Mineralogy and palaeoenvironments: the Weald Basin (Early Cretaceous), Southeast England

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ABSTRACT
Determination of the mineralogy of sedimentary rocks is important in palaeoenvironmental interpretations, especially when outcrop and field data are insufficient or not accessible. The Lower Cretaceous Wealden facies, presented here as a case study, is one such example. Petrographic analysis of this suite of sediments reveals that the arenaceous facies are mainly quartz arenites, quartzose siltstones and lack significant feldspar. The clay minerals are illite, kaolinite, illite-montmorillonite, vermiculite and illite-smectite. The presence of quartz arenites and kaolinite suggests that the rocks were reworked from granitic and/or gneissic rocks. Directly or indirectly, the rocks may have been obtained from a stable craton. The mineral and textural maturity, together with a travel distance of ca 300 km point to matured sources. A warm and humid palaeoclimate in the source areas resulted in extensive weathering.

INTRODUCTION
The mineralogy of sedimentary rocks presents useful information on provenance, tectonic settings, palaeoclimate and weathering patterns, the transport system, and any post-depositional alteration or diagenesis (Singer, 1984; Dickinson, 1985). The mineralogy of the Lower Cretaceous Wealden facies (Fig. 1) demonstrates the importance of mineralogical composition of sedimentary rocks for palaeoenvironmental analysis. In the Weald in Southeast England (Fig. 1), some Lower Cretaceous deposits are excellently exposed in some of the most complete successions in northwest Europe (Hopson et al., 2008; Radley & Allen, 2012). The lowermost Cretaceous section (Hastings Beds, Fig. 2) allows non-marine and fluvial-related sedimentation patterns to be studied in a variety of conditions and this can be applied to similar sedimentary basins elsewhere (Allen & Wimbledon, 1991). These facies also make it possible to study changes that accompanied the transition to the Early Cretaceous in northwest Europe (Ruffell, 1991; Akinlotan, 2017b), China (Li et al., 2016), South America (Richiano, 2014) and other non-marine Lower Cretaceous facies. The Wealden sections may also be useful for analogue studies of basin tectonics (Ziegler, 1981; Mansy et al., 2003) and hydrocarbon reservoirs (Akinlotan, 2016).

Compared to studies using outcrop and fossil data sets, the petrography of these sandstones has received relatively little consideration. The minerals in the Ashdown and Wadhurst Clay formations have been described (Milner & Bull, 1925; Sweeting, 1925; Allen, 1948) while Cook (1995) explained the dominance of monocrystalline quartz grains in the Wadhurst Clay Formation. The clay minerals within these strata have been documented (Butterworth & Honeyborne, 1952; Tank, 1962; Sladen, 1980, 1987; Taylor, 1996; Jeans et al., 2001; Jeans, 2006) but previously the focus has been on the general trends. The aim of this study is to use the mineralogy of the Ashdown (Late Berriasian-Early Valanginian) and Wadhurst Clay (Early-Middle Valanginian) formations (Fig. 2) to review the palaeoenvironment of the Weald Basin (Fig. 1). Petrographic descriptions (qualitative and quantitative) and photomicrographs are presented from these formations using a combination of optical and scanning electron microscopy (SEM) while petrographic data from inland sections are presented. A more detailed clay mineralogical study of the two formations is presented and the relative abundance of the clay minerals is used to review their palaeoenvironment. Employing both petrographic and clay mineral data in the palaeoenvironmental analysis of these two formations is a relatively novel approach. The interpretations made from mineralogical composition are...
used to test previous interpretations based on outcrop and fossil data.

GEOLOGICAL SETTING

The Lower Cretaceous non-marine rocks of the Weald (Fig. 1) are mainly sandstones and mudstones and they are generally referred to as Wealden (Goldring et al., 2005; Hopson et al., 2008). This area in Southeast England represents the type area for the Lower Cretaceous facies of northwest Europe (Fig. 2) (Radley & Allen, 2012). Within the Ashdown Formation, the lithology consists of fine-grained sandstones, siltstones and mudstones with small quantities of shale, clay (mottled) and lignite (Lake & Shephard-Thorn, 1987). Dark grey shales and mudstones, sandstone, clay ironstone and lignite are the main materials in the Wadhurst Clay Formation (Lake & Shephard-Thorn, 1987). The stratigraphy and the lithology of the sections used for this study are given in Fig. 3. The rocks were deposited in channel and floodplain sub-environments within braided and meandering river systems (Allen, 1981; Stewart, 1983; Akinlotan, 2015).

