[AMERICAN JOURNAL OF SCIENCE, VOL. 275, JANUARY, 1975, P. 31-56]

SILURIAN MARINE RED BEDS

A. M. ZIEGLER* and W. S. McKERROW**

ABSTRACT. Paleoecologic and sedimentologic studies show that red shales and siltstones originated in some deep shelf, basin, and ocean floor environments during the Silurian. In the late Precambian and Early Paleozoic, before the development of advanced land plants, a plentiful supply of oxidized iron would have been concentrated during the weathering process on most land surfaces. The incorporation of this material in the marine sedimentary record is correlated with Llandovery (Clinton) marine transgressions in the British Isles, Norway, and the Appalachian Basin. Therefore, the oxidized material is probably second-cycle, derived through coastal erosion of soil or alluvial complexes, and in most cases the source can be identified. In England and Wales, the sea overlapped Ordovician marine deposits onto the English Midlands, which had been exposed to weathering throughout the Ordovician Period. In Scotland, the source of oxidized material was probably contemporary andesitic volcanics exposed to coastal erosion. In the Appalachian Basin, the sea transgressed the recently uplifted Queenston fluvial complex, and the red shales of the Clinton Group were probably derived from these late Ordovician red beds. Red beds are not universal during Llandovery transgressions but are restricted to the quiet offshore shelf and those adjacent deeper sea areas which had relatively high sedimentation rates. Elsewhere, the sediments were apparently reduced in the presence of organic matter, and this process was probably aided by physical and biological reworking in the near-shore areas. Offshore marine red beds are also associated with Cambrian and Ordovician transgressions. We conclude that the presence of red coloration can no longer be taken as proof that sediments accumulated in non-marine or shallow water environments.

INTRODUCTION

Red beds are of frequent occurrence in Lower Paleozoic marine sequences, though the evidence of their marine environment has usually been questioned (Whittard, 1928, p. 747; Warren, 1963, p. 246) because accumulation of oxidized sediments at the present time is largely confined to nonmarine areas (Van Houten, 1973, p. 40), apart from red or brown clays of the deep oceans. Grim has said "One can conceive of an area of rapid accumulation having very mild reducing conditions, in which yellow or red material might be present because of rapid burial" (1951, p. 23). This explanation has recently been invoked to explain contemporary marine red beds in the Persian Gulf (Lange, 1971) and red beds in a Cambrian flysch sequence in the Canadian Appalachians (La Joie and Chagnon, 1973).

Since most clastic deposits are originally derived from land they are likely to be oxidized at the source or during transportation, and this would have been especially true prior to the evolution of land plants and the concommitant reducing effect of organic material. In principle, then, much of the sediment supplied to marine areas during the Early Paleozoic and Precambrian would have been oxidized, and it is, therefore, not surprising to find that some of it remained in this state through deposition. The purpose of this paper is to document the marine nature of widespread red beds in the Silurian rocks of Britain, Ireland, Norway, the east Baltic states, Maine and New Brunswick, and the area between

* Department of the Geophysical Sciences, University of Chicago, Chicago, Illinois 60637

** Department of Geology and Mineralogy, Oxford University, Parks Road, Oxford OX1 3PR England

New York State and Kentucky. Further, we offer some speculations as to why these sediments remained oxidized despite the normal reducing effect in sediments buried, with or without organic matter, below the sea floor.

In recent years much progress has been made in interpreting the environment of deposition of sedimentary rocks. The recognition of Lower Silurian depth-related brachiopod communities allows five divisions of the shelf; from shore to shelf margin, these are: *Lingula, Eocoelia, Pentamerus, Stricklandia,* and *Clorinda* (Ziegler, 1965; Ziegler, Cocks, and Bambach, 1968). Red beds are common in terrestrial environments and in littoral environments equivalent to the *Lingula* Community throughout the Phanerozoic, but in the Silurian, red beds are also present in the deep shelf *Stricklandia* and *Clorinda* Communities and in still deeper areas where only graptolites are found. These deeper marine red beds form the main subject of this paper.

Present day shallow water marine sediments normally contain enough organic matter for the reduction of transported iron oxides, and textbook writers therefore typically make the assertion that "almost all red beds are non-marine". The very presence of red color in sediments is apt to influence the field geologist in his environmental interpretation. But, in the Silurian, the amount of organic matter was apparently not always enough to reduce the ferric iron in marine environments.

The red color in sediments is usually due to the presence of the ferric iron oxide, hematite. All the hematite may not be original, as limonite and other iron-bearing minerals may revert to hematite during diagenesis (Berner, 1971, p. 197). The iron oxides form from sub-aerial weathering of ferrous minerals. They "are carried mainly as colloids or adsorbed coatings on fine-grained minerals . . . this is why shales, on the average, contain more iron than do sandstones" (Berner, 1971, p. 201). In the sea, the iron can be reduced by iron-reducing bacteria, organic reducing agents, or H_2S (Berner, 1971, p. 197). This reduction occurs in most modern marine environments, except in areas of low organic yields, such as abyssal regions of the oceans where red or brown clays are forming, or in areas, like parts of the Persian Gulf, where a high supply of ferric oxide is combined with high sedimentation rates, which "do not allow sufficient time for complete reduction and in such areas red sediment is found preserved at greater sediment depths" (Lange, 1971).

As has been pointed out (Van Houten, 1968, p. 404) there is no reliable way of telling if the hematite pigment is inherited from the soil, derived from limonite formed in transit or at the deposition site, or is diagenetic. For this reason we have turned to stratigraphic evidence, such as the relation of red strata to transgressive cycles, to relative thicknesses of enclosing units, and to facies distribution. We have found significant correlations of Silurian red bed occurrence with all these effects and believe this is sufficient to determine their origin.

Some Silurian beds that lie beneath unconformities have been secondarily reddened, but these can usually be distinguished by the fact that the more porous coarser beds are red (whereas the red color of primary red beds is typically confined to the more argillaceous sediments). Secondary reddening occurs in most of the Silurian sandstone beds of the Tortworth Inlier, Gloucestershire (Curtis, 1972). Secondarily reddened rocks also commonly show a concentration of red color along joint planes or may show liesegang rings, for example Silurian beds of the Lake District below the Carboniferous unconformity (Rickards, 1964, p. 447). Only the primary red beds are the subject of this paper.

Some previous workers have been tempted to use the red beds themselves as a basis for stratigraphic correlation. Although most of the Silurian marine red beds fall within the Upper Llandovery interval, many beds of this age are not red, and one of our purposes in determining the origin of these red beds is to examine their value in correlation within the Upper Llandovery. This can be attempted reasonably because paleontologic correlation in the Upper Llandovery is now relatively precise, even between shelly and graptolitic facies (Cocks, 1971). Table 1 summarizes correlation information and stratigraphic terminology for this time interval.

TABLE 1

Correlation information and stratigraphic terminology for the Middle Llandovery through Lower Wenlock interval of the Silurian Period (after Cocks, 1971)

	Stage	Formation at Llandovery	Graptolite Zone
Lower Wenlock	——	Wenlock Shales	*Monograptus riccartonensis*
			Cyrtograptus murchisoni
			C. centrifugus
Upper Llandovery	Telychian	C_6	*Monoclimacis crenulata*
		C_5	*Monoclimacis griestoniensis*
			Monogr. crispus
		C_4	*Monograptus turriculatus*
			Rastrites maximus Band
	Fronian	$C_{2\text{-}3}$	*Monograptus sedgwickii*
		C_1	
Middle Llandovery	Idwian	B_3	*Monograptus convolutus*
		B_2	*Monograptus gregarius*
		B_1	

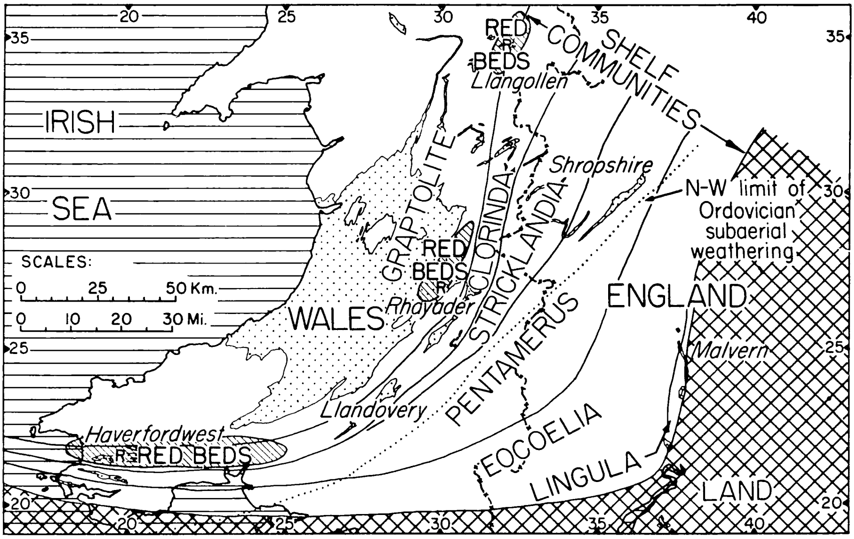

Fig. 1. Idwian (B_{1-3}) or Fronian (C_{1-3}) marine red beds of Wales in their paleogeographic setting, with the distribution of shelf benthic communities during the Fronian. R = red bed exposure (see table 2). Areas with marine red beds are represented by diagonal shading; land areas crosshatched; Llandovery outcrops dotted. The probable limit of the Ordovician sea (at its maximum extent) is shown. The marginal numbers refer to the British National Grid.

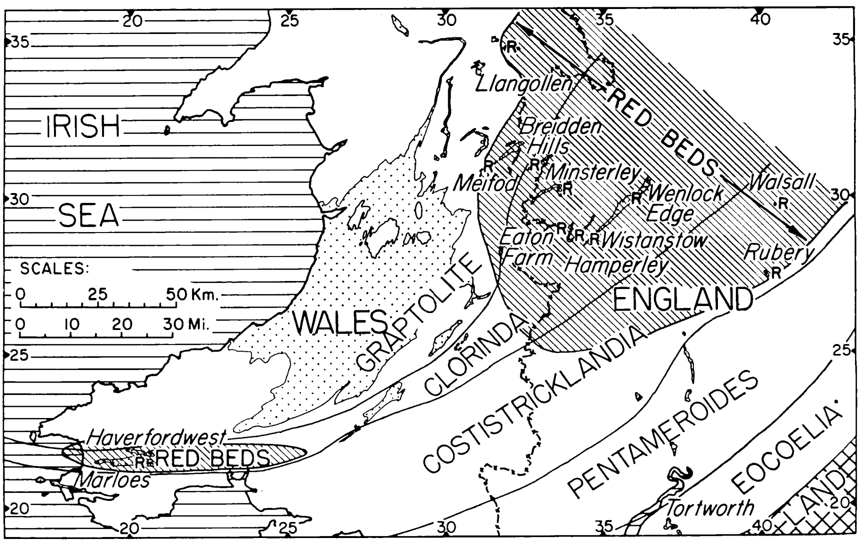

Fig. 2. Lower Telychian (C_{4-5}) marine red beds of Wales and the Welsh Borderland in their paleogeographic setting. R = red bed exposure (see table 3). For explanation of other symbols, see figure 1.

RED BEDS IN WALES AND THE WELSH BORDERLAND

Red beds occur at three distinct horizons: (1) Idwian or Fronian in Wales, (2) Lower Telychian (C_{4-5}) in the northern parts of the Welsh Borderland and adjacent parts of Wales, and probably also at Haverfordwest, Pembrokeshire, and (3) Upper Telychian (C_6 or the *M. crenulata* Zone) of central Wales and the Welsh Borderland.

A. Distribution.—During the Fronian, red bed deposition was limited to small patches just off the shelf margin at Haverfordwest, Rhayader, and Llangollen (fig. 1). In the Lower Telychian, red bed deposition was more widespread (fig. 2) and covered an extensive outer shelf in Shropshire and adjacent areas as well as areas off the shelf in Haverfordwest and Llangollen. Finally, the Upper Telychian red beds occur in two distinct patches, the outer shelf of Shropshire and surrounding areas, and an extensive off-shore patch in central Wales (fig. 3).

B. Age.—Precise correlation of the earliest red beds has only been established at Rhayader as Fronian (table 2). The other two areas are of Idwian or Fronian age. The Lower Telychian occurrences (table 3) all contain either graptolites or stricklandiids which provide accurate correlation, except for the occurrences in the Breidden Hills and Haverfordwest. The red Buttington Shales of the Breidden Hills probably include beds of C_{4-5} age (Ziegler, Cocks, and McKerrow, 1968, p. 766), and the red shales at the top of the Uzmaston Beds of Haverfordwest are overlain by the Canaston Beds which contain a C_6 fauna. The Lower Telychian red beds of Haverfordwest and Llangollen are separated from the earlier red beds of the same area by substantial thicknesses

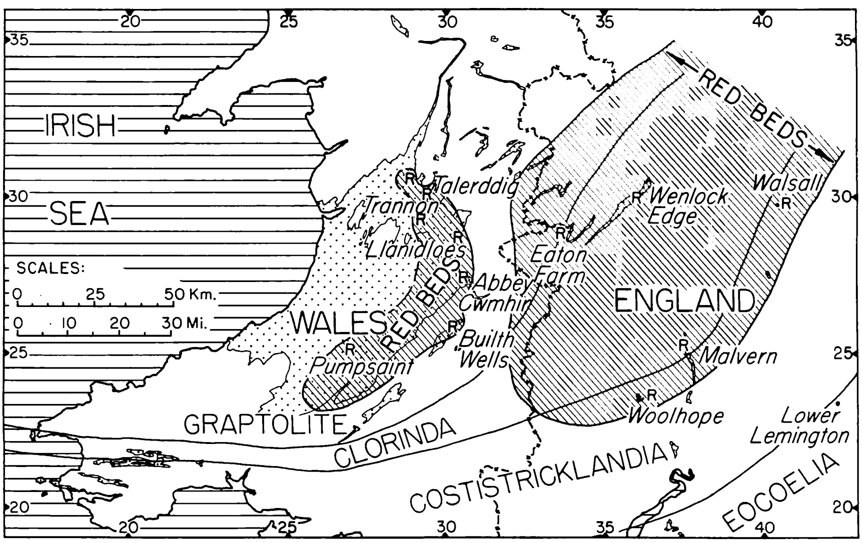

Fig. 3. Upper Telychian (C_6) marine red beds of Wales and the Welsh Borderland in their paleogeographic setting. R = red bed exposure (see table 4). For explanation of other symbols, see figure 1.

TABLE 2
Idwian and Fronian red beds in Wales

Locality and formation	Age	Community	Thickness	Reference
North of Llangollen: Fron-Frys Slates	Idwian or Fronian	*Clorinda*/ graptolite	15 m	Wills and Smith, 1922, p. 193-194.
South of Rhayader: Rhayader Pale Shales	*M. sedgwickii*	No fossils; graptolites above and below	?	Lapworth, 1900, p. 120.
Haverfordwest: Uzmaston Beds	Idwian or Fronian	No fossils; *Clorinda* above	? 15 m	Strachan and others, 1914, p. 79, 81.

TABLE 3
Lower Telychian red beds in Wales and the Welsh Borderland

Locality and formation	Community	Thickness	Reference
North of Llangollen: Tydraw Slates	graptolite and marginal *Clorinda*	18 m	Wills and Smith, 1922, p. 193.
Meifod: V_3	graptolite	60 m	Ziegler, Cocks, and McKerrow, 1968, p. 768-769.
Breidden Hills: Buttington Shales	*Clorinda*	60 m	Ziegler, Cocks, and McKerrow, 1968, p. 766.
Minsterley: Minsterley Formation	*Clorinda*	49 m	Ziegler, Cocks, and McKerrow, 1968, p. 744; Cocks and Rickards, 1969, p. 224-225.
Eaton Farm: Hughley Shales	*Clorinda* and marginal *Clorinda*	150 m	Cocks and Rickards, 1969, p. 216-218, 228.
Hamperley: Hughley Shales	*Clorinda*	?30 m	Cocks and Rickards, 1969, p. 217, 221, 228.
Wistanstow: Hughley Shales	*Clorinda*	?30 m	Ziegler, Cocks, and McKerrow, 1968, p. 748-749.
Wenlock Edge: Hughley Shales	*Clorinda*	~45 m	Ziegler, Cocks, and McKerrow, 1968, p. 748-749.
Walsall	*Costistricklandia*	~60 m	Ziegler, Cocks, and McKerrow, 1968, p. 763.
Rubery: Rubery Shales	*Costistricklandia*	~3 m	Ziegler, Cocks, and McKerrow, 1968, p. 764; Wills and Laurie, 1938, p. 179.
Haverfordwest: top of Uzmaston Beds	? *Clorinda*	3 m	Strachan and others, 1914, p. 81, 102.

of non-red strata. The Upper Telychian occurrences (table 4) are all well dated by graptolites or stricklandiids. In the areas where these succeed the Lower Telychian red beds, there is no break in red bed deposition.

C. Source.—In the Idwian, the sea extended as far east as Wenlock Edge and the Malvern Hills (Ziegler, Cocks, and McKerrow, 1968, p. 774), where it started to overlap the Ordovician (fig. 1). The earliest appearance of Silurian marine red beds thus coincides with the initial coastal erosion of terrane which had been exposed to weathering throughout the Ordovician Period. This terrane included Precambrian volcanics, sediments, and low rank metamorphic rocks as well as Cambrian quartzites and shales. Further transgression occurred in the Telychian (Ziegler, Cocks, and McKerrow, 1968), and the centers of red bed deposition occur offshore of the areas of maximum overstep (figs. 2 and 3).

D. Deposition.—The occurrence of red strata seems to be related to the environment of deposition (table 5). In particular, on this southeast

TABLE 4

Upper Telychian red beds in Wales and the Welsh Borderland

Locality and formation	Community	Thickness	Reference
Talerddig: Dolgau Group	graptolite	south: 26 m west: 55 m north: 0 northeast :0	Bassett, 1955, p. 248.
South of Trannon: Dolgau Group	graptolite	54 m	Wood, 1906, p. 655-656.
Llanidloes: Pale Shales	graptolite	97 m	Jones, W. D. V., 1945, p. 323-324.
Abbey-Cymhir: Pale Shales	graptolite	"Numerous bands, 1 or 2 inches thick"	Roberts, 1929, p. 664.
Builth: Pale Shales	graptolite	28 m	Jones, O. T., 1947, p. 9.
Pumpsaint: Green and Purple Shales	graptolite	?	Davies, 1933, p. 189.
Walsall	*Costistricklandia*	~77 m	Ziegler, Cocks, and McKerrow, 1968, p. 763.
Wenlock Edge: Hughley Shales	*Clorinda* with *Costistricklandia* at top in northwest	~37 m	Ziegler, Cocks, and McKerrow, 1968, p. 748-749.
Eaton Farm: Hughley Shales	marginal *Clorinda*	~25 m	Cocks and Rickards, 1969, p. 216-218, 228.
Malverns: Wych Beds (Woolhope Shale)	*Clorinda* and *Costistricklandia*	?	Phipps and Reeve, 1967, p. 341; Ziegler, Cocks, and McKerrow, 1968, p. 755-757.
Woolhope: Upper Haugh Wood Beds	*Costistricklandia*	<6 m	Ziegler, Cocks, and McKerrow, 1968, p. 757.

TABLE 5

Color of sediments in relation to the environmental spectrum on the southeast margin of the Proto-Atlantic Ocean (Welsh Borderland, Wales, Lake District). For localities, see text and Ziegler, Cocks, and McKerrow (1968)

Environment	Deeper marine			Outer shelf		Inner shelf		Coastal Alluvial	
Community	Graptolitic	Graptolitic	Graptolitic	Clorinda	Stricklandia	Pentamerus	Eocoelia	Lingula	None
Typical lithologies	shale	graywacke (axially transported turbidites)	shale	shale	shale with some sandstone	shale and sandstone	sandstone with some shale	muddy sandstone	mudstones and poorly sorted sandstone
Relative thickness	thin to moderately thick	very thick	thin to thick	thin to thick (sometimes absent)	thick	thick	thick	thin (if developed at all)	thin (if developed at all)
Typical colors	black to red	gray	green and red	red	red or brown	gray or brown	gray or brown	red or brown	red or brown
Examples	C_6 of Lake District	C_5 of Central Wales	C_6 of Llanidloes	C_4-C_6 of Shropshire	C_5-C_6 of Rubery and Walsall	C_5 of Malvern District	C_6 of Lower Lemington	B? of Malvern District	B? of Malvern District

side of the Proto-Atlantic Ocean, red beds never occur in "inner shelf" environments where the *Eocoelia* and *Pentamerus* Communities were established. Apparently, the relatively abundant organic matter was sufficient to reduce the iron oxides present in the sediments; current activity and bioturbation may have assisted in the distribution of the organic matter throughout the sediments. We conclude that these sediments must have been supplied originally with the iron minerals in the oxidized state since there is no reason to suspect that they were derived from a different source than their offshore red equivalents.

Even in the offshore areas, red beds are not universally developed, and here their distribution seems to be correlated positively with the total thickness of the enclosing unit and presumably with the rate of sedimentation. At Cwm Cignant, in the Llanlidloes area, the Pale Shales are 385 m thick and contain a total of 100 m of red mudstone (Jones, W.D.V., 1945, p. 323). At Penrhuddlan, in the same area, this unit is only 185 m thick and contains no red material (Jones, 1945, p. 327). A similar relationship is demonstrable at Garth, near Builth Wells, where Unit C_d increases northward from 45 m to 345 m and only contains red in the thicker developments (Andrew, 1925, p. 399, 402). At Talerddig, the Dolgau Group increases from 122 m at Dolfach to 153 m at Lawr-y-coed, to 162 m at Dolgach, and the respective thicknesses of red mudstone increase from 2 m, to 18 m and 26 m (Bassett, 1955, p. 248). Further north the Dolgau Group is thicker but contains little or no red mudstone. Here, however, thick wedges of siltstones appear (Bassett, 1955, p. 252) and, when subtracted from the total thickness of the group, indicate relatively low rates of deposition for the mudstone sequences.

In conclusion, red marine strata occur only in offshore shelf and deeper environments, and here only where rates of deposition were rapid enough to counteract the normal reducing effect below the sediment-water interface.

UPPER TELYCHIAN RED BEDS IN SOUTHERN NORWAY, NORTHERN ENGLAND AND EASTERN IRELAND

A. Distribution.—In the Oslo area, there is a transition from deep shelf environments in the west to graptolitic environments east of Oslo Fjord. Upper Telychian red beds occur in both facies to the north of Oslo but are absent in both to the south (fig. 4). They reach a maximum thickness at Mjøsa in the north of the area of Silurian outcrops (table 6).

Red beds assigned to the *M. crenulata* Zone occur in the Upper Browgill Beds of the Cross Fell Inlier and parts of the Howgill Fells and probably the Lake District (fig. 6; table 7). They are thickest in the northeast (Cross Fell) and thin to the south and southwest. Although they are absent in the western parts of the Lake District, one meter of red shale is present at Balbriggan (Rickards, Burns, and Archer, 1973, p. 308); this lies along strike on the west side of the Irish Sea in a lithological succession with many similarities to that in the Lake District.

The areas with red beds in the Howgill Fells are separated by a belt (which extends northeast from Sedbergh) in which no red beds are present; in a similar manner the two occurrences of red beds in the Lake District (at Pull Beck and Stockdale Beck) are separated by outcrops without red shales at Skelgill. The distribution of Upper Telychian red beds in the north of England (fig. 6) is thus patchy as is the case with the other areas we have studied.

B. Age.—Graptolites at Mjøsa and stricklandiids at Ringerike and Baerum prove the Upper Telychian age of the red beds at these localities; the red beds at Hadeland are thought to be of the same age.

The Upper Browgill Beds of the north of England yield graptolites of the *M. crenulata* Zone; no graptolites have been recorded from primary red beds, but assemblages characteristic of the *M. crenulata* Zone occur in thin dark interbeds in the red shales in Swindale Beck, Cross Fell (Burgess, Rickards, and Strachan, 1970, p. 177), and in Habbleth-

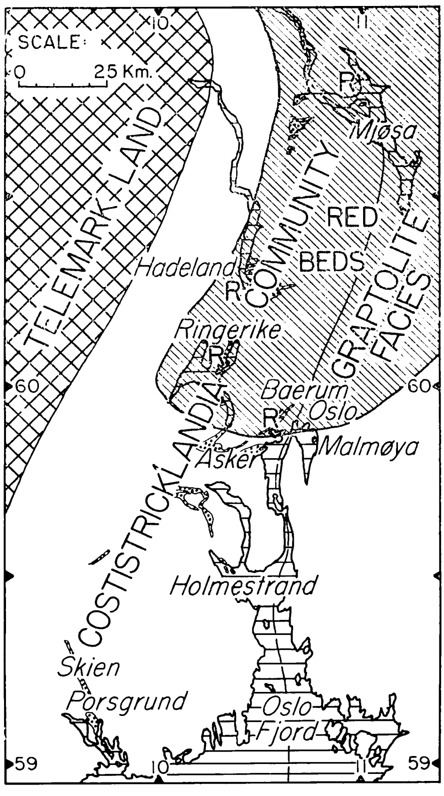

Fig. 4. Upper Telychian (C_6) marine red beds of southern Norway in their paleogeographic setting. R = red bed exposure (see table 6). Silurian outcrops dotted. The marginal numbers refer to latitude and longitude. For explanation of other symbols, see figure 1.

waite Hall Gill, northeast of Sedbergh (Rickards, 1973). Dr. Rickards believes that the red mudstones of Balbriggan are probably the same age.

C. Source.—The red beds of the Oslo area can be linked with a marine transgression over the Precambrian rocks of Telemark Land to the northwest of Oslo (Henningsmoen, 1960, p. 146) from which the Silurian clastic material was derived.

TABLE 6
Upper Telychian red beds in southern Norway

Locality and formation	Community	Thickness	Reference
Mjøsa: 7cβ	graptolite	<35 m	Kiaer, 1908, p. 433.
Hadeland: 7cα and 7cβ-γ	fauna poor	>25 m	Kiaer, 1908, p. 389.
Ringerike: 7cα and 7cγ	*Costistricklandia*	~10 m	Kiaer, 1908, p. 63, 67-68.
Baerum: 7cα and 7cβ	overlain by *Costistricklandia*	<12 m	Kiaer, 1908, p. 354-356.

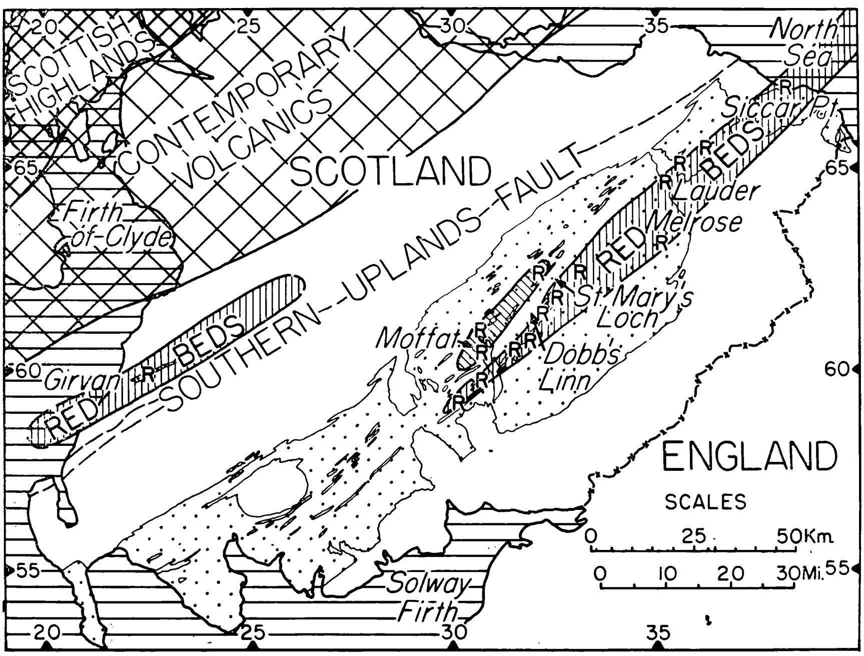

Fig. 5. Idwian, Fronian, and basal Telychian marine red beds of Scotland in their paleographic setting. R = red bed exposure (see tables 7 and 8). Areas with Idwian (*M. gregarius* Zone) marine red beds are represented by diagonal shading; areas with Fronian (*M. sedgwickii* Zone) and/or basal Telychian (*M. turriculatus* Zone) marine red beds by vertical shading; land areas crosshatched; Llandovery outcrops dotted. The marginal numbers refer to the British National Grid.

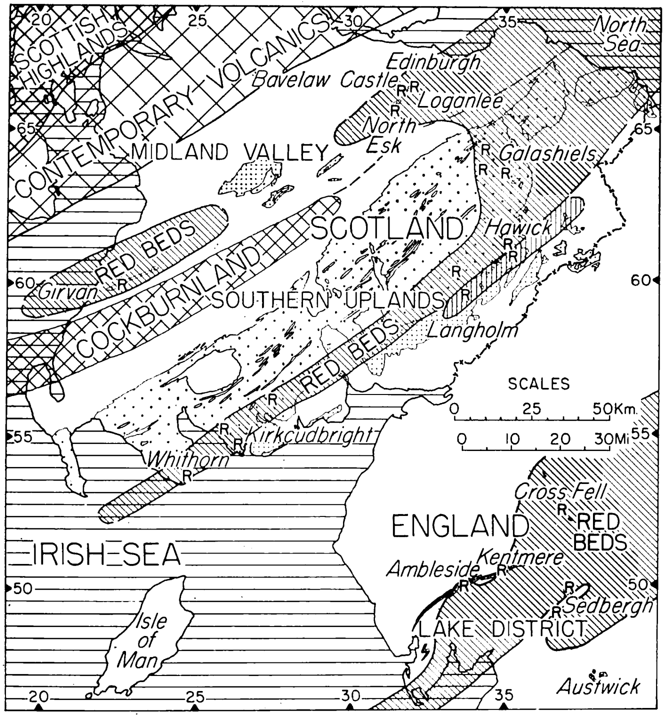

Fig. 6. Telychian and Lower Wenlock marine red beds of Scotland and northern England in their paleogeographic setting. R = red bed exposure (see tables 9, 10, 11). Areas with Telychian (later than the *M. turriculatus* Zone) marine red beds are represented by diagonal shading; areas with Lower Wenlock marine red beds by vertical shading; land areas by crosshatching; Llandovery outcrops by coarse dots; Wenlock outcrops by fine dots. The marginal numbers refer to the British National Grid.

TABLE 7

Upper Telychian red beds in northern England and eastern Ireland: all graptolitic

Locality and formation	Thickness	Reference
Swindale Beck, 1 km north-northeast of Knock, Cross Fell Inlier: Browgill Beds	42 m	Shotton, 1935, p. 661; Burgess, Rickards, and Strachan, 1970, p. 172, 176, 177
Spengill and Stockless Gill, 9 km north-northeast of Sedbergh, Howgill Fells: Browgill Beds	18 m	Marr and Nicholson, 1888, p. 705; Rickards, 1964, p. 437, 447, and 1972 personal commun.
Between Hebblethwaite Hall Gill, 4 km east-northeast of Sedbergh and Bluecaster Hill, 7 km northeast of Sedbergh: Howgill Fells: Browgill Beds	12 m	Rickards, 1973
Stockdale Beck, 3½ km east-northeast of Kentmere, Lake District: Browgill Beds	1.5 m	Marr and Nicholson, 1888, p. 678; Hutt, 1972 personal commun.
Pull Beck, 3 km southwest of Ambleside, Lake District: Browgill Beds	1 m	Hutt, 1972 personal commun.
Shore, 1½ km, southeast of Balbriggan, County Dublin: Balbriggan Formation	1 m	Rickards, Burns, and Archer, 1973, p. 308

The source of the northern England red sediments is more problematical. They may have been derived from a land area to the east of the Lake District which was covered by the same transgression as Telemark Land and the English Midlands, and which may very well have been part of a single land mass. The apparent absence of red beds at Austwick (fig. 6), to the south of the Lake District, may have been due to lower rates of deposition; the Upper Llandovery at Austwick is only about half the thickness in the Lake District (King and Wilcockson, 1934, p. 20).

D. Deposition.—We cannot support Hagemann's (1957) conclusion that the Llandovery red beds of the Oslo area must have been deposited subaerially, for they contain *Costistricklandia* or graptolitic communities. Rickards (1964, p. 447), too, reported marine faunas from red beds in the Howgill Fells. Hagemann (1957, p. 241-242) has examined the chemistry of the slates from Hadeland, north of Oslo (fig. 4). He showed that the red slates have 2.5 to 5 percent Fe in Fe_2O_3 and 0.8 to 1.2 percent Fe in FeO. The percentages for the green slates are 0.6 to 1.6 Fe in Fe_2O_3 and 2.9 to 5.3 Fe in FeO. Purple slates also occur; they are intermediate between the red and the green in the proportion of ferric to ferrous iron. The color thus depends not on the total amount of iron in the sediments but on how much is in the ferric state, a relationship that seems to be generally true for shales (Pettijohn, 1957, p. 347). Both the red and green beds are marine.

RED BEDS IN SCOTLAND

The Silurian marine red beds in the Southern Uplands and the Midland Valley of Scotland (figs. 5 and 6) occur in three distinct sedimentary associations: (1) Above condensed sequences of black graptolitic shales (the Birkhill Shales of tables 8, 9), where they are often followed by graywackes of the Gala Group; the red beds are usually mudstones, between 0.5 and 10 m in thickness, but in places the basal graywackes are also red. In this association, the red shales seldom contain graptolites. Normally the graptolites occur above or below the red shales or in thin dark interbeds. (2) As thin (2 cm to 2 m) unfossiliferous shale beds in thick sequences of graywackes (the Hawick Rocks, Gala Group, Stobs Castle Beds, and unnamed Wenlock rocks of Langholm, tables 9, 10, and 11). (3) As thicker (up to 40 m) sequences of fossiliferous red mudstones on or near the shelf margin (Penkill Fm., Maxwellston Mudstones and Lauchlan Fm. of Girvan, and Reservoir Beds and Deerhope Burn Flagstones in the Pentland Hills, tables 8 and 9).

A. Distribution.—The Scottish red beds occur both in the Midland Valley shelf sequences and in the Southern Uplands trench and oceanic sequences (figs. 5 and 6). They are limited on the seaward side by the attenuated black graptolitic shale sequences, and their continuity is otherwise broken by the thick graywacke turbidite sequences of the Southern Uplands trench which migrated southward in time (Ziegler,

Table 8

Idwian red beds in southern Scotland; all above graptolitic beds

Locality and formation	Zone	Thickness	Reference
Boar Cleuch, 5 km west-northwest of St. Mary's Loch: Birkhill Shales	above *M. gregarius*	?	Lapworth, 1878, p. 297.
Headshaw Linn and Ruttonside, 5.5 km north-northwest and 5 km northwest of Moffat: Birkhill Shales	above *M. gregarius*	1 to 9 m	Lapworth, 1878, p. 291-292; Peach and Horne, 1899, p. 138.
Duffkinnel Water, 10 km south-southwest of Moffat: Birkhill Shales	above *M. gregarius*	?	Peach and Horne, 1899, p. 150.

Table 9

Fronian and Lower Telychian red beds in southern Scotland; all graptolitic or above graptolitic beds

Locality and formation	Zone	Thickness	Reference
0.8 km southwest of Siccar Point	?*M. convolutus* to *M. crispus*	?	Peach and Horne, 1899, p. 209.
1.5 km southwest, 3 and 10 km northeast of Lauder	*M. sedgwickii* and *M. turriculatus*	?	Peach and Horne, 1899, p. 206-207.
Coldshiels Loch, 5 km southwest of Melrose	"Birkhill"	?	Peach and Horne, 1899, p. 191.
Mount Benger Burne, 5.5 km northeast of St. Mary's Loch: Birkhill Shales	*R. maximus*	?	Lapworth, 1878, p. 280-281.
Crosscleuch, Thirlstane Score and Moory Syke, 1 to 1.5 km south and southeast of St. Mary's Loch: Birkhill Shales	Above or with *M. sedgwickii* and *R. maximus*	2.4 m	Lapworth, 1878, p. 266-270, 326, pl. 13; Peach and Horne, 1899, p. 110
Black Grain, 7.5 km south-southwest of St. Mary's Loch: Birkhill Shales	*M. sedgwickii* and *R. maximus*	?	Lapworth, 1878, p. 275; Peach and Horne, 1899, p. 112.
Craigmichan Scaurs, Selcoth Burn, and Entertrona Burn, 7 and 11 km east of Moffat: Birkhill Shales	Above and with *M. sedgwickii* and *R. maximus*	2 to 7 m	Lapworth, 1878, p. 264, 326; Peach and Horne, 1899, p. 105, 116.
Garpol Water, 1.5 km southwest of Moffat: Birkhill Shales	Above *M. sedgwickii*	?	Lapworth, 1878, p. 289-291, pl. 13; Peach and Horne, 1899, p. 132.
Glenkiln Burn, 16 km south-southwest of Moffat: Birkhill Shales	Above and with *M. sedgwickii* and *R. maximus*	0.7 m	Lapworth, 1878, p. 287, 327, pl. 13.
Penwhapple Glen, 4 km east of Girvan: Penkill Formation	*M. turriculatus*	40 m	Cocks and Toghill, 1973, p. 227.
Penwhapple Glen, 4 km east of Girvan: Maxwellston Mudstones	*R. maximus*	13 m	Cocks and Toghill, 1973, p. 226.

Table 10

Telychian red beds in Scotland (probably zones of *M. crispus, M. griestoniensis* and *M. crenulata*)

Locality and formation	Zone	Community	Thickness	Reference
North Esk, Loganlee, and Bavelaw Castle: Reservoir Beds and Deerhope Burn Flagstones	?*M. crenulata* or earlier	*Clorinda*	?	Mitchell and Mykura, 1962, p. 12-15, 19.
Westa Hill and Buckholmside, Galashiels: Gala Group	*M. crispus*	graptolite	?	Peach and Horne, 1899, p. 203.
Meigle Farmhouse, 3 km west-northwest of Galashiels: Gala Group	?*M. crispus*	graptolite	?	Peach and Horne, 1899, p. 204; Toghill and Strachan, 1970, p. 513.
Thornilee and Newhall, 6 km west and 8 km northwest of Galashiels: Gala Group	?*M. crispus*	graptolite	?	Peach and Horne, 1899, p. 204-205; Toghill and Strachan, 1970, p. 513.
1 to 3 km south of Hawick: Hawick Rocks	?(beds pass laterally into Hawick Rocks of Whithorn)	no fossils	Less than 2% of 3700 m	Warren, 1964, p. 198-199, pl. 9.
10 to 40 km southwest of Hawick: Hawick Rocks	?(beds pass laterally into Hawick Rocks of Whithorn)	no fossils	?	Peach and Horne, 1899, p. 213.
Up to 20 km northeast and up to 10 km southwest and north-west of Kirkcudbright: Hawick Rocks	?(beds pass laterally into Hawick Rocks of Whithorn)	no fossils	?	Peach and Horne, 1899, p. 214; Craig and Walton, 1959, p. 212-214.
Whithorn: lower part of Hawick Rocks	?*M. griestoniensis* and ?*M. crenulata*	graptolite	?	Peach and Horne, 1899, p. 551; Rust, 1965a, p. 103-106; Rust, 1965b, p. 234-235.
Penwhapple Glen, 4 km east of Girvan: Lauchlan Formation	*M. griestoniensis*	graptolite	51 m	Cocks and Toghill, 1973, p. 229.

Table 11

Lower Wenlock red beds in southern Scotland; all graptolitic

Locality and formation	Zone	Thickness	Reference
5 to 6.5 km south of Hawick: Stobs Castle Beds	*C. murchisoni*	2% of 1400 m	Warren, 1964, p. 198-199, pl. 9.
Up to 40 km northeast of Langholm	Wenlock	?	Peach and Horne, 1899, p. 558.
Eweslees, 12 km north of Langholm	*C. murchisoni*	?	Lumsden and others, 1967, p. 13, 34, pl. 2.
Unthank, 10 km north of Langholm	*M. riccartonensis*	?	Lumsden and others, 1967, p. 13, 36, pl. 2.

1970, 1972). However, they do occur as thin interbeds in some of the graywacke units as mentioned above.

B. Age.—The earliest red beds occur above graptolitic shales containing the zone of *M. gregarius* and are therefore probably Idwian in age (table 8), whereas the latest contain the early Wenlock zone of *M. riccartonensis* (table 10). Many horizons within this relatively long interval also contain red beds (tables 9 and 10).

C. Source.—Some of the sediments of the Southern Uplands were derived from Dalradian rocks of the Scottish Highlands, but we think it unlikely that the red material came from this area. Although folded and metamorphosed prior to the Silurian, the Dalradian rocks yield abundant K/Ar dates of 450 to 400 m.y., which point to continued uplift during the Silurian Period (Dewey, McKerrow, and Moorbath, 1970; Dewey and Pankhurst, 1970). The uplift was probably accompanied by rapid erosion without prolonged weathering.

The Midland Valley to the south of the Highlands is the most likely source for the oxidized material, but direct evidence of the nature of the source is obscured by later deposits. There are, however, several indications of contemporaneous volcanism and this may have been concentrated in the Midland Valley. Kelling (1962, p. 127) found abundant andesitic detritus, derived from the northwest, in the Upper Ordovician or Lower Silurian Portpatrick Group of Wigtownshire, in the extreme western part of the Southern Uplands. Toghill (1968, p. 655) implied a volcanic origin for thin claystone bands throughout Upper Ordovician and Lower Silurian rocks at Dobb's Linn. Finally, Walton (1955, p. 355), recognized andesitic tuffs and lavas in the source of the Lower Silurian graywackes west of Galashiels. We believe that weathering and erosion of these volcanics may have produced the oxidized sediments in the Southern Uplands, and that the most likely site of this volcanism was the Midland Valley of Scotland.

The stratigraphic evidence at Girvan suggests repeated transgressions during the Llandovery (Cocks and Toghill, 1973), and red beds in this sequence occur above a Lower Telychian transgressive pulse.

D. Deposition.—All red beds of Scotland contain a graptolitic assemblage, a *Clorinda* Community, or are intimately associated with graptolitic shales or graywacke turbidites. This points to a deep water distribution associated with the Southern Uplands trench. In some cases they occur within the trench deposits themselves, but here they tend to be masked by the thick graywacke sequences most probably derived from the tectonically active areas of Cockburnland and the Scottish Highlands. Red beds are best developed in the shelf sequences adjacent to the trench and in the deeper sequences on the seaward side of the trench. We note that both Warren (1963, p. 246-247) and Rust (1965b, p. 242) were apparently influenced by the red color of sediments interbedded with graywackes in postulating an "oxidizing environment" at the site of deposition. We point out that all that is necessary is for the sediments to have been oxidized at some stage between weathering and final deposition. We feel that rapid sedimentation and burial in a reducing environment would be sufficient to maintain the original ferric oxide state.

RED BEDS IN WESTERN IRELAND

A. Distribution.—The Tonalee Formation, of northwest County Galway, extends for 30 km from Lettershanbally, south of Killary Harbour, to the shores of Lough Corrib at Ardaun and of Lough Mask at Trean (McKerrow and Campbell, 1960; Piper, 1967, p. 259). The formation consists of up to 75 m of red and purple mudstones and siltstones, with some green and gray sandstones and siltstones. Equivalent red beds may occur in the Curlew Mountains, 50 km to the northeast (Charlesworth, 1960, p. 46), but it is not clear whether they are littoral or deeper marine deposits.

B. Age.—The Tonalee Formation contains graptolites indicative of a *M. crenulata* zone age (Rickards, 1973, p. 71). It is therefore Upper Telychian in age.

C. