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Provenance, palaeoclimate and palaeoenvironments of a non-marine Lower Cretaceous facies: Petrographic evidence from the Wealden Succession

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ABSTRACT

Petrographic datasets from sedimentary rocks are very useful for reconstructing their palaeoenvironmental settings especially when field and fossil datasets are unobtainable or inadequate. This study presents the first detailed and comprehensive petrographic study of the four formations constituting the non–marine Lower Cretaceous of the Weald Sub-basin of south-east England and employed petrographic descriptions to reconstruct their palaeoenvironmental settings. >120 samples were subjected to petrographic (QEMSCAN®, SEM, and thin section) analyses, which revealed that the framework composition of sediments is largely quartz-dominated (quartz arenites and subarkose) and has minor amounts of feldspar and lithics. The nature of the quartz arenites suggests that the Wealden successions were likely sourced from a stable interior craton/passive platform within a continental block and possibly from recycled flat-lying platforms such as low-lying granitic and gneissic bedrocks. The nature, maturity and the compositions of the sandstones suggest palaeoclimatic conditions were probably mildly hot and moist at the massifs and these perhaps favoured intense chemical weathering. The significant quantity of micas suggests that the Wealden sediments largely experienced very insignificant degrees of turbulence and agitation en-route depositional sites, thus yielding unwinnowed sediments. The presence of micaceous minerals, poor winnowing effect, and the general absence of diagenetic glauconite validate non-marine depositional environments. The palaeoenvironmental changes that occurred in the Lower Cretaceous in the Weald Sub-basin reflect (at least in part) palaeogeographic changes in NW Europe.

1. Introduction

The Early Cretaceous recorded significant geological events including recession of global sea-level, which eventually altered the nature of sedimentation (e.g., Ziegler, 1981; Hallam et al., 1991; Ruffell, 1991; Rawson, 2006; Föllmi, 2012). The period between the Jurassic and Early Cretaceous witnessed dramatic climatic and eustatic changes (e.g., Allen and Wimbledon, 1991; Taylor and Ruffell, 1993). These changes resulted in non-marine sedimentation in south-east England (e.g., Allen, 1975, 1989; Stewart, 1981), northwest Europe (e.g., Allen and Wimbledon, 1991; Rippen et al., 2013), South America (e.g., Anjos, 1986; Rodrigues et al., 1988), and China (e.g., Chen et al., 2014). Gaining an insight into Early Cretaceous palaeoenvironments is therefore extremely important for understanding a geologically significant period.

Reconstructing the palaeoenvironments of non-marine facies can often be cumbersome partly because of the general paucity of significant fossils that could enhance interpretations in the arenaceous beds (e.g., Cooper, 1977; Föllmi, 2012). This problem may also be exacerbated by restricted access to modern outcrop analogues or their general unavailability, which could have allowed a detailed observation of sedimentary structures. Hence, sedimentologists usually rely on compositions of sediments using diverse discriminatory plots as alternatives, and petrography had been at best a complementary dataset (e.g., Hallam et al., 1991; Dudek, 2012; Akinlotan, 2017a; Mohammedyasin and Wudie, 2019). Thus, when field and fossil datasets are unobtainable or inadequate, the petrographic data of sedimentary rocks could be useful for reconstructing palaeoenvironmental settings, thereby complementing interpretations from other proxies.

The English Wealden facies are part of the regionally important Lower Cretaceous facies of northwest Europe (Fig. 1A). The early Mesozoic palaeogeography of Northwest Europe (Fig. 1B) shows that the London-Brabant Massif (East), the Armorican Massif (South), and the Cornubian Massif (West) were the major massifs that supplied the Wealden facies across northwest Europe (e.g., Allen, 1975; Lake and

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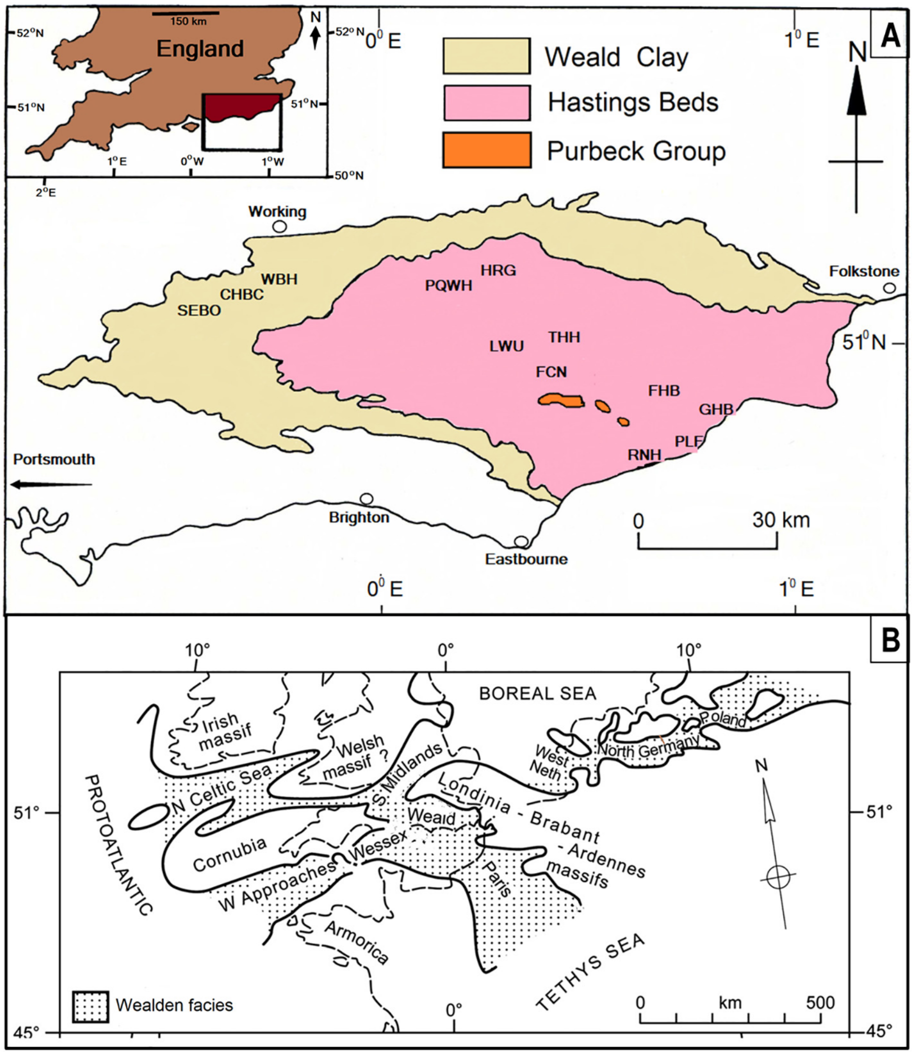

Fig. 1. (A) Geological map of the Weald Subbasin showing the approximate study and sample locations. Modified after Taylor (1991) and Akinlotan (2018). Ashdown and Wadhurst Clay formations: RNH: Rock-a-Nore, Old Town, Hastings, East Sussex, [TQ 827095]; PLF: Pett Level including Haddock's Cottages and Cliff End, Fairlight, near Hastings, East Sussex, [TQ 880118 to TQ 885125]. Tunbridge Wells Sand Formation: THH: Hermitage, High Hurstwood, East Sussex, [TQ495250]; HRG: Harrison's Rocks, Mott Hill. East Sussex [TQ531356]; FCN: Founthill Cutting, Newick, East Sussex [TQ419201]; LWU: Lake Wood, Uckfield, East Sussex, [TQ462216]; PQWH: Philpots Quarry, West Hoathly, West Sussex [TQ355323]; GHB: Galley Hill, Bexhill, East Sussex [TQ759076]; FHB: Freckley Hollow, Battle, East Sussex [TQ71001480 to TQ71021423]. Weald Clay Formation: WBH: Warnham Brickworks, Warnham, West Sussex [TQ179352-TQ182354]; CHBC: Clock House Brickworks, Capel, Surrey [TQ176387-TQ177387]; SEBO: Smokejack Brickworks (Ewhurst), Ockley, Surrey [TQ112372-TQ114375]. National grid references in square [ ] brackets. (B) Palaeogeographic setting of north-western Europe in the Early Cretaceous times showing sediments' sources and the distribution of the Wealden facies.
(Modified from Allen, 1989; Radley and Allen, 2012.)

Shephard-Thorn, 1987; Rippen et al., 2013). In the United Kingdom, the Lower Cretaceous non-marine facies were deposited in two sub-basins: Weald in the southeast southern England (Fig. 1A) and Wessex in central-southern England. The Wessex Sub-basin is not part of the current study. In these sub-basins, Lower Cretaceous non-marine facies comprise fluvio-lacustrine and lagoonal strata (e.g., Allen, 1981; Stewart, 1981; Sweetman and Insole, 2010; Akinlotan, 2018). The Weald Sub-basin is geologically and economically important. The basin remains an extremely rich source of important vertebrate fossils including dinosaurs (e.g., Parkes, 1993; Naish and Sweetman, 2011) and has also become a major focus for unconventional hydrocarbon exploration in southeast England.

In this study, the petrography of Wealden sandstones in the Weald Sub-basin was used for modelling the palaeoenvironments of Lower Cretaceous facies, which can be applied to other Lower Cretaceous non-marine successions across the world owing to similar climatic and environmental conditions. The compositions of the sediments in the Weald Sub-basin have been used to reveal information about their mode of deposition. These include data concerning tectonic settings, the nature of source rocks and source regions, palaeoclimatic conditions, weathering regimes, transport system, and post-depositional changes (e.g., Basu, 1985; Dickinson, 1985; Akinlotan, 2017b). These data are very important for an understanding of palaeoenvironments, geological history, and geodynamic processes (e.g., von Eynatten and Gaupp, 1999; Akinlotan, 2015; Jenchen, 2018; Mohammedyasin and Wudie, 2019). In the Weald Sub-basin, petrographic descriptions of sandstones are scarce, as previous studies were limited to outline descriptions of some parts of the basin (e.g., Allen, 1948; Cook, 1995). More recently, Akinlotan (2017b) used petrographic descriptions of sandstones within the two lowermost formations of the Hasting Beds in the Weald Sub-basin to make palaeoenvironmental reconstructions of Wealden facies.

However, these studies have been limited in scope. The present study builds on the petrographic studies presented by Akinlotan (2015), and it is the first detailed and comprehensive petrographic study of all formations within the Weald Sub-basin using modern analytical methods (Quantitative Evaluation of Materials by Scanning Electron Microscopy (QEMSCAN®), Scanning Electron Microscopy (SEM), and thin section). Previous studies have been mostly limited to thin section studies. This study provides detailed petrographic (qualitative and quantitative) descriptions, uses these to make palaeoenvironmental reconstructions, and test these against previous interpretations based on other proxies. This petrographic study of the Wealden sandstones demonstrates the potential economic importance of sandstones as reservoir rocks in petroleum exploration, although the Wealden sandstones are not currently acting as reservoir rocks in the United Kingdom.

2. Geological setting

The Weald Sub-basin (Fig. 1) in southern England is one of the Mesozoic basins in northwest Europe that started their development as a result of the Permo-Triassic rifting (e.g., Sweeting, 1925; Stoneley, 1982; Lake and Karner, 1987). The subsequent and complex tectonic activities resulted in the formation of several half-grabens in the Weald Sub-basin (e.g., Chadwick, 1986). The sediments within the basin were sourced from the adjacent source massifs and were deposited in non-marine environments with fluvial, deltaic, lacustrine, and lagoonal origins (Allen, 1975). These sediments were never buried >2 km below the surface (Allen, 1981).

The Weald Sub-basin exposes the major sections of the Lower Cretaceous deposits revealing their comprehensive sequences (e.g., Hopson et al., 2008; Radley and Allen, 2012; Akinlotan, 2017a). It is made up of two major units: Hastings Beds (Subgroup) and Weald Clay (Fig. 1). The Hastings Beds (Subgroup) hereafter simply referred to as the Hastings Beds comprises the Ashdown, Wadhurst Clay, and Tunbridge Wells Sand formations in stratigraphic order (Figs. 2, 3). The second unit: 'Weald Clay' is considered as a single formation and its subdivision into lower and upper Weald Clay is rather informal (Hopson et al., 2008). These formations, briefly described below, present excellent exposures of the Lower Cretaceous deposits in England.

The Ashdown Formation (Late Berriasian to Early Valanginian) (Fig. 2) has some foreshore and cliff exposures at East Hill, Hastings known locally as Rock-a-Nore (Fig. 1) in addition to other small outcrops in the Weald (e.g., Hopson et al., 2008; Akinlotan, 2015, 2019). It is mainly composed of fine-grained sand, silt, and mud, which sometimes form cyclothems (e.g., Lake and Shephard-Thorn, 1987; Akinlotan, 2018). Channel deposits, coarsening-upward sandstones, red-mottled argillaceous beds, and point bars are the main sedimentary facies described from the formation (e.g., Stewart, 1981; Akinlotan, 2018). Subdivisions within the formation are generally informal (e.g., Taylor, 1963; Morter, 1984). The total thickness of Ashdown Formation ranges from 115 m in boreholes to between 180 and 215 m in outcrops SW of Hastings (Lake and Shephard-Thorn, 1987). The maximum thickness is generally between 200 and 230 m (Hopson et al., 2008).

The Early to Late Valanginian Wadhurst Clay Formation (Figs. 2, 3) also has some foreshore and cliff exposures at East Hill, Hastings known locally as Rock-a-Nore (Fig. 1) and other minor exposures in the Weald (e.g., Lake and Shephard-Thorn, 1987). The three Wadhurst Park boreholes and Cuckfield No. 1 borehole are the main reference units (Hopson et al., 2008). The formation consists mostly of soft, and dark coloured shales, mudstones, and clay. There are also sandstone, calcareous (Tilgate Stone), shelly limestones, sideritic mudstones (clay-ironstones), and lignite units within the formation (e.g., Lake and Young, 1978; Akinlotan, 2015). Brede Bone Bed, Brede Soil Bed, Cliff End Sandstone, Cliff End Pebble (Bone) Bed, Telham Pebble (Bone) Bed, Hog Hill Sand Member and Northiam Sand Member are recognised members (e.g., Allen, 1975; Lake and Shephard-Thorn, 1987). Although there are no published formal divisions, 'Tilgate Stone' is used informally for the calcareous sandstones within the formation. The entire formation thickness is about 15 m in the Dungeness borehole and perhaps up to 70 m at Cuckfield (Hopson et al., 2008).

The Late Valanginian Tunbridge Wells Sand Formation is principally fine- to medium-grained sand and silt (Rawson, 1992) (Fig. 2). It is divided into the Ardingly Sandstone and the Grinstead Clay members, and the latter includes the Cuckfield Stone Bed. The primary reference sections are from the Cuckfield No. 1 borehole, described by Lake and Thurrell (1974). The formation occurs throughout the central Weald, such as Kent, Surrey, and Sussex; and each of these outcrops represents different parts of the formation. Northwards, the basin is limited in subcrop. Westwards into the Wessex Basin, the formation is poorly

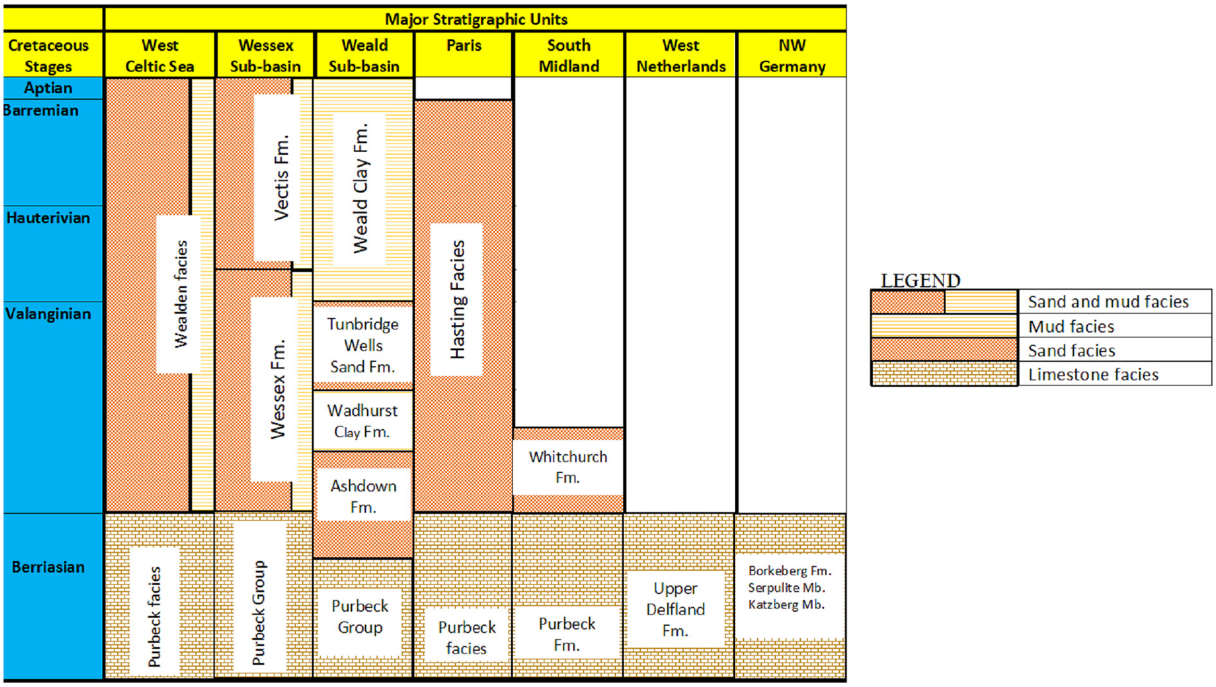

Fig. 2. Stratigraphic correlation of major units of the Early Cretaceous Wealden rocks across northwest Europe. Modified from Allen, (1989, Fig. 1) and Radley and Allen (2012, Fig. 4).

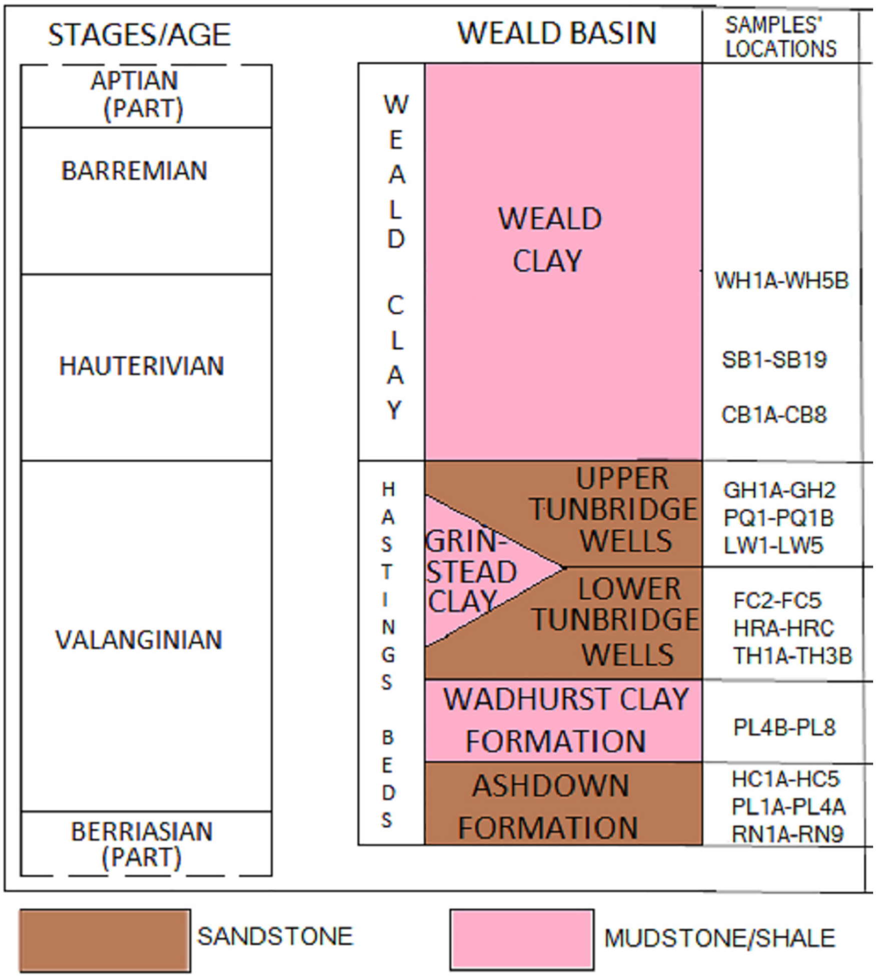

Fig. 3. A hypothetical lithological log showing the sample range and codes from each formation. Note that defined lithological units are representatives of the relative dominant lithology in each formation.
Adapted from Allen and Wimbledon (1991, Fig. 2) and Akinlotan, (2017a Fig. 2), not drawn to scale.

known at subcrop because it becomes very thin. The thickness ranges from 46 m around Hellingly to about 122 m around Grinstead (Hopson et al., 2008).

The Weald Clay Formation (Hauterivian to Barremian) (Fig. 2) is made up of predominantly grey shales, silty mudstones, minor and alternating horizons of siltstones, sandstones, calcareous sands, shelly limestones, and clay ironstones, which are normally weathered to mottled clays (e.g., Jarzembowski, 1991a; Batten, 1998). The lower and upper parts of the formation were recognised as two major cyclic units which represent the Hauterivian and Barremian Stages, respectively. These units have brackish-marine facies near their tops (Worssam, 1978). Fluvio-deltaic/lacustrine/lagoonal floodplain deposits characterise the Weald Clay Formation (e.g., Nye et al., 2008). Fossils such as insects, reptiles, foraminifera, fishes, molluscs, arthropods, insects, and plants have also been recovered in the formation (e.g., Jarzembowski, 1991b; Cook and Ross, 1996; Ross, 1996). It ranges from 122 m at Hythe to up to 460 m around Guildford and reaches a maximum thickness of 740 m (Hopson et al., 2008).

3. Methodology

3.1. Samples and study locations

A total of 122 surface samples collected from 13 locations across the Ashdown, Wadhurst Clay, Tunbridge Wells Sand, and Weald Clay formations of the Weald Sub-basin were used (Fig. 3; Appendices 1, 2, 3). All these locations are situated in the neighbouring counties of Sussex and Surrey in southeast England (Fig. 1). The locations characterise the primary reference sections within the Weald and Weald Sub-basins and they reveal some excellent outcrops in southeast England. They also represent a good combination of present-day inland and coastline units.

3.2. QEMSCAN® and SEM analyses

Automated mineralogical analysis (QEMSCAN®) provides digital imaging and quantitative mineralogical and petrological analyses. This system can acquire and process vast amounts of chemical and mineralogical data, which allows the fully automated acquisition of quantitative mineralogical data from a range of widely available samples. All 122 samples were subjected to QEMSCAN® analysis at CGG Robertson (a geo-consulting company based in North Wales, United Kingdom). Some of the samples were initially made straight into thin sections, whereas others were initially made into polished blocks. In both cases, samples were impregnated with blue dye to ensure that the same surface were subjected to both QEMSCAN® and thin section analysis. This did not affect the QEMSCAN results but ensured the samples were ready for subsequent petrographic analysis.

QEMSCAN® analysis was carried out using a Quanta 650F machine. The Quanta 650F system comprises a scanning electron microscope with two energy dispersive spectrometers (EDS), a backscattered electron detector, a microanalyser and an electronic processing unit.

Automated acquisition of sample mineralogy is achieved through the QEMSCAN® mode of operation. The resulting data were integrated using the iDiscover software suite and CGG's proprietary mineral dictionary to provide information about the 2D textural and mineralogical compositions of the samples. The prepared blocks and thin sections were each divided by the machine into a series of 1.0 × 1.0 mm fields and analysed sequentially by a 15 kV electron beam directed at the sample. Samples were set in thin sections and polished blocks with a maximum sample surface area of 7.29 cm^2 and 5.4 cm^2, respectively. Each sample surface was split into 532 fields with 20 measurement points per field at a scanning resolution of 50 μm. This resulted in a maximum of $(532 \times 20 \times 50 = 532{,}000)$ mineral measurements per sample. The primary and secondary backscattered electrons were initially measured with brightness indicating sample density, and the surface detections were equated to atomic weights. A backscatter cut-off was then used to identify the rock fragments from the mounting medium, and these were further analysed with X-rays collected by the EDS detectors, providing a mineralogical map of each sample.

The quartz (Q), feldspar (F), and lithic (L) compositions obtained from QEMSCAN® were expressed as percentages, and the resultant values were plotted on ternary diagrams to interpret sediments' classifications based on the McBride (1963) and Garzanti (2016) schemes. The percentage of total clay composition (detrital and authigenic) was computed by adding percentages of chlorite, illite, glauconite, smectite, and kaolinite in each sample. The total cement was estimated as the sum of calcite, ferroan calcite, dolomite, ferroan dolomite, gypsum/anhydrite, siderite, and pyrite in each sample.

3.3. Petrographic and SEM analyses

A total of 17 petrographic thin sections were made from unweathered representative sandstone and ironstone samples selected from the 122 samples analysed by QEMSCAN® (Fig. 1). All the 13 study locations were represented in the sampling. More than one sample was selected in localities with very thick sections. The Ashdown and Wadhurst Clay Formations were represented by two samples each, while seven and six samples were selected from the Tunbridge Wells Sands and Weald Clay Formations, respectively. For the samples that have been previously made straight into thin sections, the carbon coatings were cleaned off from the thin section slides using methanol and a coverslip was added. The samples were cut and shaped to fit the 30 mm diameter sample moulds which were impregnated with blue-dyed epoxy resin to highlight porosity. Petrographic thin sections were made by cutting the polished blocks with a diamond saw. Petrographic photographs were taken using a transmitted light microscope (Zeiss AX10) at CGG Robertson.

Rock chips of the same 17 sandstone samples subjected to thin section analysis were prepared for SEM analyses at CGG Robertson. Approximately 1 cm^3 of each sample was attached to metal SEM stubs using Struers' Epofix glue. In the case of disaggregated samples, a small piece of adhesive carbon tape was stuck to the top of the stub and the sample material attached on top of it. A thin coating (approximately 20 nm) of carbon was then deposited on the surface of all samples using a carbon coating machine.

All the SEM samples were analysed using the same QUANTA 650F machine but via manual analysis – not the automated QEMSCAN mode of operation. The samples were imaged first, locations saved, and then the same locations re-visited at revised beam settings to obtain the EDS measurements. All EDS measurements were taken at 15 keV, but some of the images were taken at lower keV due to random areas of surface charging caused by clay and other minerals that would slightly distort the saved image. No EDS measurements were taken from charged areas. The individual SEM images display the varying level of accelerating voltage and spot size settings for the electron beam applied throughout the analyses, which generally ranged from 5 to 15 keV and 3–4 spot. EDX data was obtained using ×2 Bruker EDX detectors and Bruker's ESpirit analysis software.

4. Results

The basal Ashdown Formation lithologically comprises greyish fine sands/sandstones to grey mudstones with inconsistent ironstone layers. The samples are texturally mature- to submature, and primarily medium- to fine-grained, well-sorted, subrounded to rounded with textural frameworks that are rarely matrix-supported (Fig. 4A, B, C). They dominantly comprise quartz grains showing tangential and long grain-to-grain contacts with undulous extinction (Fig. 4B, C), rare clay matrix (Fig. 4A), and evolving interstitial sericite and clay-coats (Fig. 4B). Monocrystalline quartz (≥ 95%) dominated polycrystalline quartz (≤ 5%) and feldspar, which seldom exceeds 2% (Fig. 3C). The samples are generally barren of lithic/rock fragments (Fig. 4B). SEM images of representative samples indicate quartz grains are commonly euhedral in shape (Fig. 4A, B). Kaolinite booklets occur mainly as detrital grains (Fig. 5B), whereas muddy matrices and cement materials sometimes obscure quartz grains (Fig. 5B). QEMSCAN® quantitative petrography across the Pett Level, Fairlight (AF-PLF; $n = 7$), the Haddock's Cottages, Fairlight (AF-HCF; $n = 6$), and the Rock-a-Nore, Hastings (AF-RNH; $n = 14$) localities shows an average quartz composition of 69.2, 76.5 and 62.8%, respectively (Appendix 1) (here and below percentages are percent volume). The computed mean ($n = 27$) quartz-feldspar-lithic (QFL) composition ($Q_{99.5}F_{0.5}L_0$) classified the samples as mainly quartz arenite and quartzose (Fig. 6). The Ashdown Formation's samples generally have low (<1%) total cement, biotite, K-feldspars, and plagioclase. There is no consistent trend between the two feldspar types (Fig. 6; Appendix 1). The mean muscovite composition of 3.4% (Pett Level, Fairlight), 1.7% (Haddock's Cottages, Fairlight), and 6.1% (Rock-a-Nore, Hastings) were documented across the three localities (Appendix 1). Average total clay content (16.5–27.0%) is dominated by kaolinite (8.6–14.8%) and illite (6.2–11.2%), with samples from the Haddock's Cottages, Fairlight and Rock-a-Nore, Hastings localities yielding the least and highest mean values, respectively for both minerals (Fig. 7).

The overlying Wadhurst Clay Formation comprises mainly brownish to greyish sandstone and mudstone, with generally more consistent ironstone layers than the Ashdown Formation. The ten samples of the Wadhurst Clay Formation in this study were all collected from the Pett Level, Fairlight (WCF-PLF) location (Appendix 1). The formation is texturally composed of subangular to subrounded, well-sorted, and fine to very fine-grained materials with significant intergranular haematitic cement (Fig. 3D). Quartz grains occur mainly as subhedral to anhedral shape with undulating extinction under crossed-polarised light. Pyrite clusters are conspicuous in some SEM micrographs (Fig. 5C). Estimated QFL composition of the Wadhurst Clay Formation is $Q_{98.2}F_{1.8}$ L_0 (Fig. 6). Although the clay and ironstone samples recorded low quartz composition and plotted away from the quartz arenite region in Fig. 5, the sandstone samples generally recorded high percentage quartz content up to 98.0% (Appendix 1). Feldspar components (0.4%) are notably low (Appendix 1), with plagioclase (0.4%) and K-feldspars (0.4%) constituting <1% cumulatively (Appendix 1). The formation is clay-rich (mean 19.6%), with contributions from chlorite (6.6%), illite (7.2%), glauconite (0.1%), smectite (0.2%), and kaolinite (5.6%), while the cement (average 21.8%) is mainly contributed by siderite (17.4%) and calcite (4.3%). Mica compositions are mainly biotite (mean 2.0%) and muscovite (mean 1.5%).

The early to mid-Valanginian Tunbridge Wells Sand Formation (the topmost formation of the Hasting Beds) is essentially comprised of brownish to greyish sandstones with lesser occurrences of mudstones and ironstone. It is moderately- to poorly sorted, angular to subangular, and quartz-dominated with an estimated 5–29% intergranular porosity (Fig. 4E). Grain-to-grain contacts are mainly tangential and long types (Fig. 4E). Quartz displayed undulous extinction, and its shape ranges

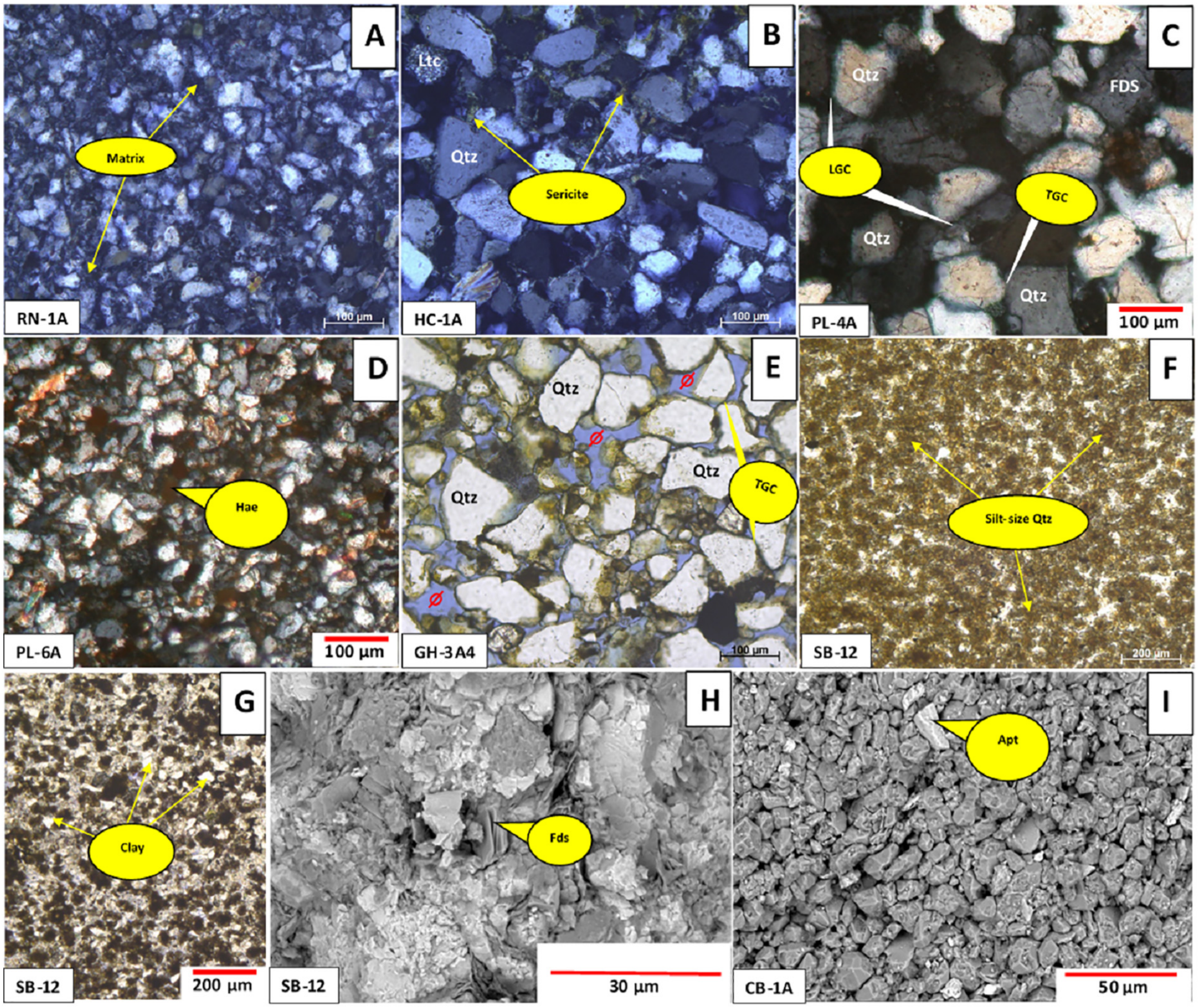

Fig. 4. Micrographs of some of the Wealden sandstones and ironstones: (A) fine-grained, well-sorted, sub-rounded to rounded and matrix-supported muddy sandstone (Ashdown Fm; XPL); (B) evolving interstitial sericite and clay coats within a typically grain-supported sandstone framework (Ashdown Fm; XPL); (C) medium grained sandstone showing tangential and fairly long grain-grain contacts (Ashdown Fm; XPL); (D) very fine-grained ironstone showing significant intergranular haematite cement (Wadhurst Clay Fm; XPL); (E) medium to fine-grained, poorly sorted, sub-angular to sub-rounded grains showing tangential grain contacts, grain-supported framework and substantial porosity in sandstone (Tunbridge Wells Sand Fm., PPL); (F) silt-sized quartz in clay-bearing ironstone (Weald Clay Fm., PPL); (G) distribution of clay patches in clay bearing ironstone (Weald Clay Fm., XPL micrograph of Fig. 4F); (H) SEM image of Fig. 1F, G showing feldspar grain (Weald Clay Fm); (I) SEM image showing detrital nature of grains and broken apatite crystals (Weald Clay Fm). Note that Qtz, Fds, Ltc, and Apt denote quartz, feldspar, lithics, and apatite, respectively. LGC is long grain contact, TGC is tangential grain contact, and Hae is haematite.

from euhedral to subhedral (Fig. 4D). Ferroan-dolomite rarely occurs as grain-coating (pore-preserving) and pore-occluding cement (Fig. 5D). The QFL composition of the Tunbridge Wells Sand Formation's sediments ($n = 39$) is $Q_{99.6}F_{0.4}L_0$ (Fig. 6). The formation yielded average quartz compositions that commonly exceed 85.4% in the Freckley Hollow, Battle (FHB; $n = 10$); Philpots Quarry, West Hoathly (PQWH; $n = 2$), Lake Wood, Uckfield (LWU; $n = 5$), Founthill Cutting, Newick (FCN; n = 5), Harrison's Rocks, Groombridge (HRG; n = 3), and The Hermitage, High Hurstwood (THH; $n = 6$) localities (Fig. 7B; Appendix 2). However, samples of the Tunbridge Wells Sand Formation from the Galley Hill, Bexhill (GHB; $n = 11$) locality yielded a quartz concentration that varies, and ranges from 19.81 to 91.72% (mean 56.08%) (Fig. 7B). The highest mean concentration of quartz was recorded in the Lake Wood, Uckfield location (Appendix 2). Biotite, muscovite, and feldspar (plagioclase and K-feldspars) across the entire seven localities show mean compositions that are generally <1% for the Tunbridge Wells Sand Formation (Fig. 7B). The predominance of plagioclase by K-feldspar characterises most of the studied representative samples of the formation (Appendix 2). Compared to other studied formations, the Tunbridge Wells Sand Formation generally has less muscovite with mean values of 0.17% (Freckley Hollow, Battle), 3.08% (Galley Hill, Bexhill), 0.14% (Philpots Quarry, West Hoathly), 0.01% (LWU), 0.26% (FCN), 0.01% (Harrison's Rocks, Groombridge) and 0.34% (The Hermitage, High Hurstwood). Other notable mineralogical and textural parameters in the formation are total clay (0.1–27.8%; mean 7.1%) and total cement (<0.1–7.3%; mean 2.3%) (Fig. 7B; Appendix 2).

The uppermost Hauterivian to Barremian Weald Clay Formation in the Weald Sub-basin is lithologically composed of greyish to blackish mudrocks (mudstone and shale) with rare ironstone interval (Appendix 3; SB-11 to SB 16). It is texturally clay-bearing with silt-sized quartz, clay patches, and non-conspicuous grain-to-grain contacts (Fig. 4F, G). High-resolution SEM analysis indicated the occurrences of K-feldspar grains (Fig. 4H), apatite (Fig. 3I), calcite crystallites (Fig. 5E), and pyrite (Fig. 5F). Quartz grains are generally of anhedral shape with undulating extinction. The Weald Clay Formation ($n = 43$) yielded significant average percentage clay components of 42.6%, 43.8%, and 33.4% in the Warnham Brickworks, Horsham (WBH; n = 10), Smokejack/Ewhurst Brickworks, Ockley (SEBO; $n = 21$), and Clock House Brickworks, Capel (CHBC; $n = 12$) localities, respectively (Appendix 3). The mean quartz and feldspar compositions across the three studied locations range from 31.4% (Smokejack/Ewhurst Brickworks, Ockley) to 43.3% (Warnham Brickworks, Horsham) and 0.7% (Smokejack/Ewhurst

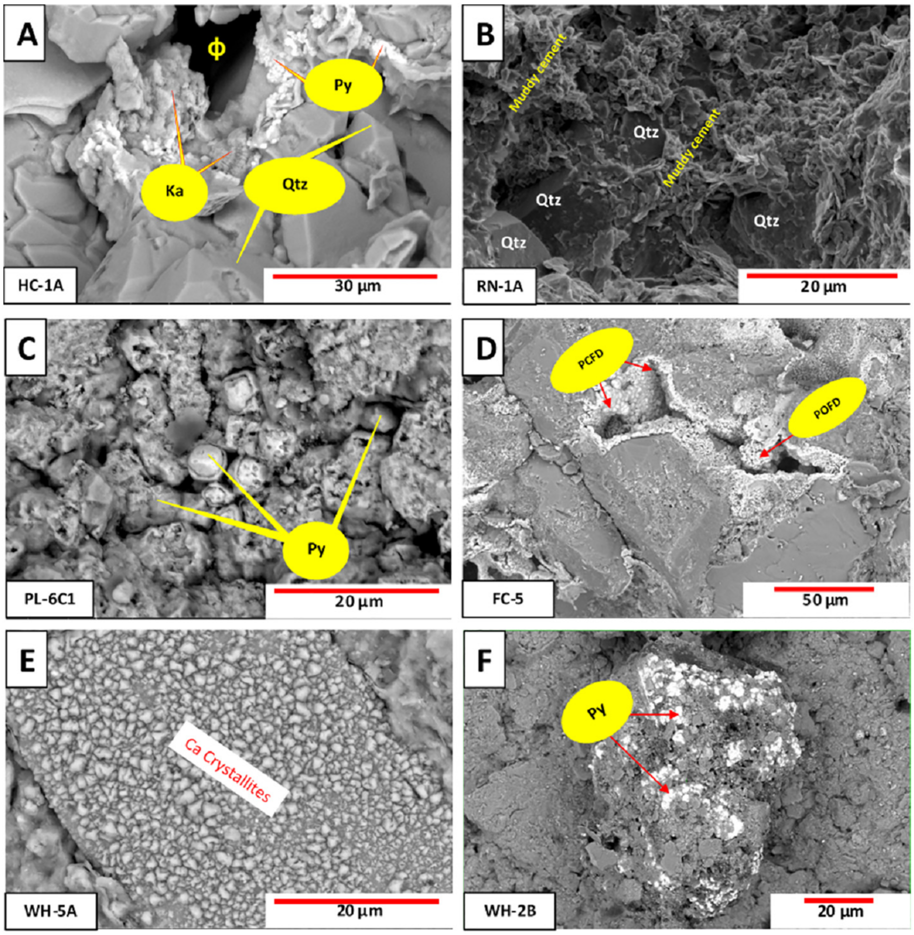

Fig. 5. Backscatter SEM micrographs of representative samples showing high resolution petrographic and mineralogical characteristics: (A) tetrahedral quartz crystals with detrital kaolinite and pyrite in Ashdown Formation; (B) quartz grains obscured by muddy Matrices and cements; (C) pyrite crystals within the Wadhurst Clay Formation; (D) grain-coating and cementing ferroan dolomite crystallites in the Tunbridge Wells Sand Formation; (E) aggregate crystallites of calcite in Weald Clay Formation, (F) evolving diagenetic pyrite crystals in the Weald Clay Formation. Ka is kaolinite, Py is pyrite, Qtz is quartz, PCFD is pore-cementing ferroan dolomite, POFD is pore-filling ferroan dolomite, and Ca is calcite.

Brickworks, Ockley) to 2.9% (Clock House Brickworks, Capel), respectively (Appendix 3), and the predominance of plagioclase over K-feldspars is noticeable (Appendix 3). The calculated QFL composition (n = 43) for the Weald Clay Formation is $Q_{93.7}F_{6.3}L_0$ (Fig. 5). Some samples of the Weald Clay Formation plotted in the sub arkose/arkose (Fig. 5A) and feldspatho-quartzose/quartzose feldspathic (Fig. 5B) fields. Although mean quartz composition generally predominates other mineralogical components, the trends of key mineralogical composition across the 43 samples of this formation indicate quartz content is quite irregular and ranges from ~2.9% (SB 11) to ~73.2% (CB 1C) (Appendix 3). The intervals with lower quartz composition typically have high clay or sideritic cement compositions (Appendix 3). The highest muscovite composition (24.0%) was found in sample SB 17 at the Smokejack/Ewhurst Brickworks, Ockley locality, and the percentage mean composition in the Warnham Brickworks, Horsham (5.5%), Smokejack/Ewhurst Brickworks (4.4%), and Clock House Brickworks, Capel (3.3%) generally exceeds that of biotite, which ranges from <0.1 to 2.0% across the localities.

5. Interpretation and discussion

5.1. Detrital compositions

The composition of major framework grains in the studied Wealden rocks ($Q_{97}F_3L_0$) characterises them as being dominantly quartz-rich, and by implication classified as quartz arenites with less subarkosic input (McBride, 1963) or quartzose with fewer contributions from fedspatho-quartzose and quartzose-feldspathic materials (Garzanti, 2016), as shown in Fig. 5. The general absence of ductile lithic fragments (e.g., slate and shale), in addition to the predominance of brittle grains, such as quartz and feldspars (Fig. 4, Appendices 1, 2, 3), suggests largely unaltered original detrital composition, insignificant compactional effects, and minor grain packing or rearrangement (Fig. 4). This is because brittle grains do not enhance early compactional alteration, like ductile grains (Rittenhouse, 1971a, 1971b). Theoretically, the detrital compositions of sandstone facies can be deduced from the frequency of secondary porosity (grain dissolution), as the latter genetically develops from the chemical interactions of unstable grains with pore fluids. Thus, the general absence of grain dissolution and intraparticle porosity in the studied Wealden facies further support that their detrital compositions are largely preserved (Figs. 3, 4).

The rarity of detrital pyrites and non-pore occluding kaolinitic booklets, alongside the absence of dickite in the Ashdown Formation indicate detrital compositions are intact (Fig. 5A). This is further substantiated by the quantitatively low mean total cement compositions across the Pett Level, Fairlight (0.3%), Haddock's Cottages, Fairlight (0.3%), and the Rock-a-Nore, Hastings (0.5%) localities (Fig. 7A). Similarly, the presence of non-diagenetic pyrite crystallites within the framework of the overlying Wadhurst Clay Formation points to the preservation of detrital imprints in the formation (see Fig. 5C). The preservation of primary intergranular porosity in the Tunbridge Wells Sand Formation further stressed the predomination of brittle detrital grains in the formation (Fig. 4D), which in turn suggest lesser compaction and higher detrital framework preservation than in the underlying Wadhurst Clay and

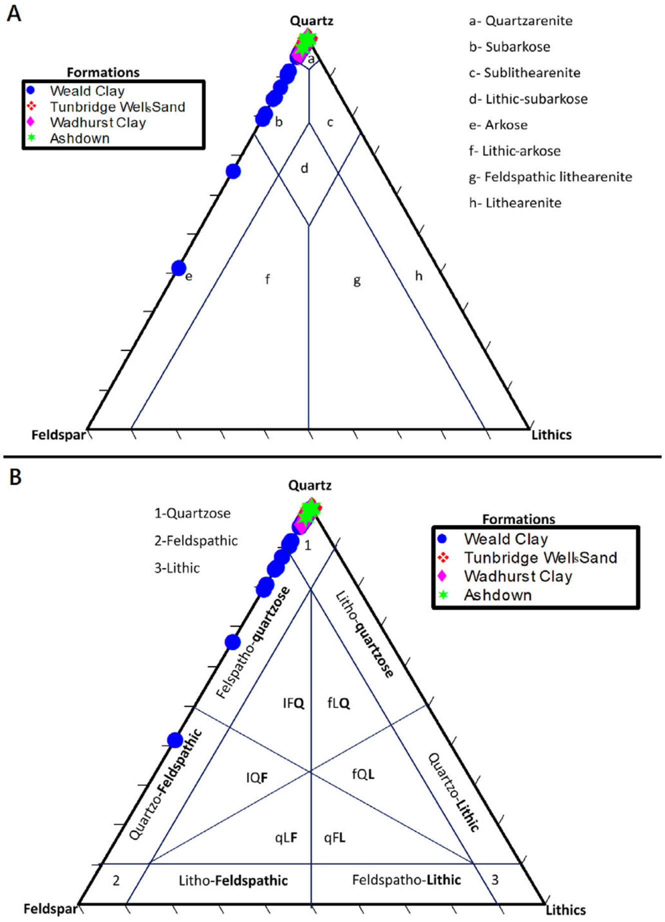

Fig. 6. Classification of the studied Wealden sandstones using ternary plots; (A) The McBride (1963) classification scheme, and (B) the Garzanti (2016) classification scheme. AS: Ashdown Formation; WF: Wadhurst Clay Formation; TWSF: Tunbridge Wells Sands Formation, WC: Weald Clay Formation.

Ashdown formations (Fig. 4). Since cementation is mainly a post-depositional alteration, the low average total cement composition (9.0%) in the uppermost Weald Clay Formation reasonably reflects preservation of some of its detrital compositions (Fig. 7C), Thus, the documented high total clay components are interpreted to be largely detrital (Fig. 7).

5.2. Authigenic imprints

Presented petrographic evidence has shown that the detrital composition of the Wealden rocks in the Weald Sub-basin is largely preserved (Figs. 3, 4). However, these datasets also indicate the samples have experienced minor eogenetic alterations (Appendices 1, 2, 3). Eogenesis refers to early diagenetic modifications (e.g., compaction and cementation) that occur in the vicinity of the depositional environment when the diagenetic fluids are still in communication with the depositional/formational fluids (Brand et al., 1998; Adepehin et al., 2019a). The co-occurrences of tangential and long grain contacts in the representative thin sections (Fig. 4) are suggestive of minor to moderate compaction (Taylor, 1950; Rittenhouse, 1971a, 1971b). This is supported by the near-dearth occurrence of glauconite (Appendices 1, 2, 3), a proven early diagenetic indicator across the four formations (Selley, 1976; Ola and Adepehin, 2017). Although Light (1952) indicated that glauconite could also be detrital, it is generally regarded as an authigenic mineral (e.g., Odin, 1972; Bjerkli and Oestmo-Saeter, 1973). Besides, glauconite is generally friable and highly susceptible to weathering. Hence, it could not have survived the predominantly humid climate/weathering that characterised the Jurassic-Cretaceous transition in NW Europe (e.g., Sladen and Batten, 1984; Haywood et al., 2004; Schnyder et al., 2006), as implied by the current data and discussed in Section 5.4.

