pipe.

2. Sedimentary facies present include: a) thick units of dark, organic-rich mudstone and oil shale, attributed to deposition in the stagnant dysoxic hypolimnion of a small quiet lake, b) thin, sharp-based siltstone beds, interpreted as the result of minor influxes of clastic material from crater margins into shallow lake waters, c) massive silty mudstone with wood fragments, burrows and pedogenic features, interpreted as the deposits at muddy lacustrine shorelines, d) thick units of poorly-consolidated peat, attributed to accumulation in subaerial mires as the crater filled, and e) a few thin bentonite clay beds, interpreted as volcanic ash-fall deposits.

3. The sedimentary succession is divisible into three stratigraphic units which depict the maar lake basin filling process: a Lower Lacustrine Zone dominated by subaqueous deposits of oil shale, a Middle Transitional Zone with evidence of both subaqueous and subaerial deposition in a nearshore/shoreline setting, and an Upper Mire Zone dominated by thick units of subaerial peat. Both the Lower and Upper Zone sediments are typically arranged into stacked, coarsening-upward/shallowing-upward sequences up to 15 m thick, interpreted as the result of periodic wet/dry climatic phases and/or episodic kimberlite collapse/downward-stoping subsidence and fill phases.

4. The thermal maturity of these deposits is low, essentially at "zero coalification", and only slightly greater than modern peats, indicating that post-depositional burial, compaction and thermal alteration have been insignificant. However, within the Middle Transitional Zone, a distinct post-eruptive cooling event is recorded which, if widespread in extent, could be important in tectonic interpretation of the Lac de Gras region.

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LIST OF FIGURES