THE EARLY-MIDDLE TRIASSIC OF ARRAN (SCOTLAND): A DRYLAND TERMINAL FLUVIAL-PLAYA LAKE SYSTEM

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Abstract: The Early-Middle Triassic sediments at Largybeg point on the isle of Arran (southwestern Scotland) were deposited on northern Pangaea at about 25° N. The sediments comprise a retrogradational dryland terminal fluvial system (Lamlash Sandstone Formation) overlain by a playa lake system (Auchenhew Mudstone formation). The proximal part of the dryland terminal fluvial system is composed of clast-rich channel sandstones, while the distal part of this system is dominated by sheetflood sandstones. The distal fluvial sediments are associated with red siliciclastic sabkha deposits, and thin sandstone sheets of aeolian origin. The overlying playa lake deposits are composed of red mudstones and heterolithic sediments with abundant wave ripples and evidence of common subaerial exposure. The playa lake sediments form thin shallowing-upward successions topped by aeolian or mixed aeolian and wave-reworked sand sheets. The studied sediments have many features in common with other Early-Middle Triassic terrestrial systems in Europe, which were deposited during an overall arid climate; monsoons brought precipitation to the Scottish Highlands and drove fluvial transport southwards into the Arran Basin. North-northeasterly winds blew sand across the sabkhas and dry playa surfaces.

Key words: *Triassic, sandstone, fluvial, playa-lake, aeolian, Arran, Scotland.*

Resum: Els sediments del triàsic mitjà de Largybeg a l'illa d'Arran (SW d'Escòcia) es depositaren al nord de Pangea; a una latitud estimada de 25°N. Es tracta d'un conjunt de depòsits característics d'un sistema fluvial terminal retrogradacional d'ambient àrid (Fm de gresos Lamlash) als que se superposa un sistema de *playa-lake* (Fm lutítica d'Auchenhew). La part proximal del sistema fluvial està formada per gresos canalitzats amb abundants clasts, mentre que les zones distals del sistema es caracteritzen pel domini de gresos resultat de l'acció de l'escolament en mantell. Aquests dipòsits fluvials distals duen associats dipòsits siliciclàstics vermellosos típics d'ambient de sabkha, així com paquets d'escassa potència de gresos d'origen eòlic. Tot el conjunt està recobert per sediments polimíctics i lutites vermelles corresponents a un ambient de *playa-lake*, amb abundants ripples d'onatge i evidències de períodes d'exposició subaèria. En conjunt, la seqüència presenta una successió cap a aigües de cada cop més somes, a sostre queda recoberta per capes d'arenes eòliques o bé d'arenes remanegades per l'onatge i el vent. Les seqüències descrites tenen moltes característiques en comú amb altres sistemes de deposició terrestre del triàsic inferior i mitjà d'Europa, que foren depositades en un context de clima àrid, amb períodes humits associats al monsó que descarregant sobre les Terres Altes escoceses menaren el transport fluvial cap el sud vers la conca d'Arran. Els vents procedents del nord i el nord-est transportaren arreu les arenes tot creuant els sebkhas y les superfícies d'inundació properes.

Paraules clau: *Trias, gres, fluvials, playa-lake, eòlic, Arran, Scotland.*

Introduction

Early Triassic fluvial depositional systems are widely distributed in southern, central and northwestern Europe. Well-exposed localities are present on the Balearic Islands (Fig. 1; RAMOS, 1995; LINOL *et al*. 2009), Sardinia (COSTAMAGNA, 2012), in Spain (e.g. GALÁN-ABELLÁN *et al*., 2013), SE France and Germany (e.g. BURQUIN *et al*., 2009), and in the UK (e.g. JONES & AMBROSE, 1994). These Early Triassic fluvial systems in Europe all formed on the northern hemisphere on the super continent Pangaea. Palaeolatitude 20° N ran through northern France and southernmost England (BOURQUIN *et al*., 2011). Climate modelling suggests that most parts of Europe had annual surface temperatures of more than 30° C and an arid climate (PERON *et al*., 2005). Although precipitation was scarce over large parts of low-lying areas in Europe, enhanced precipitation in the mountains over Fennoscandia and the Scottish Highlands has been proposed (PERON *et al*., 2005; MCKIE & WILLIAMS, 2009; MCKIE, 2014).