Cementation in sedimentary rocks is generally an early eogenetic- to mesogenetic process (e.g., Houseknecht, 1987; Adepehin et al., 2019b, 2020). Thus, the generally low total cement counts in most samples of the Wealden rocks, especially the Ashdown Formation and Tunbridge Wells Sands Formation (Fig. 7; Appendices 1, 2, 3), and the corresponding lack of essentially mesodiagenetic signatures, such as grain/cement dissolution, recrystallisation, and replacements, known to result from progressive burial depth after eogenesis also advocate relatively insignificant early diagenetic imprints (Figs. 3, 4). The very low cement counts (0.4%) in the Ashdown Formation (Appendix 1) substantiate minor early diagenesis, in addition to the interpreted compactional effects. The 21.8% average total cement in the Wadhurst Clay Formation is largely dominated by sideritic cement (17.4%) and thus indicated a relatively more intense eogenetic influence than the underlying Ashdown Formation. The use of siderite as a proxy for early diagenesis is a widely explored concept (e.g., Rossi et al., 2001; Alekseeva et al., 2016; Kim et al., 2019) and had been specifically applied to the lower Hasting Beds (Akinlotan, 2019). Notwithstanding the low mean total cement (<0.1 to 7.3%), the evidence of authigenic alteration in the overlying Tunbridge Wells Sand Formation includes pore-coating and pore-filling ferroan dolomite cement (Fig. 5D), which significantly impacts intergranular pore spaces. Cementation in the uppermost Weald Clay Formation is mainly sideritic and calcitic in nature (Figs. 5e, f, 6c), with average percentage compositions that range from 1.5 (Warnham Brickworks, Horsham) to 14.2% (Clock House Brickworks, Capel). The interpreted mild insignificant diagenetic influence on the studied Wealden successions agrees with Kemp et al. (2012) assertion that the Wealden Beds of the Weald Sub-basin (Hasting Beds and Weald Clay Formation) are dominated by their detrital composition and only very slight diagenetic overprints could be detected. These data demonstrate that the compositions of the sediments largely reflect their detrital nature and are thus suitable to interpret sediment sources.

5.3. Provenance of the Wealden detritus

Sediment detrital compositions are useful for provenance determination (Dickinson, 1970, 1974; Dickinson and Suczek, 1979). The constructed provenance discriminatory plot interpreted the studied Wealden facies to have been principally derived from the continental block (Fig. 8), with all formations of the Hastings Beds indicating a stable craton/craton interior provenance. Conversely, the Weald Clay Formation indicated provenances sourced across the three subclasses of the continental blocks; that is basement uplift, transitional continental, and craton interior (Fig. 5). Craton-sourced arenites are mainly products of flat-lying granite and gneiss, with lesser contributions from associated reworked low-lying platform detritus (Dickinson, 1985). A predominantly plutonic igneous provenance is indicated as the source of the Weald Sub-basin's sediments/sedimentary rocks based on the high dominance of monocrystalline quartz over polycrystalline quartz in this study. This notwithstanding, contributions from metamorphic rocks may not be ruled out. For instance, the presence of euhedral quartz observed in some of the representative samples suggest reasonable contribution from quartzite or its sandstone derivatives (Figs. 4A, B, D). Quartzite components of the source rocks were perhaps produced from the invasion of magma into country rocks (in this case sandstones) of the source area. The occurrence of arenite as first-cycle sediments from the craton had been queried, as the sedimentary reworking of craton-derived sediments was thought to be crucial in its maturation (Suttner et al., 1981). Nevertheless, evidence that modern quartz arenites were derived as first cycle materials from intensely weathered bedrocks (granites and gneisses) in the Amazon Basin (Franzinelli and Potter, 1983), supports the possible generation of the Wealden facies from dominantly low-lying gneissic and granitic bedrocks, as interpreted from its textural composition in this study.

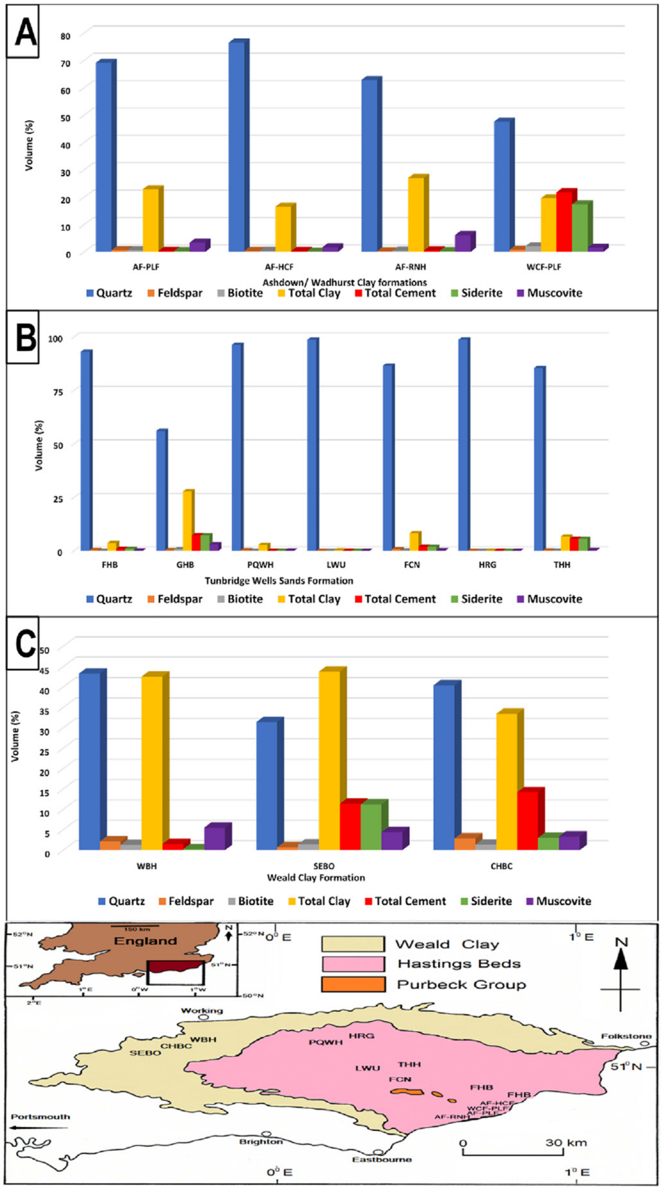

Fig. 7. Bar charts showing average QEMSCAN® mineralogical components across the four studied formations. (A) The lower Hastings Beds (the Ashdown Formation and the Wadhurst Clay Formation). WF-PLF represents Wadhurst Clay Formation samples from Pett Level, Fairlight (*n* = 10). AS-PLF, AS-HCF and AS-RNH respectively denote samples of the Ashdown Formation from Pett Level Fairlight (*n* = 7), Haddock's Cottages Fairlight (*n* = 6) and Rock-a-Nore Hastings (*n* = 14). (B) The Tunbridge Wells Sand Formation across the seven studied localities. FHB is Freckley Hollow, Battle (n = 10); GHB is Galley Hill, Bexhill (*n* = 11); PQWH is Philpots Quarry, West Hoathly (*n* = 2); LWU is Lake Wood, Uckfield (n = 5); FCN is Founthill Cutting, Newick (n = 5); HRG is Harrison's Rocks, Groombridge (*n* = 3); and THH is The Hermitage, High Hurstwood (n = 6), (C) The Weald Clay Formation across the three studied localities. WBH is Warnham Brickworks, Horsham (n = 10); SEBO is Smokejack/Ewhurst Brickworks, Ockley (*n* = 21), and CHBC is Clock House Brickwroks, Capel (*n* = 12).

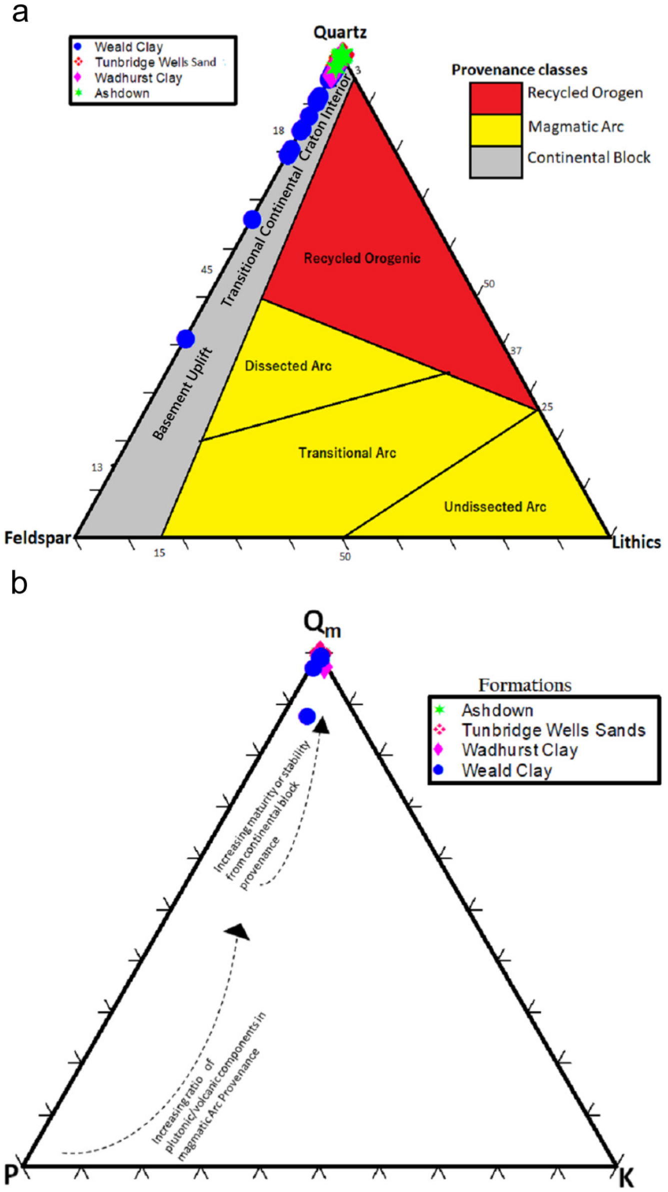

Fig. 8. (A) Provenance discrimination QFL plot (Dickinson, 1985) for Wealden sandstones examined in this study (*n* = 122) showing the dominance of continental block provenance with >95% of samples clustered within the craton interior tectonic setting. Note the overlapping of plotted points within the craton interior field. (B) Qm-P-K sediments' provenance and maturity discriminatory plot suggesting increasing maturity influenced by continental block (*n* = 17). Note that only samples subjected to thin section analysis are plotted on the figure.

In addition to source composition, the production of quartz arenite/quartzose is arguably influenced by some processes from source-to-sink: (i) sedimentary reworking (e.g., Ola and Adepehin, 2017; Lorentzen et al., 2019), (ii) interplay of climate, relief, and sedimentation rate (Potter, 1978; Suttner et al., 1981; Avigad et al., 2005), and (iii) diagenetic breakdown of less stable framework minerals (Mcbride, 1985). The near-dearth occurrence of feldspars and the complete absence of lithic fragments in the Wealden successions appear to justify multiple cycles of transportation and deposition (Fig. 4; Appendices 1, 2, 3). Nevertheless, the variations in grain sizes, sorting classes, degrees of angularity, and the significant presence of detrital clay size particles in the samples provide textural signatures against sedimentary recycling being a dominant process in the generation of these quartz-rich sediments (Fig. 6). Muscovite and biotite are unstable micas that are generally vulnerable to rigours of multicyclic sedimentary transportation-deposition (e.g., Ola and Adepehin, 2017; Adepehin et al., 2019a). Therefore, the documented notable quantity of muscovite in the Ashdown, Wadhurst Clay, and Weald Clay formations (Fig. 7A, C) further discredited sediment recycling as a dominant process in their maturity, whereas the low muscovite and biotite in the dominantly arenaceous Tunbridge Wells Sands Formation (Fig. 7B) somewhat favour mineralogical maturity process. However, recent sedimentological datasets have shown that mineralogical maturity does not necessarily increase with transportation in high energy fluvial system, even after thousands of kilometres (Garzanti, 2017).

Based on a study in Kraków-Silesia Homocline in Poland, probable felsic magmatic and metamorphic rocks (granite/gneiss) provenances were interpreted from high cumulative concentration (>80%) of quartz (34.0–67.0%), illite (12.9–31.7%), kaolinite (1.8–15.6%), plagioclase (0.0–2.5%), and K-feldspars (0.8–7.2%) in ore-bearing argillaceous sediments and sedimentary rocks. Thus, the high cumulative composition of these minerals above the 80% cut-off in the Ashdown (90.0%), and Tunbridge Wells Sand (88.9%) formations supports the derivation of the formations from dominantly granitic and/or gneissic provenance (s). Conversely, the fact that the collective composition of these minerals in the Wadhurst Clay (61.2%), and Weald Clay (74.6%) falls short of the 80% threshold probably supports predominantly recycled provenance(s). Nevertheless, the absence of significant feldspars (Figs. 3–6; Appendices 1, 2, 3) in the Wealden succession is inconsistent with the typical high feldspar content associated with granitic rocks (e.g., Brown and Parsons, 1994; Thompson et al., 1998). While this anomaly could have resulted from the chemical breakdown of microcline and plagioclase to form clay (e.g., Lanson et al., 2002; Yuan et al., 2019), petrographic micrographs and QEMSCAN® data do not support this (Figs. 3, 4; Appendices 1, 2, 3).

Sediments within the Weald Sub-basin were largely derived from the London and Cornubian Massifs with minor additions from the Armorican Massif (Allen, 1975) and the Boreal Sea (Allen, 1991). Materials derived from granite and gneiss are present within these sources (Allen, 1981; Andre, 1991). The uplifted London-Kent horsts system had been interpreted as the provenance of the Hastings Beds formations (Allen, 1975), but in particular as the main source of the arenaceous sedimentary infill in the Weald Sub-basin, and its contiguous Wessex Sub-basin (Fig. 1B). However, heavy mineral suites from the upper part of the Hastings Beds (Tunbridge Wells Sand Formation) indicated its derivation from the Cornubian Massifs and sediments spilt over from the Wessex Sub-basin (Kemp et al., 2012) (Fig. 1B). Situated in the East of the Anglo-Brabant Massif, the London block comprises Precambrian to Lower Palaeozoic basement rocks, extrusive rocks, metasedimentary rocks, and intensely folded strata (Allen, 1991; Andre, 1991).

The documented dwindling and cessation of major sediment-sourcing from the London and Kent parts of the Massif during the Hauterivian to Barremian (Allen, 1975), when the deposition of the Weald Clay Formation took place, indicates that these horst systems had minimal (if any) contribution to its provenance. During this time, a lack of uplift of the London Massif paved way for the incursion of the muddy 'Snettisham' Sea (Allen, 1975). However, the provenance of the uppermost Weald Clay Formation detritus has been linked with the Cornubian Massif to the West and south-western Armorican Massif in northern France (Kemp et al., 2012; Akinlotan, 2017a, 2018). The latter consists predominantly of Precambrian suites including quartzites and granites, New Red Sandstone (Permo-Triassic), and borderline Mesozoic deposits (Allen, 1991). The Late Carboniferous-Permian Cornubian batholith is a two-mica (muscovite and biotite) alkali granite uncovered as the eroded basement of the Palaeozoic Variscan mountain belt (Allen, 1975). The petrological characteristics of the Cornubian and Armorican Massifs support the interpretation that the Weald Clay Formation quartzose was mainly derived from igneous provenances, in agreement with a dominant craton interior source (Fig. 8). The plotting of some of its points away from the arenitic/quartzose field, however, indicates some contributions from other sources as discussed above.

5.4. Climate and weathering patterns

Although the SiO_2 (quartz) composition of sediments impacted by arid and semi-arid climate may be up to 80%, such sediments are generally feldspar-rich (10–25%) (Suttner and Dutta, 1986). Thus, the co-occurrences of high mean quartz compositions, alongside very low feldspar contents in the Ashdown (Q-69.5%; F-0.4%) and Tunbridge Wells Sand (Q-87.8%; F-0.3%) (Fig. 7A, C) reasonably imply impacts of humid climate. The textural characteristics (Figs. 4–6) of the Wealden of the Wealds in this study generally reflect the impact of subtropical to warm temperate palaeoclimatic conditions, in agreement with earlier interpretations from other proxies (e.g., Sladen and Batten, 1984; Ruffell and Worden, 2000; Haywood et al., 2004). In the Early Cretaceous, a fault-induced uplift of source massifs (mainly the London-Brabrant and Armorican massifs) resulted in irregular elevation, which was adequate to locally influence the climate (Sladen and Batten, 1984). The high precipitation (>1000 mm) that characterised the source environments at that time facilitated intense chemical weathering and acid leaching that were accompanied by basin-bound and sediments-carrying run-off, leading to rapid sedimentation of sandy detritus in SE England (e.g., Ruffell and Worden, 2000; Haywood et al., 2004).

However, the relatively lower quartz composition in the Weald Clay Formation (intermediate formation between the Ashdown and Tunbridge Wells Sands Formations) and the uppermost Weald Clay Formation (Fig. 7A, C) does not necessarily rule out the influence of humid climate, but the recorded low feldspar contents (Wadhurst Clay Formation −0.8%, Weald Clay Formation −1.9%) fall short of what is expected in sediments influenced by arid climate (e.g., Hallam, 1984; Suttner and Dutta, 1986). The generally low occurrences of biotite (<2%) and muscovite (<4) in over 90% and 80% of the samples, respectively (Appendices 1, 2, 3) in contrast to the average 15% mica petrologically expected in granite, somewhat suggest intense chemical weathering triggered by the predominantly humid palaeoclimatic condition (e.g., Sladen and Batten, 1984). The relatively low quartz composition in the Wadhurst Clay Formation is complemented by the notable increase in total cement, siderite, and total clay, whereas a significant increment in percentage clay composition contributed to quartz decline in the Weald Clay Formation. Given the interpreted multiple provenances (Fig. 8), and the mature to submature nature of the rocks, it is postulated that the Ashdown, Wadhurst Clay, Tunbridge Wells Sands, and Weald Clay Formations probably experienced slightly different palaeoclimate and palaeoweathering conditions.

5.5. Tectonic setting

Using the quartz-feldspars-lithic (QFL) provenance plot of Dickinson (1985), the resultant ternary plot suggests the detritus of the Weald Sub-basin was primarily sourced from the craton interior of a continental block (Fig. 8A). Quartz-rich rocks are mostly derivatives of the passive continental margin, while those that are deficient in significant quartz content are linked with volcanogenic origin in magmatic islands arcs (Crook, 1974; Schwab, 1975). Craton interior quartzose sediments originate mainly as weathering products from low-lying granitic and gneissic bedrocks with possible contributions from recycled flat-lying platform sediments (Dickinson, 1974; Dickinson and Suczek, 1979; Franzinelli and Potter, 1983). Thus, the Wealden detritus can be interpreted as passive margin's derived materials based on the contrastingly high quartz and very low feldspar contents (Fig. 6; Appendices 1, 2, 3). Similarly, the high ratio of monocrystalline to polycrystalline grains (ca. 95:5) within the Wealden successions supports a stable interior craton/passive platform within a continental block (Fig. 8A), based on Dickinson and Suczek (1979) and Dickinson (1985). This is also shown by the concentration of the representative samples of the four formations around the Qm vertex in the Qm-P-K plot, which indicates significant sediments' maturity/stability from continental block provenance (Fig. 8B).

A high K-feldspar to plagioclase ratio and high quartz content in craton-derived detritus reflects substantial weathering on low relief cratons, as well as protracted transport across low-gradient continental surfaces (Dickinson and Suczek, 1979; Dickinson, 1985). The general predominance of orthoclase (K-feldspar) over plagioclase in the Ashdown Formation (K-feldspar: 0.22%, plagioclase: 0.16%) and Tunbridge Wells Sands Formation (K-feldspar: 0.21%, plagioclase: 0.16%) (Appendices 1, 2) supports the conclusion that their sediments were mainly sourced from the craton interior within a continental block (Fig. 8A, B). However, the converse dominance of the mean percentage K-feldspar (Wadhurst Clay Formation: 0.38%, Weald Clay Formation: 0.62%) by plagioclase (Wadhurst Clay Formation: 0.42%, Weald Clay Formation: 1.28%) in the Wadhurst Clay and Weald Clay formations seems to negate this interpretation. The fact that other tested proxies above favoured continental block tectonic setting outweighs this. Besides, the tectonic stability of the London Massif, which is the principal source of the materials within the Hastings Beds, is well documented (Tubb et al., 1986; Rijkers, 1994; Green et al., 2001), and thus supports the proposed stable interior craton (continental block) model presented in this study.

5.6. Transport history and depositional setting

Grain shape is an indicator of transport history (travel distance and depositional energy). Sediments' degree of roundness generally increases with longer transport distance, whereas the degree of angularity has an inverse relationship with the distance of travel (e.g., Plumley, 1948). Although Garzanti (2017) stated that textural maturity is not necessarily affected by sorting and winnowing index, textural parameters are still of invaluable sedimentological interpretations. The dominantly sub-angular to sub-rounded geometry of the grains in thin section suggests moderate to long transport distances between sediment sources and depositional sites (Fig. 4). Realistically, suspension-transported sediments (silt and clay) could be angular despite a long travel distance. However, the travel history interpretation above is based on sand samples (Fig. 4), which are characteristically deposited as product of saltation in fluvial systems. Furthermore, the significant occurrence of well-sorted to moderately well-sorted grains (except the Tunbridge Wells Sands Formation, which is moderate to poorly sorted) supports moderate travel distances (Figs. 3, 4). The documented presence of muscovite and biotite that are generally known to be mineralogically unstable across the studied formations advocates low energy transport over moderate distances (Appendices 1, 2, 3). The textural parameters of the Wealden facies show substantial silty composition (Fig. 3D, F,), especially within the dominantly argillaceous formations (Wadhurst Clay and Weald Clay). The silt-size quartz within the silty lamina of the Weald Clay Formation ranges from 40 to 70% (MacDougall and Prentice, 1964). This co-occurrence of different particle sizes is indicative of relatively moderate to poor winnowing (Selley, 1976). In summary, the mature- to submature nature of the sandstones examined in this study confirm that the sediments have been transported over relatively moderate to short travel distances from the source to sink. For example, detritus of the Hasting Beds have experienced a travel distance of ≤300 km from their main source (the London-Brabant massif) to sink (Sladen and Batten, 1984; Sladen, 1987). The lack of mineralogical maturity in the studied Wealden facies despite the interpreted transport distance from source-to-sink corroborates Garzanti (2017)'s postulations that transport distance of thousands of kilometres does not significantly increase mineralogical maturity.

Sediments textural and mineralogical signatures were integrated to provide reliable clues on the depositional setting of the sedimentary infill in the Weald Sub-basin using the Selley (1976)'s model. The model uses the occurrence or non-occurrence of carbonaceous detritus and/or detrital micas together with the presence or lack of glauconite (glauconitic mineral of Odin and Fullagar, 1988), and/or shelly debris to differentiate between marine and non-marine environments. It had been successfully applied to interpret depositional settings of sediments in the late Pannonian Ivanić Grad Formation, NW Croatia (Vrbanac, 2002), Green River Formation, Uinta Basin, USA (Burton et al., 2014), and Dahomey Embayment, Nigeria (Ola and Adepehin, 2017), among others.

Owing to their physical instability, mica flakes break down in high energy depositional settings. These include barrier islands, shallow shelf bars or dunes, transport in strong and turbulent currents (Selley, 1976). Winnowing has the same sorting effect on carbonaceous debris and mica, hence either of these accessory minerals is useful as winnowing index. The datasets obtained in this study lack information on carbonaceous detritus and shell material. Consequently, mica and glauconite contents were used instead of carbonaceous detritus and shell materials, respectively, to infer the depositional environment. The Selley (1976)'s model provides four possible depositional settings: (i) non-micaceous, glauconitic well-winnowed marine depositional setting, (ii) non-micaceous, non-glauconitic well-winnowed non-marine depositional setting (aeolian), (iii) micaceous and poorly-winnowed submarine channel or fan, and (iv) micaceous, poorly-winnowed non-marine depositional setting (e.g., fluvial, lacustrine and deltaic). The consistent occurrence of micaceous minerals (Fig. 7; Appendices 1, 2, 3), the poorly winnowed character, and the general absence of significant glauconite content (Appendices 1, 2, 3) suggest the deposition of the Wealden facies probably occurred in a poorly-winnowed non-marine depositional setting. The occurrence of pyrite crystallites within the framework of the Wealden facies (Fig. 5C) somewhat suggests the depositional systems were probably of anoxic- to low oxygen settings. Detrital pyrites are redox-sensitive and excellent indicators of low oxygen in the pre- Palaeoproterozoic Era (da Costa et al., 2017), whereas diagenetic pyrites in younger sediments are established indicators of anoxic conditions (e.g., Clennell et al., 2010; Rahman and Worden, 2016; Adepehin et al., 2019b).

The lithological components of the Ashdown, Wadhurst Clay, and Tunbridge Wells Sand formations show varying degrees of sand-shale intercalation. The sandy layers were interpreted as out-washed fans and sandy braided stream deposits, whereas the clay beds/laminae connote deposition in mud-plain, lacustrine (lake) and lagoonal environments (e.g., Allen, 1975; Kemp et al., 2012). However, minor marine influx evidenced by brackish water forms such as *Cassiope Ostrea* and *Nemocardium* in the (uppermost layer) north-western reach of the Weald Sub-basin has been noted in the upper part of the Weald Clay Formation (e.g., Dines and Edmunds, 1933; Gale, 2000). This notwithstanding, the adaptation of the living relatives of these probable marine forms to both marine and non-marine settings suggest earlier marine connotations may be misleading (Casey, 1955; MacDougall and Prentice, 1964). Earlier authors indicated that the depositional setting of the Weald Clay Formation was relatively stable, dominated by shallow waters, and saline incursion was quite minimal (Thurrell et al., 1970; Allen, 1975, 1981). These are suggestive of an overall lacustrine-to-lagoonal and fluviatile-to-mud plain environments and confirm our interpretation of an essentially non-marine depositional system for the Wealden of the Wealds.

5.7. Wider implications

The petrographic interpretations of the Wealden successions presented in this study provide useful insight into the early Mesozoic palaeogeography of Northwest Europe. The interpreted non-marine depositional systems for the Wealden formations indicate oceanic recession within the southeast England and northwest Europe land masses, thus, affirming the well-documented decline of relative sea level at the end of the Jurassic in a significant portion of the current day northwest Europe (e.g., Ruffell and Rawson, 1994; Ziegler, 1981). This led to the emergence of much of the landmass from which the sediments in the Wealden facies across northwest Europe were sourced. The conservative palaeogeographic model of Hopson et al. (2008) indicated that the London-Brabant Massif was located to the east, while the Armorican Massif and the Cornubian Massifs are in the southern and western reaches respectively of the Wealden basins in southeast England. The London-Brabant, Armorican and Cornubian Massifs formed the major sources of the beds within the Wealden facies across the whole of northwest Europe (e.g., Allen, 1975; Lake and Shephard-Thorn, 1987).

The Hastings Beds (Late Berriasian to Valanginian) within the Weald Sub-basin received their sediments mainly from the Londinia within the London-Brabant massif (north and northeast) although minor amounts of material also came from Armorica in the south (e.g., Allen, 1975). By Weald Clay Formation's times (Barremian-Hauterivian) the main source of sediments had shifted to the Cornubian Massif in the west and the northern Boreal Sea with minor inputs from Armorica (e.g., Allen, 1954). The materials of the Boreal Sea are more evident in the northern and north-eastern margin of the Sub-basin (e.g., Allen, 1991). This indicates that the Londinia had ceased to be the main sediment supply source for the Weald Sub-basin as early as the Barremian. Hopson et al. (2008) suggested that by the late Aptian Londinia had been completely submerged. However, it appears that this part of the massif may have been submerged much earlier. Evidence for this is the lack of significant sediment supply from this source to the Weald Sub-basin by the end of the Valanginian demonstrated by analysis of the Weald Clay Formation's detritus (e.g., Allen, 1991).

The English Wealden sedimentation was strongly influenced by the vertical movements of the source massifs that surrounded the basins (e.g., Allen, 1975, 1991; Sladen and Batten, 1984). These movements influenced climate, subsidence, accommodation space and sediment supply in the basin (Sladen and Batten, 1984). The repeated movements of these massifs provide valuable information concerning regional tectonics occurring in NW Europe during the Early Cretaceous (Ziegler, 1981). The current datasets provide insights into the Early Cretaceous palaeogeography of NW Europe and confirms that palaeogeographic changes that affected the Weald Sub-basin during the deposition of its detritus reflect (at least in part) Early Cretaceous events in NW Europe (Fig. 1B).

The fact that the interpretations of palaeoenvironments using petrographic datasets are in broad agreement with the findings of previous workers, who used different proxies (e.g., Stewart, 1981; Lake and Shephard-Thorn, 1987; Ross, 1996) attests to the reliability and suitability of petrographic datasets for understanding paleoenvironmental conditions. Thus, it could be replicated in similar non-marine Lower Cretaceous terrains across the world such as in the Tataouine Basin, Southern Tunisia (Anderson et al., 2007), Romania (Grigorescu, 1992), the North American Western Interior Basin (Sames et al., 2010), the Escucha Formation in eastern Spain (Tibert et al., 2013), the Xiazhuang Formation in north China (Pan and Zhu, 2007), the Kyongsang Basin in Korea (Jo, 2003), and the Jinju Formation in South Korea (Choi and Huh, 2016), and elsewhere (e.g., Haywood et al., 2004; Dejax et al., 2007).

6. Conclusion

Petrographic analyses of sandstones from the four formations (Ashdown, Wadhurst Clay, Tunbridge Wells Sand, and Weald Clay) constituting the Wealden succession of the Lower Cretaceous Weald Sub-basin show that they are mainly quartz-dominated and lacking in any major amount of feldspar and lithics. The Wealden sequences represent derivatives from granitic and gneissic bedrocks from a stable interior craton/passive platform within a continental block. Their mature to submature characteristics revealed moderate to short transport distance from the source to sink. Lack of significant feldspar suggested that the climatic settings were moist and hot and that this promoted significant chemical weathering at source regions. The unwinnowed Wealden sediments experienced insignificant degrees of turbulence and agitation during transport. Data from this study confirm that palaeogeographic changes affecting the Weald Sub-basin during deposition of the Wealden succession reflect (at least in part) palaeogeographic events that occurred during the Early Cretaceous in NW Europe. This study demonstrates that when traditional datasets are unattainable and/or unsatisfactory, petrographic datasets can be useful for describing palaeoenvironmental conditions controlling the deposition of sedimentary rocks.

Declaration of competing interest

Authors declared that they have no conflict of interest.

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Data sharing statement

Additional data are available as supplementary materials (Appendices). Further clarification should be directed to the corresponding author.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.sedgeo.2020.105848.

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