MATERIALS AND METHODS

Study locations

For this study, 38 samples were collected from seven locations (Figs 1 and 3) where the Ashdown and Wadhurst Clay formations were exposed. The rationale for selecting the sites are as follows: (i) they are among the principal partial reference sections of the Wealden rocks in the Weald; (ii) they have some of the best-exposed sections of the Wealden in Southeast England; (iii) they provide good spread across the Weald Basin (Hopson et al., 2008). The study locations present a mix of both coastal and inland sections to allow variation in the mineralogy to be determined unlike previous studies (Sladen, 1987; Jeans, 2006) which focused mainly on the coastal areas. Sampling was rationed and focused on key stratigraphic sections because all the locations are either Sites of Special Scientific Interest (SSSIs) and/or Geological Conservation Review (GCR) sites.

Petrographic analysis

A total of 23 sandstone samples were subjected to petrographic analysis using a Nikon Eclipse E400 POL microscope. Mineral identification was carried out using the descriptions of MacKenzie & Adams (1994). The mineralogy was quantified using point counting and expressed in percentage. The grain size was measured and each sample classified using the method of Tucker (2001). The degree
of sorting was described based on Folk & Ward (1957) and Tucker (2001). SEM was also carried out on the sandstones. Seven sandstone samples were crushed into rock chips, coated with platinum and analysed using a Zeiss EVO LS 15 (current: $10^{-11}$ amp, accelerating voltage: 20 Kv).

Clay mineral analysis

Clay mineral analysis was conducted using 15 mudstone and shale samples. Samples were powdered, with the 2 µm fraction obtained by sieving, before analysis using a Panalytical X’Pert Pro X-Ray diffractometer in a 10 mm diameter deep well-oriented mount (Cu-K radiation, voltage: 40 kV current: 40 Ma). The samples were analysed for clay minerals under three conditions: air-dried, glycolated and 375°C. For glycolation analysis, the clay fraction sample was placed on a slide and put in an ethyl glycol desiccator for at least 24 h. After glycolation analysis, the samples were then heated to 375°C for 1 h. Samples were run on both a slow and high-count scan. The data interpretation was carried out using Panalytical’s HighScore Plus software using search-match routines. The HighScore Plus uses Reference Intensity Ratio (RIR) technique (Hubbard & Snyder, 1988) to give a semi quantitative estimation of the identified minerals. For the first time, cluster analysis was carried out on the clay minerals within the two formations using Panalytical’s HighScore Plus.

RESULTS

Petrographic descriptions

Quantitative and qualitative descriptions of the sandstones and siltstones are summarized in Table 1 with microphotographs of selected samples given in Fig. 4. They are quartz arenites and quartzose siltstones. One of the arenites is calcite-cemented. Apart from one arenite (see below), all the sandstones and siltstones contain monocrystalline quartz grains (100%), lack feldspar, and lithic grains. The matrix includes small traces of muscovite (ca 1%), zircon (ca 1%) and glauconite while iron coatings are common (Fig. 4A, E and I). The grains are mostly sub-rounded to rounded and are moderately well-sorted to well-sorted (Fig. 5). An exception to this compositional trend is in the lower Wadhurst Clay Formation. This arenite (Fig. 4F) has 99% quartz grains (monocrystalline: 99-5%, polycrystalline 0-5%) and feldspar (1%).

The grain size commonly increases upwards in the Ashdown Formation while it decreases within the Wadhurst
| Lower ASH Fm. | Upper ASH Fm. | Upper ASH Fm.-Lower WAC Fm. | Lower WAC Fm. | Upper WAC Fm. |
|-------------|--------------|-----------------------------|--------------|--------------|
| RN | HA | WA | CE | HC | HGR | NT |
Quartzose siltstone. 100% mono-crystalline quartz. Very fine (0.035 mm). Sub-rounded to rounded. Moderately to well-sorted (Fig. 4A).
Quartzose arenite. 100% mono-crystalline quartz. Very fine (0.05 mm). Muscovite, glauconite and zircon are present. Sub-rounded to rounded. Moderately well-sorted. Point contact (Fig. 4E).
Quartzose arenite. 100% mono-crystalline quartz. Very fine (0.06 mm). Zircon and muscovite are present. Sub-rounded. Moderately well-sorted. Long and point contacts (Figs 4C and 5B).
Quartz arenite. 99% quartz mono & poly crystalline. Fine to medium (0.06 to 0.36 mm). Feldspar and muscovite are present. Moderately to well-sorted. Long and concavo-convex contacts (Figs 4B, F, G, I and 5A, C, D).
Quartz arenite. 100% mono-crystalline quartz. Medium (0.4 mm). Zircon is present. Shelly fragments. Very fine (0.06 mm). Zircon and muscovite are present. Sub-rounded to rounded. Well-sorted. Long and point contacts (Fig. 4D).
Calcite-cemented quartz arenite. 100% mono-crystalline quartz. Medium (0.15 mm). Zircon is present. Sub-rounded to rounded. Well-sorted. Long and point contacts (Figs 4I and 5F).
Quartz arenite. 100% mono-crystalline quartz. Medium (0.15 mm). Zircon is present. Sub-rounded to rounded. Well-sorted. Long and point contacts (Figs 4E, H and 5E).
Clay Formation (Table 1). On a basin scale, the Ashdown Formation’s sandstones are finer than the sandstones in the Wadhurst Clay Formation. The largest grain sizes were observed in the Wadhurst Clay Formation. Physical compaction is apparent by tight grain packing leading to grain-to-grain penetration. Some of the grains are welded into adjacent grains (Fig. 4B) leading to reduced visual porosity.

Long and point contacts between grains are very common while compaction is low to moderate. In some cases, concavo-convex grain contacts are present, typically occurring when compaction is high. Apart from the sandstone at Houghton Green, Rye (Fig. 4H), the common cement is silica and may have been precipitated from solution. Some sandstones display a combination of tight and loose cementation. Geochemical analysis confirmed
that the iron stains observed in the thin sections are siderites (Akinlotan, 2015, 2017a,b). In the base of the Wadhurst Clay Formation (syntaxial) quartz overgrowth forms a secondary outline on the primary quartz grain. This overgrowth may have been precipitated from solution.

Clay minerals

The results of the XRD clay mineralogical analysis show that illite (ca 53%), kaolinite (ca 31%), illite-montmorillonite (10%), vermiculite (ca 5%) and illite-smectite (ca 1%) are the clay minerals present within the two formations (Table 2, Fig. 6) while the 1 M and 2 M polymorphs of illite are (ca 86%) and (ca 14%), respectively. The distribution and estimates of the clay minerals are given in Table 3. Illite and kaolinite are present in all air-dried samples. Illite is the dominant mineral except at Northiam (upper Wadhurst Clay Formation) where the kaolinite contribution is equal to that of illite. Illite-montmorillonite is present in substantial amounts in some samples but vermiculite and illite-smectite only occur in small amounts. Vermiculite is absent at West Hoathly (lower Wadhurst Clay Formation) while illite-smectite is not present at Rock-a-Nore (lower Ashdown Formation). The degradation of illite to structures similar to vermiculite and montmorillonite in the Ashdown and Wadhurst Clay formations has been previously suggested by Tank (1962). In this present study, illite-montmorillonite is observed in significant quantity as one of the mixed-layer minerals in the lower Ashdown and upper Wadhurst Clay formations.

Glycolation confirmed the presence of vermiculite in the samples where it was not identified when air-dried. In addition, glycolation confirmed that illite-smectite and illite-montmorillonite are present. At 375°C, illite and kaolinite continue to be the dominant clay minerals. The changes in the quantity of illite and kaolinite may result from the relative increase/decrease of one mineral based on the loss/gain of other minerals due to the relative changes in peak height. In terms of mineralogy, there is no important consequence on heating the samples to

Fig. 5. Selected SEM photographs. Ashdown Formation (A: Cliff End: fine-grained sandstone, same as Fig. 4B; B: Waldron: fine-grained sandstone, same as Fig. 4C). Wadhurst Clay Formation (C: Cliff End: medium-grained sandstone, same as Fig. 4F; D: Pett Level: medium-grained sandstone, same as Fig. 4G; E: Houghton Green, Rye: calcareous sandstone, same as Fig. 4H; F: Northiam: medium-grained sandstone, same as Fig. 4I). Additional descriptions of photographs are given in Table 1.
375°C apart from demonstrating that illite-smectite is present in the Wadhurst Clay Formation. Cluster analysis yielded three groups with similar mineralogy as shown in Table 4. This analysis enabled beds to be arranged into assemblages primarily based on similar clay mineral compositions. The three clusters are: (i) Ashdown Formation, (ii) Wadhurst Clay Formation and (iii) a mixture of Ashdown and Wadhurst Clay formations.

### Table 2. The clay mineral assemblage in the study locations. Values are in (%) and are semi quantitative estimates based on Reference Intensity Ratio technique. I: Illite, K: Kaolinite, I-M: Illite-Montmorillonite, V: Vermiculite, I-S: Illite-Smectite

| Age       | Formation       | Division | Location   | Sample no. | Air-dried | Glycolated | 375°C |
|------------|-----------------|----------|------------|------------|-----------|------------|--------|
| Valanginian| Wadhurst Clay   | Upper    | Northiam   | NT/2       | I (17)    | I (69)     | I (26) |
|            |                 |          |            |            | I-M (64)  | K (30)     | I-S (16) |
|            |                 |          |            |            | K (19)    | V (1)      | K (17) |
|            |                 |          |            |            | V (3)     |            | V (41) |
|            | Wadhurst Clay   | Lower    | West Hoathy| WH/4       | I (70)    | I (60)     | I (65) |
|            |                 |          |            |            | K (30)    | I-M (28)   | I-S (7) |
|            |                 |          |            |            | K (11)    |            | I-M (19) |
|            |                 |          |            |            | K (9)     |            | K (9)  |
|            | Wadhurst Clay   | Lower    | Cliff End  | CE/8       | I (72)    | I (59)     | I (61) |
|            |                 |          |            |            | K (27)    | K (41)     | K (39) |
|            |                 |          |            |            | I (79)    | I (54)     | I (22) |
|            |                 |          |            |            | K (21)    | I-S (20)   | V (59) |
|            |                 |          |            |            | K (16)    |            | K (45) |
|            | Wadhurst Clay   | Lower    | Cliff End  | CE/6       | I (72)    | I (59)     | I (61) |
|            |                 |          |            |            | K (27)    | K (41)     | K (39) |
|            |                 |          |            |            | I (79)    | I (54)     | I (22) |
|            |                 |          |            |            | K (21)    | I-S (20)   | V (59) |
|            | Ashdown Clay    | Lower    | Rock-a-Nore| RN/13      | I (78)    | I (54)     | I (69) |
|            |                 |          |            |            | K (21)    | K (46)     | K (31) |
|            |                 |          |            |            | K (27)    |            | V (1)  |
|            |                 |          |            |            | V (1)     |            | V (1)  |
|            | Ashdown Clay    | Lower    | Rock-a-Nore| RN/10      | I (19)    | I (19)     | I (21) |
|            |                 |          |            |            | I-M (53)  | I-M (54)   | I-M (45) |
|            |                 |          |            |            | K (28)    | K (26)     | K (34) |
|            |                 |          |            |            | I-M (55)  | V (1)      | V (1)  |
|            | Ashdown Clay    | Lower    | Rock-a-Nore| RN/9       | I (64)    | I (32)     | I (18) |
|            |                 |          |            |            | K (36)    | K (34)     | I-M (45) |
|            |                 |          |            |            | V (35)    |            | K (37) |
|            |                 |          |            |            | K (7)     |            | K (45) |
|            | Ashdown Clay    | Lower    | Rock-a-Nore| RN/7       | I (78)    | I (5)      | I (55) |
|            |                 |          |            |            | K (22)    | K (28)     | K (45) |
|            |                 |          |            |            | V (1)     |            | V (1)  |
|            | Ashdown Clay    | Lower    | Rock-a-Nore| RN/6       | I (17)    | I (14)     | I (24) |
|            |                 |          |            |            | I-M (40)  | I-M (63)   | K (33) |
|            |                 |          |            |            | K (15)    | K (15)     | V (43) |
|            |                 |          |            |            | V (27)    | V (8)      | V (8)  |
|            | Ashdown Clay    | Lower    | Rock-a-Nore| RN/5       | I (34)    | I (52)     | I (41) |
|            |                 |          |            |            | I-M (49)  | K (27)     | K (59) |
|            |                 |          |            |            | K (17)    | V (21)     | K (41) |
|            | Ashdown Clay    | Lower    | Rock-a-Nore| RN/4       | I (49)    | I (37)     | I (40) |
|            |                 |          |            |            | K (18)    | K (41)     | K (60) |
|            |                 |          |            |            | V (34)    | V (21)     | V (21) |
|            | Ashdown Clay    | Lower    | Rock-a-Nore| RN/2       | I (42)    | I (51)     | I (53) |
|            |                 |          |            |            | I-M (32)  | K (48)     | K (47) |
|            |                 |          |            |            | K (25)    | V (1)      | V (1)  |
INTERPRETATION AND DISCUSSION

Detrital clay minerals

The clay minerals used for interpretation in this section are principally detrital in origin and have not been affected by diagenetic alteration. The first line of evidence to support this is that it is well-established that the rocks within the two formations have experienced very negligible diagenetic modification (Allen, 1981; Sladen & Batten, 1984). In addition, the shallow burial depth of the Wealden rocks, 2 km or less below sea level, is well-known. A

Fig. 6. The XRD peak patterns of the representative beds used in the study: I: illite; K: kaolinite; V: vermiculite; I-M: illite-Montmorillonite, I-S: illite-Smectite. (A) West Hoathly, sample heated to 3750°C (lower Wadhurst Clay Formation). (B) Northiam, sample heated to 3750°C (upper Wadhurst Clay Formation). (C) Cliff End, glycolated sample (upper Ashdown Formation). (D) Cliff End, glycolated sample (lower Wadhurst Clay Formation). (E) Rock-a-Nore (lowermost section), air-dried sample (lower Ashdown Formation). (F) Rock-a-Nore (uppermost section), air-dried sample (lower Ashdown Formation). Additional descriptions of peak patterns are given in Table 2.
geothermal gradient of $ca$ 10°C km$^{-1}$ (Rollin, 1995; Westaway et al., 2002) will give a temperature of about 20°C at a depth of 2 km underneath the continental crust of the United Kingdom. In the present study, illite-smectite is about 1% and illite is about 53% (Table 3). The 1 M polymorph, which is the main constituent of the illite group, is detrital in origin. All these lines of evidence confirm that any modification of smectite to illite-smectite in these rocks is insignificant. Previous studies (Sladen, 1983, 1987) have observed that any diagenetic alteration to the clay minerals in these formations was negligible (Jeans et al., 2001). Jeans et al. (2001) confirmed that the clay minerals are dominantly detrital in origin and largely unaffected by burial diagenetic alteration (Jeans, 2006).

**Palaeoclimate conditions**

The palaeoclimate (see below) at the time both formations were deposited has been described as subtropical to warm temperate, with a temperature of 5 to 10°C and a mean annual rainfall of 600 to 1200 mm (Sladen & Batten, 1984; Allen et al., 1998). These conclusions were based on sedimentological, palaeobotanical, palaeozoological and clay mineral data sets and the current data support this interpretation. In this present study, the absence of feldspar and the presence of zircon, a weathering-resistant mineral confirm severe weathering that resulted from seasonal humid conditions (Hurford et al., 1984; Dickinson, 1985). The alteration of feldspars into clays (see below) happened at the source and/or before the rocks were deposited (Sladen & Batten, 1984; Sladen, 1987). The physical breakdown of the rocks probably happened during transportation as evident in their significant textural maturity (Bryer & Bart, 1978; Franzinelli & Potter, 1983). The relative quantity of illite and kaolinite has been used for palaeoclimatic reconstructions (Singer, 1980, 1984). The quantity of kaolinite in the

Table 3. Summary of the clay mineral assemblage in the study locations. Values are in (%) and are semi quantitative estimates based on Reference Intensity Ratio technique. RN: Rock-a-Nore, CE: Cliff End, WH: West Hoathly, NT: Northiam. Standard deviation values are to the nearest whole number

|                  | Ashdown Formation | Wadhurst Clay FM. | Total | SD |
|------------------|-------------------|-------------------|-------|----|
| Illite           | 47                | 62                | 53    | 12 |
| Kaolinite        | 33                | 26                | 31    | 4  |
| Illite-Montmorillonite | 14           | 16                | 10    | 5  |
| Vermiculite      | 5                 | 11                | 5     | 4  |
| Illite-Smectite  | 0                 | 4                 | 1     | 1  |

|                  | Lower  | Upper | SD |
|------------------|--------|-------|----|
| Illite           | 47     | 34    | 14 |
| Kaolinite        | 33     | 42    | 6  |
| Illite-Montmorillonite | 14   | 14    | 6  |
| Vermiculite      | 5      | 10    | 3  |
| Illite-Smectite  | 0      | 0     | 2  |

Table 4. The three clusters from this study

| Clusters          | Cluster 1 | Cluster 2 | Cluster 3 |
|-------------------|-----------|-----------|-----------|
| Ashdown Formation | Cl:2      | Cl:1      | Cl:3      |
| Wadhurst Clay     | Fo:1      | Fo:2      | Fo:3      |

Air-dried samples
- RN4 CE/8 WH/4
- RN5 WH/1 CE/2
- RN9 WH/2 RN2
- RN7 CE/6 RN13
- RN10 NT/2 RN6

Glycolated samples
- CE/2 WH/1 RN2
- RN7 CE/8 RN6
- RN9 WH/2 CE/6
- RN10 NT/2 RN6
- RN4 RN13 RN6
- RN5 WH/4 RN6

Heated to 375°C
- CE/2 RN/2 RN/2
- RN7 RN/13 RN/2
- RN9 WH/4 WH/4
- RN10 RN/6 RN/2
- RN4 CE/8 WH/1
- RN5 WH/2 WH/2
- NT/2 CE/6
The present study demonstrates a warm and humid palaeoclimate, which favoured extensive chemical weathering for the formation of kaolinite. The modification of illite to montmorillonite occurs under advanced weathering patterns (Tank, 1962). In this present study, illite-montmorillonite has been recognized as one of the mixed-layers and its quantity supports severe weathering patterns.

The presence of kaolinite within these two formations also points to an effective drainage system plus fluctuation of wet and dry conditions at the source areas (Moore & Reynolds, 1989). The vertical movements of the massifs in the source areas, which were attributed to faulting (Sladen & Batten, 1984; Allen, 1989), were likely to have favoured a good drainage system. The presence of kaolinite and vermiculite in the clay mineral assemblage from this study suggests periodic rainfall (Moore & Reynolds, 1989). The concentration of kaolinite in these rocks as shown by the present study revealed a high level of rainfall during the wet seasons and this agrees with the rainfall data of Sladen & Batten (1984) above. The clay minerals observed in this study demonstrates that weathering was at its peak near the end of the Ashdown Formation. The leaching then quickly increased in the Wadhurst Clay Formation but did not match the rate observed in the upper Ashdown Formation. Unlike previous studies (Sladen, 1983, 1987; Hallam et al., 1991), this study demonstrates that the quantity of kaolinite initially declined in the lower part of the Wadhurst Clay Formation before increasing in the upper part of the formation (see Table 3).

Jeans et al. (2001) and Jeans (2006) suggested that climate played a less significant role in controlling the clay mineral assemblage present in the Wealden rocks, proposing instead that volcanic influences dominated (Jeans, 2006). In any case, the role of climate on clay mineral composition is well-documented in the Weald and beyond (Singer, 1980, 1984; Sladen, 1980; Sladen & Batten, 1984; Moore & Reynolds, 1989; Hallam et al., 1991; Oboh, 1992). For instance, spectral gamma-ray data on the Wealden deposits in the Weald (Akinlotan, 2015, 2017b) correlate well with palaeoclimate interpretations made from the data presented in this study. Thorium is normally enriched when kaolinite is formed from the alteration of feldspars (Ruffell & Worden, 2000; Schnyder et al., 2006) and its significant quantity in the Wealden rocks point to the dominantly warm with periodically wet conditions that favoured the intensive weathering that is required for the formation of kaolinite.

Nature of provenance

Previous studies have suggested that the rocks within the two formations were sourced mainly from the London

Massif in addition to slight contributions from the Armorica (Allen, 1975, 1981). Other suggested sources were the Cornubia in the west and (Boreal) Sea in the north (e.g. Kirkaldy, 1947; Allen, 1975, 1989, 1991; Radley & Allen, 2012). All of these four sources have both granitic and gneissic materials within them and these may have been primarily or secondarily sourced. The London-Barrant Massif in the north and northeast of the Weald Basin consisted of Precambrian, Palaeozoic Devonian and Carboniferous rocks (Old Red Sandstone). The Armorican Massif in the south-west of the Weald Basin exposed Precambrian rocks including granites, Permian-Triassic facies known as New Red Sandstone, and Jurassic volcanogenic materials. The Cornubia consisted of Permian-Triassic beds, the New Red Sandstone, some volcanic debris and Jurassic sediments (Allen, 1981, 1991; Andre, 1991). The clay minerals in the two formations revealed by this study support the London Massif as the main source and Armorica as a secondary source. This is because the clay minerals point to granitic and gneissic sources, which are all present within the massifs. The presence of three clay mineral clusters (Table 4) namely Ashdown Formation; Wadhurst Clay Formation and a mixture of the two formations, which reflect distinct mineralogical compositions may also support multiple sources for the rocks.

Recycled materials

The results of the petrographic analysis on the two formations from this study reveal that the arenaceous facies are quartz arenites and quartzose siltstones and contain predominantly quartz grains. It further suggests that the bulk of the materials within the two formations was sourced from recycled materials (probably obtained from older granitic and/or gneissic rocks) within the source areas. The dominance of quartz within the Ashdown and Wadhurst Clay formation reported here suggests that the rocks within these formations were acquired mainly from materials recycled from granites and/or gneisses in the source areas described above. In the Amazon Basin, evidence for the production of modern quartz arenites from granitic and gneissic rocks has been presented by Franzinelli & Potter (1983).

Igneous or metamorphic rocks

Clay mineral analysis from this study shows that kaolinite which makes up a third of the clay minerals is a significant mineral within the two formations while illite is more than half of the total clay minerals (Table 3). Feldspar-rich rocks are essential for the production of kaolinite and to a lesser extent for the formation of illite and
Transport distance

The small amount of feldspar, lack of lithic fragments, the roundness and sorting of the grains as demonstrated by this study reveal that the sandstones are matured in terms of mineralogy and texture (Dickinson, 1985). In order to produce quartz arenites from primary sources, a significant amount of travel distance will be required to adequately ensure that feldspar and unstable minerals are completely broken down (Dickinson, 1985). This is evident in the sands described from the Platte River in Nebraska, USA (Bryer & Bart, 1978) where a travel distance of 600 km was insufficient to significantly change the ratio of quartz: feldspar (Q : F). Similarly, it required a travel distance of about 4000 km to substantially increase the quantity of quartz compared to that of feldspar in the Amazon River sands as demonstrated by Fragninelli & Potter (1983). Previous studies have noted that the materials within the Ashdown and Wadhurst Clay formations have travelled less than 300 km from their original sources (Sladen & Batten, 1984; Sladen, 1987). It is evident that the relatively short travel distance of 300 km would not be sufficient to produce the arenites that have been observed within the Ashdown and Wadhurst Clay formations from a primary source and this would confirm that they were sourced from matured sources.

Stable craton

It has been observed that quartzose sands that have a very high ratio of monocristalline to polycristalline grains and a high ratio of K-feldspar to plagioclase feldspar have tendency to be sourced from a stable craton/passive platform (Dickinson & Suczek, 1979; Dickinson, 1985). In this present study, the ratio of monocristalline to polycristalline grains is very high (ca 99 : 1). Similarly, the trace element assemblage of sandstones has been used to define their tectonic origin such that rocks derived from passive margins have characteristically high concentrations of Zr, low Ba, Rb, and Sr. (Bhatia, 1983; Bhatia & Crook, 1986). In the Ashdown and Wadhurst Clay formations, the concentration of Zr is high while that of Cr, Ni, Rb and Sr are very low (Akinlotan, 2015, 2017a). When these petrographic and geochemical data are compared to the trends described above (Dickinson & Suczek, 1979; Bhatia, 1983; Dickinson, 1985; Bhatia & Crook, 1986), it is suggested that the rocks within the Ashdown and Wadhurst Clay formations have been directly or indirectly derived from a stable craton/passive platform. The tectonic stability of the London Massif has been described (Rijkers et al., 1993) and this also supports the stable craton model. This stable craton model is presented from limited datasets from this study and is consequently subject to further discussion when, and if, more additional data become available.

SIGNIFICANCE AND WIDER IMPLICATIONS

The use of mineralogical composition of sedimentary rocks in reconstructing palaeoenvironment has wider implications outside the Weald Basin. In the Weald Basin, the palaeoenvironmental interpretations based on the sandstone petrography and clay mineral content agree with interpretations from other proxies such as outcrop (Stewart, 1981; Lake & Shephard-Thorn, 1987) and fossil (Batten, 1982; Morter, 1984; Feist et al., 1995; Jarzembowski, 1995). As a result, when commonly used data such as outcrop and palaeontological datasets are unavailable to aid comprehensive interpretations, the mineralogy of sedimentary rocks may provide useful data for understanding palaeoenvironmental conditions of sedimentary basins as well as complementing interpretations based on outcrop and fossil data. In this study, the mineralogical composition of the rocks has provided useful information on tectonic settings and nature of provenance, weathering patterns, sediment transport, and diagenesis of rocks within the Weald Basin. The interpretations presented in this work can also be applied to other non-marine Lower Cretaceous facies such as in China (Li et al., 2016) and South America (Ferreira et al., 2016) and can be used as analogue for other non-marine Lower Cretaceous facies elsewhere (Haywood et al., 2004; Dejax et al., 2007).

CONCLUSIONS

This study which has concentrated on the mineralogy within the Ashdown and Wadhurst Clay formations in
the Weald, Southeast England has increased the current understanding of the palaeoenvironmental conditions of the Weald Basin and validated previous interpretations based on field and fossil datasets. The sandstones and siltstones within the two formations are quartz arenites and quartzose siltstones, respectively and contain no significant feldspar or lithic grains. The Ashdown Formation’s sandstones are finer than the sandstones in the Wadhurst Clay Formation. Illite: ca 53%, kaolinite: ca 31%, illite-montmorillonite: ca 10%, vermiculite: ca 5% and illite-smectite (ca 1%) represent the clay minerals. Illite-montmorillonite is now reported in significant quantities as a mixed-layered mineral. The sedimentary rocks were sourced from matured sources and mainly from granitic and/or gneissic rocks. The present data now reveal that the rocks were likely to have been sourced from a stable craton. Source area palaeoclimate was warm and humid leading to severe weathering. The results presented in this study reinforces the importance of the mineralogy of sedimentary rocks as useful tool for palaeoenvironmental studies particularly when commonly used datasets such as outcrop and palaeontological data are unavailable or insufficient.

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