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Fig. 1. Lower Triassic, fluvial deposits; costal exposure on north coast of Mallorca, 1 km NW of Cala Estellencs. The cross-bedded sandstones are fine- to medium-grained and well sorted, which might indicate fluvial reworking of aeolian deposits. Pencil as scale.

Precipitation was related to summer monsoons and this precipitation drove terminal fluvial systems across large part of northern and central Europe (MCKIE, 2014).

In this study we will give a first detailed description of Early Triassic fluvial and overlying Middle Triassic playa lake deposits on Arran, SW Scotland (Fig. 2) and relate the characteristics of the sedimentary deposits to those described from Triassic dryland terminal fluvial and associated playa lake systems in northwest Europe (MCKIE & WILLLIAMS, 20009; MCKIE, 2014). New data on past fluvial transport direction as well as local palaeowind directions deduced from aeolian sandstones and wave ripple mark orientations are given.

Geological setting

The sedimentary basin on Arran contains up to 900 m of Permo-Triassic (New Red Sandstone) deposits (WARRINGTON, 1973). While the sedimentary characteristics, depositional environments, and palaeoclimatic framework of the Permian deposits have been described in some details (e.g. CLEMMENSEN & ABRAHAMSEN,1983; FREDERIKSEN *et al*., 1998), the sedimentology of the Triassic deposits has so far received less attention. The Triassic sediments are exposed at several sites along the shores of the southeastern, southern and western part of the island (Fig. 2). At most sites, however, these sedimentary successions are repeatedly broken by dykes and sills (e.g. POLLARD & STEEL, 1978).

The Early Triassic Sherwood Sandstone Group is present in large parts of England, Wales and SW Scotland (AMBROSE *et al*., 2014); it is overlain by the Middle Triassic Mercia Mudstone Group. At Largybeg Point at the southeast coast of Arran, sediments of the Early Triassic Sherwood Group is represented by the Lamlash Sandstone Formation (Lamlash Beds), (WARRINGTON *et al*., 1980; CLARK

& CORRANCE, 2009; AMBROSE *et al.*, 2014), which here has a thickness of 53 m. It is overlain by sediments of the Mercia Mudstone Group represented here by the Auchenhew Mudstone Formation (Auchenhew Beds), (WARRINGTON et al., 1980; CLARK & CORRANCE, 2009). These latter sediments have here an exposed thickness of approximately 13 m. Deposits of the Auchenhew Mudstone Formation are also seen at several sites on the south and west coast of Arran (POLLARD & STEEL,1978). The Lamlash Sandstone Formation is considered to be of Early Triassic age while the overlying Auchenhew Mudstone Formation is mostly of Middle Triassic age; miospores obtained at the base of the Auchenhew Mudstone Formation close to the study locality at Largybeg Point give at late Scythian (Early Triassic) to Anisian (early Middle Triassic) age (WARRINGTON, 1973).

Fig. 2. Map showing Arran in SW Scotland with main Triassic localities. At Largybeg Point both the Lamlash Sandstone Formation and the Auchenhew Mudstone Formation are seen. At Kildonan and King´s Cave only the Auchenhew Mudstone Formation is present.

Methods

The deposits of the Lamlash Sandstone and Auchenhew Mudstone Formations have been studied in detail at the coastal exposures at Largybeg Point at the southeast coast of Arran (Fig. 2); supplementary studies of the Auchenhew Mudstone Formation were carried out at exposures on the south and west coast of the island (Fig. 2). A sedimentary log was measured at Largybeg Point and sediments divided into characteristic sedimentary facies. Cross beds in fluvial deposits were measured to obtain data on fluvial palaeo-transport directions, and crossbeds in wind-deposited sandstones were likewise used to obtain data on palaeowind directions. Supplementary information on palaeowind directions were obtained from orientation of wave ripple marks seen on exposed bedding surfaces in the playa lake deposits. Ten sediment samples from presumed aeolian sandstones were collected and after disintegration of the loosely cemented sediment, grain-size analysis was carried out.

Results

The sediments at Largybeg Point form a dryland terminal fluvial system (0-53 m) overlain by a playa lake system (53-66 m), (Fig. 3). The section is initiated by a basic dyke and four more dykes interrupt the succession; however, little sediment appears to be missing in the measured section. In more detail the succession is composed of the following sedimentary units: channel deposits (0-20 m), interbedded sabkha and aeolian sand sheet deposits (20-31 m), channel deposits (31-36 m), interbedded sheetflood and sabkha deposits (36-47 m), interbedded sabkha and aeolian sand sheet deposits (47-53 m), and playa lake deposits with subordinate aeolian sand sheet deposits (53-66 m), (Fig. 3).

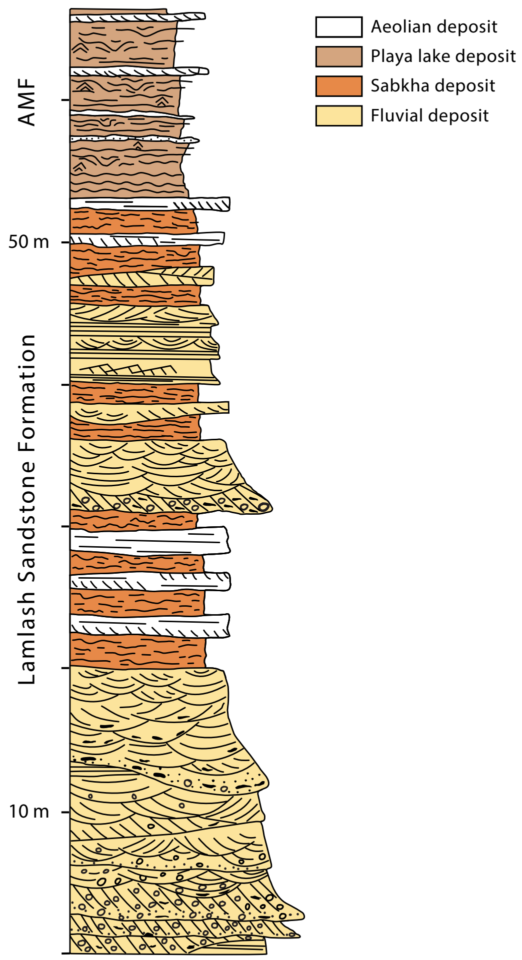

Fig. 3. Simplified log of depositional systems at Largybeg Point. Note the overall fining-upward of the succession with fluvial and sabkha deposits of a dryland terminal fluvial system at the base (Lamlash Sandstone Formation) and deposits of a playa lake system at the top in the Auchenhew Mudstone Formation, AMF. The dryland terminal fluvial systems display two smaller-scale fining-upward successions. The lower one (0-31 m) is composed of channel deposits overlain by interbedded sabkha and aeolian sand sheet deposits. The second one (31-53 m) is composed of channel deposits overlain by interbedded sheetflood and sabkha deposits with two aeolian sand sheet deposits at the top.

Dryland terminal fluvial system

Sediments of this system are composed of channel deposits, sheetflood deposits, aeolian sand sheet deposits, and sabkha deposits (Fig. 3). Sediments of the dryland terminal fluvial system belongs to the Lamlash Sandstone Formation.

Channel deposits

These deposits are primarily composed of clast-rich sandstones displaying large-scale tabular and trough cross bedding (Figs. 4, 5, 6). Cross beds indicate dominant sediment transport towards the south (see later). Clasts are both of extraformational and intraformational origin. Extraformational clasts are up to 12 cm large and typically rounded, while intraformational clasts are dominated by angular red and green mudstone fragments. The clasts-rich sandstones form units up to a few m in thickness. Associated facies are very fine- to medium-grained sandstones with horizontal lamination, and red mudstone that are massive or display wavy bedding, and/or incipient small-scale (ripple) cross lamination. The horizontally laminated sandstones occur in layers with thicknesses between 5 and 100 cm, while the mudstones occur in layers with thicknesses between a few and 30 cm. The channel facies are typically arranged in crude fining-upward succession with thicknesses from less than 1 m to almost 4 m. These successions are initiated by an erosion surface overlain by a conglomerate. The fining-upward successions are arranged in two multi-storey units forming a lower unit with channel deposits (0-20 m) and an overlying unit with channel deposits (31-36 m) separated by around 12 m of sabkha deposits with subordinate aeolian sand sheet deposits (Fig. 3).There is a complete lack of bioturbation, and no soil features were observed in the channel deposits.

The channel deposits are here interpreted to represent low-sinuosity, bedload-dominated streams; they share many characteristics with the conglomeratic fluvial and sand-prone, channel confined successions of MCKIE & WILLIAMS (2009).

Sheetflood deposits

These deposits are composed of horizontally laminated sandstone, large-scale cross-bedded sandstone, small-scale (ripple) cross-laminated muddy sandstone, and wavy to irregularly laminated muddy sandstone. The sandstones form units with thicknesses between 1 and 5 m that are separated by sabkha deposits; sandstone units can be traced laterally across most of the outcrops. Mud clasts are common in the sandstones, while extraformational clasts are rare. In the more mud-rich deposits likely adhesion ripple as well as irregular structures possibly formed by aeolian deposition on a salt-crusted

Fig. 4 Channel deposits; Largybeg Point. Cross-bedded pebbly sandstones overlie, with an erosive contact, flat-bedded to structureless sandstones. Outcrop viewed from the NNE. Ruler is 20 cm long.

surface are present. Horizons with deformation structures are present. The sheetflood deposits occur in close association with sabkha deposits and form the middle part of the succession (36-47 m), (Figs 3, 7). No soil features have been observed.

These sediments are interpreted to represent largely unconfined stream flows that deposited sediments on relatively dry sabkha surfaces. The deposits share many characteristics with the terminal splay and associated distal fluvial deposits of MCKIE (2014). Only few of the fluvial and associated sediments, however, displays coarsening-upward units, a feature that according to MCKIE (2014) should characterize terminal splay deposits. Overall arid conditions during deposition of the sediments are indicated by possible adhesion structures and/or salt-crust structures in the more mud-rich facies.

Sabkha deposits

These deposits constitute red and variegated mud-rich to heterolithic, fine-grained sandstone beds with typical bed thicknesses between 40 and 70 cm. Most of the sand is composed of quartz grains. Sedimentary structures include irregular and wavy bedding (Fig. 8), and possible adhesion ripple structures together with likely salt ridge and crust structures. Deformation structures of varying sizes are common (Fig. 9). Sabkha deposits are associated with thin aeolian sand sheet deposits (20-31 m and 47-53 m) or with sheetflood deposits (36-47 m), (Figs 3, 6, 7).

These sediments share a number of characteristics with the dry playa deposits of MCKIE (2014), but in the present context we prefer to classify this environment as a detrital-dominant inland sabkha (FRYBERGER *et al*., 1983). The sabkha deposits are arenaceous and the quartz grains are primarily of aeolian origin. During longer dry periods, wind transported sand across the sabkha surface and formed thin aeolian sand sheets. Many of the deformation structures in these sediments probably formed by

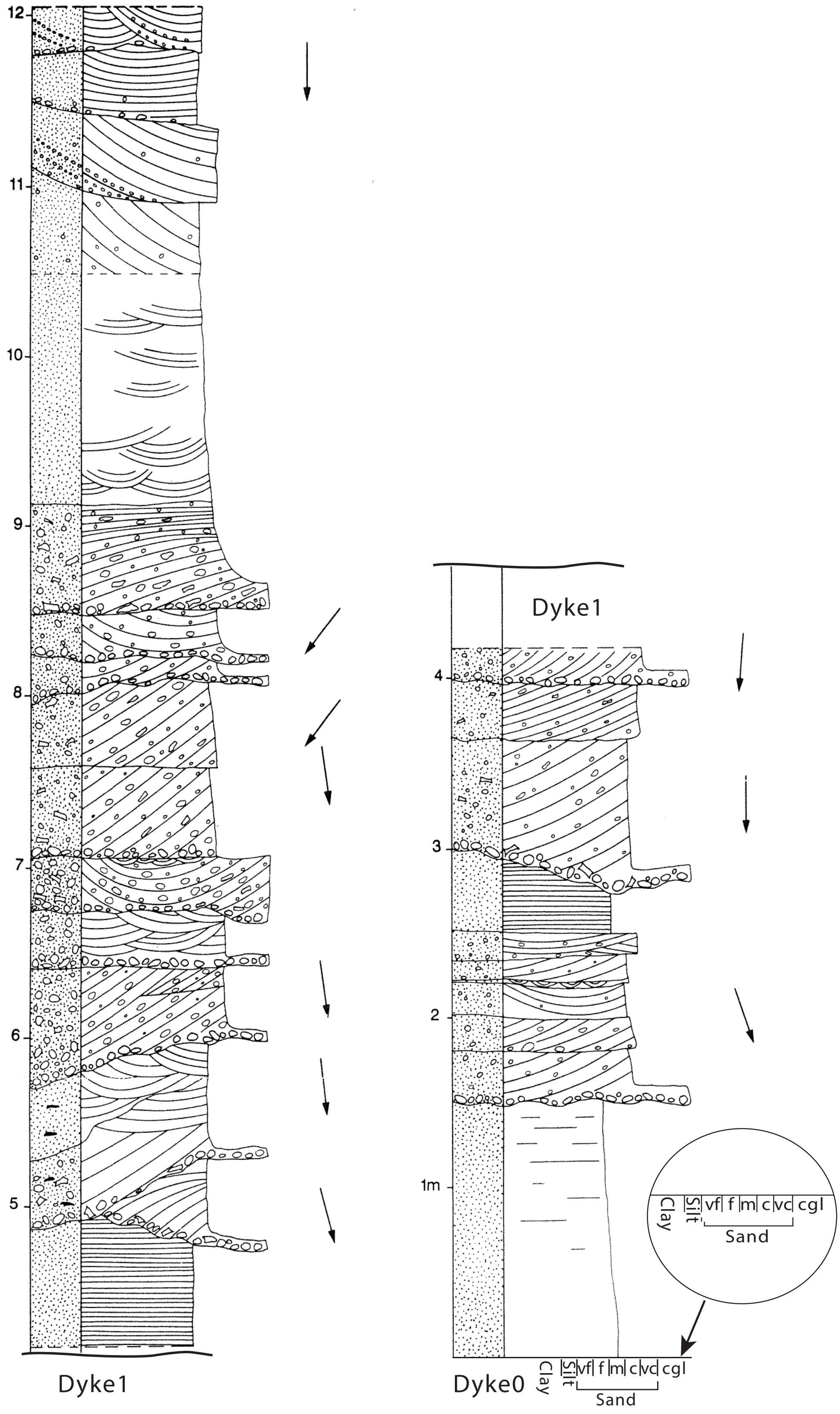

Fig. 5. Detailed log of channel deposits in the dryland terminal fluvial system (1-12 m); Largybeg Point. The succession shows a number of channel sequences; the best developed of these are initiated by a lag conglomerate overlain by trough and/or planar cross-bedded pebbly sandstone. Palaeocurrents are consistently directed towards the south.

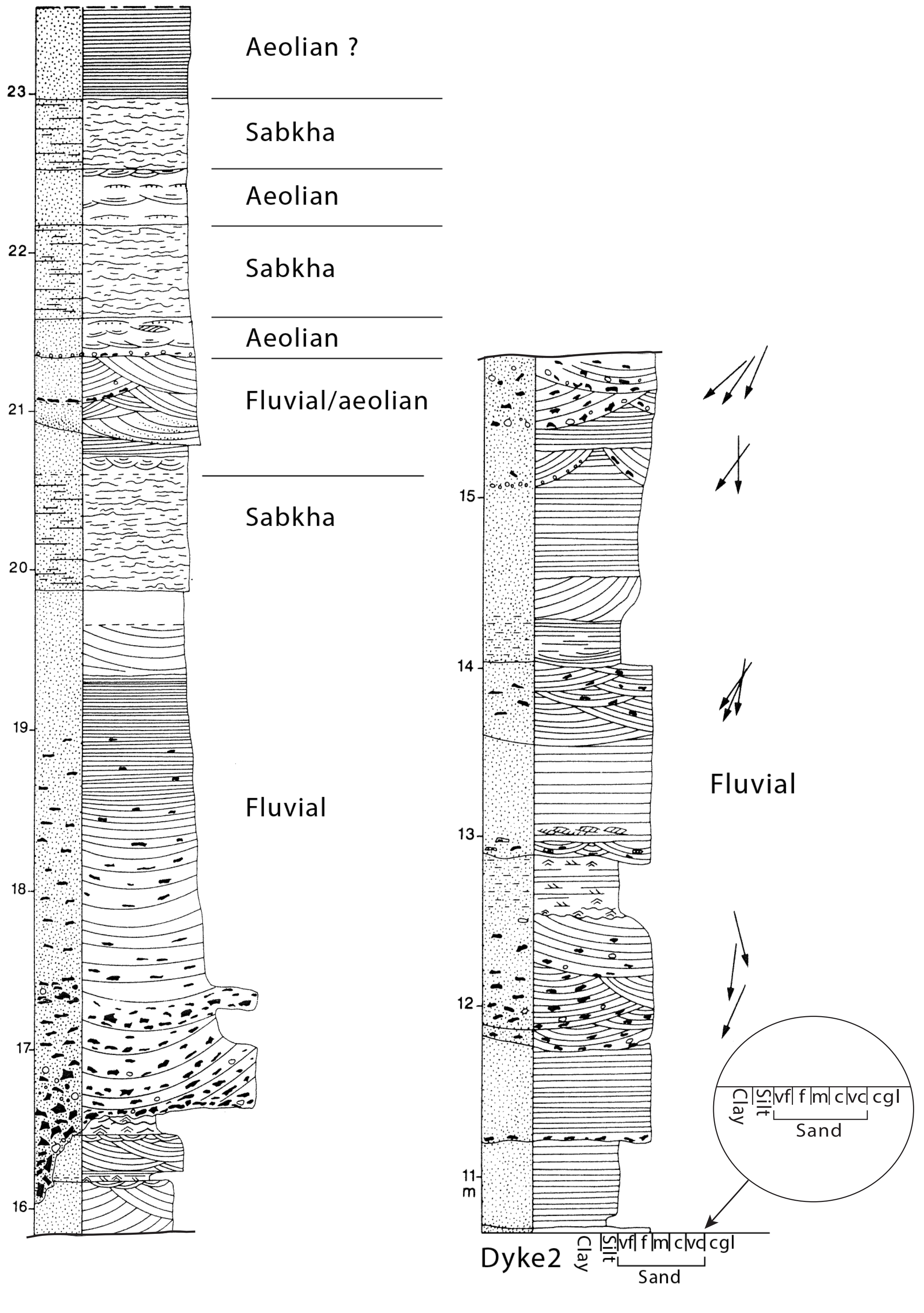

Fig. 6. Detailed log of channel deposits (11-20 m) overlain by interbedded sabkha and aeolian sand sheet deposits (20-23.5 m); Largybeg Point. One major channel succession is seen between 16 and 20 m. Small overlap in thickness between the two logs is due to shifting of line of measurement due to crossing of a dyke.

Fig. 7. Interbedded sabkha and fluvial sheetflood deposits (dyke in background); Largybeg Point. Outcrop viewed from the NNE.

reptilian animals crossing the sabkha surface. On exposed bedding planes in the overlying Auchenhew Mudstone Formation trackways and individual chirotheriid footprints are relatively common (CLARK & CORRANCE, 2009).

Aeolian sand sheet deposits

These deposits form five discrete sandstone units with thicknesses between 20 and 110 cm (an additional four of these aeolian sandstone beds are present in the overlying playa lake system; Fig. 3). The sandstones are white or light grey, relatively loosely cemented and composed of fine- to medium-grained, relatively well-sorted quartz sand. Individual sandstone beds are sheet-like in geometry with well-defined upper and lower boundaries (Fig. 8). They are closely associated with red or variegated sabkha deposits (20-31 m and 47-53 m; Figs 6, 8), but are also present in association with playa lake deposits (53-66 m). Sedimentary structures in the sandstone beds include high- and low-angle cross bedding (Fig. 8), and horizontal lamination; a few beds appear structureless. Both sandflow and wind-ripple (pinstripe) stratification are present in the cross-bedded units. A few sandstone beds contain thin intervals with mud clasts. Most of the aeolian sandstones with cross beds indicate aeolian sand movement towards southwesterly directions (see later).

Sand in this facies was brought to the area by wind; it strongly resembles the aeolian sand sheet deposits described from the Lower Triassic on the isle of Helgoland in the German Bight (CLEMMENSEN, 1991) as well as the small-scale, isolated dune deposit in cores from the Lower Triassic in the Dutch North Sea (MCKIE, 2014). Local and intermittent water reworking of the aeolian deposits is indicated by the surfaces lined with mud clasts. Similar features related to occasional water reworking are also seen in the aeolian sand sheet deposits on Helgoland (CLEMMENSEN, 1991). The presence of this facies indicates repeated episodes of aeolian sand transport across a dry sabkha surface. Sand transport resulted sometimes in the formation of small aeolian sand dunes; larger-scale aeolian sand dune accumulation was inhibited probably by general high water tables and by a low sand supply.

Playa lake system

Sediments of this system are composed primarily of lake deposits and aeolian sand sheet deposits (Fig. 3). Sediments of the playa lake system belongs to the Auchenhew Mudstone Formation.

Lake deposits

These deposits form closely associated beds of mudstone, heterolithic sediments and muddy sandstone; beds vary in thickness between 5 and 200 cm and are of large lateral persistence. The mudstones typically display faint horizontal lamination and contain casts after halite crystals. The heterolithic sediments have wave ripple structures, and exposed bedding planes show symmetrical to slightly asymmetrical wave ripples mostly trending north-south (see later). Desiccation features including polygonal desiccation patterns on bedding planes are common in these deposits. The muddy sandstones are massive or have irregular to wavy lamination; locally cm-large nodules primarily filled with calcite are present. Deformation structures are rather common in these sediments.

These sediments are interpreted as playa lake deposits; they share many characteristics with the playa deposits of MCKIE & WILLIAMS (2009) and the wet playa deposits of MCKIE (2014). While most of the facies were deposited in shallow lake water, repeated episodes of subaerial exposure are given by the desiccation features; during these periods with a dry (or almost dry lake bottom) reptilian animals seemingly crossed the area creating deformation structures in the soft lake sediments. A few trackways similar to those described by CLARK & CORRANCE (2009) were observed by the authors. Gypsum/anhydrite nodules (now replaced by calcite) and halite crystal formed during periods of lake low stands from evaporation of saline pore water. This interpretation of the sediments as playa-lake deposits is new; POLLARD & STEEL (1978) saw these sediments as tidal flat deposits.

Fig. 8. Whitish aolian sand sheet deposit over- and underlain by red, wavy bedded, muddy sandstones of the sabkha facies. The aeolian sandstone shows high-angle cross-bedding formed by the migration of a small dune; Largybeg point. Outcrop viewed from the NNE. Photo cap as scale.

Aeolian sand sheet deposits

The sedimentary characteristics of these deposits have already been described above from the Lamlash Sandstone Formation. In the Auchenhew Mudstone Formation exposed at Largybeg Point four of these thin aeolian sandstone beds are observed (Fig. 3). At the south and west coast of Arran similar thin aeolian sandstones are recognized at several sites with sediment exposures of the Auchenhew Mudstone Formation. Some of them display sedimentary structures like high-angle and low-angle cross-bedding indicative of aeolian sand transport, while others contain intervals with wave ripple structures. The aeolian sediments frequently occur on top of small-scale shallowing-upward successions (typical thicknesses are between 0.5 to 1.5 m); fine examples are seen on the south and west coast of Arran (Fig. 9). These deposits formed by aeolian sand transport across a dry playa surface. The wave-rippled intervals indicate that some aeolian sand flats repeatedly were inundated by lake water. The repeated presence of the aeolian deposits (and/or water-reworked aeolian sediments) at the top of the shallowing-upward successions probably indicates climatic control of water level in the playa lake. Mud was deposited during lake highstands and heterolithic sabkha sediment during falling water stages until aeolian sedimentation prevailed (at times interrupted by brief period of wave reworking) during lake low stands. This interpretation of the sandstone bodies as aeolian is new; POLLARD & STEEL (1978) saw these sediments as sandy tidal flat deposits.

Palaeocurrents and palaeowinds

Cross-bed data in the channel facies (n = 127) indicate consistent fluvial transport towards the south (present coordinates). The rivers drained off the Scottish Highlands, probably driven by Tethyan monsoons, and flowed into the playa system in the Arran Basin. Similar endorheic discharge also characterized nearby Early Triassic basins in northwest Europe (MCKIE, 2014).

Fig. 9. Isolated outcrop of sediments from the Auchenhew Mudstone Formation, Kildonan (south coast of Arran).

The playa system was influenced by aeolian processes and during dry periods aeolian sand deposits formed. Cross beds in aeolian dune deposits (n = 36) indicate prevailing wind transport towards southwesterly directions (present coordinates); a few cross beds indicate wind transport towards north-

The deposits show a shallowing- upward succession composed of the following facies from the base and upwards: playa mudstone (red), sabkha deposit (green), interbedded wet aeolian sand sheet and sabkha deposits (white with thin green layers), and dry aeolian sand sheet deposit with low-angle cross bedding (white). Note deformation structures in the green sabkha deposit. Photo cap for scale.

easterly or northwesterly directions. As Europe has been rotated about 18° clockwise since the Late Permian (POCHAT *et al*., 2005), it is inferred that dominant palaeowinds blew from north-northeasterly directions. Arran was situated at approximately 25° N in the Early Triassic (Bourquin *et al*., 2011). This would imply that the deduced palaeowinds probably were dry season trade winds.

Orientation of wave ripples in ancient shallow lacustrine deposits has been used as a proxy for palaeowind direction (e.g. POCHAT *et al*., 2005). The wave ripples (n = 127) in the playa lake deposits at Largybeg Point are trending N-S (350°-170°) with only little variation. Corrected for clockwise rotation of 18°, it can be inferred that winds forming the wave ripples in shallow water blew either from west-southwesterly or from east-northeasterly directions.

Discussion and Conclusions

The Lamlash Sandstone and Auchenhew Mudstone Formations at Largybeg Point form an overall fining-upward succession of sediments from a dryland terminal fluvial system overlain by sediments from a playa lake system (Fig. 3). This trend could indicate a retrogradation of the fluvial system with time probably connected to a long-term shift in climate towards more arid. A similar climatic trend is observed in Lower Triassic terrestrial sediments in core data from the Central North Sea, here fluvial sandstones from the Early Triassic (Olenikian) are gradually replaced by playa mudstones in the late Early Triassic and early Middle Triassic (Anisian), (MCKIE, 2014).

The overall characteristics of the fluvial deposits in the Early Triassic Lamlash Sandstone Formation resemble those given for a dryland terminal fluvial system by MCKIE (2014). The channelled deposits presumably formed in the more proximal part of the system, while the sheetflood deposits formed in the distal part of the system at the fringe of the inland sabkha/playa lake. A lack of coarsening-upward successions in the presumed terminal splay deposits is tentatively explained by relatively low water levels in the adjacent playa lake. Repeated aeolian activity is evidence of an overall dry climate. It is envisaged that summer monsoon brought precipitation to the Scottish Highlands and that rivers draining this highland transported sand southwards into the Arran Basin. Aeolian sand transport across the basin took place in the dry season and resulted in the formation of thin aeolian sand sheet deposits with local development of small aeolian dunes. Sand-transporting winds were primarily from northeasterly directions (present coordinates) and north-northeasterly directions in an Early Triassic context.

The origin of sediments in the Middle-Late Triassic Mercia Mudstone Group and time equivalent deposits in the UK and nearby areas has long been an issue of debate (e.g. TALBOT *et al*., 1994; RUFFELS & HOUNSLOW, 2006; MCKIE & WILLIAMS, 2009). While some have regarded the sediments as marine or influenced by marine water, most now consider the sediments as strictly continental. In addition the origin of the Auchenhew Mudstone Formation on Arran has received different views. WARRINGTON (1973) suggested marine influence based on the occurrence of miospores with marine affinity at the base of this unit, and POLLARD & STEEL (1978) interpreted these sediments as intertidal. While it is possible that the basin occasionally was influenced by marine water, we see no evidence for persistent tidal conditions in the sediments. The coarsening-upward successions topped by sandy deposits interpreted as prograding intertidal flat sequences by POLLARD & STEEL (1978) are here shown to represent shallowing-up successions in a playa lake that eventually dried up and was covered with a thin sand sheet of aeolian or mixed aeolian and water-lain origin.

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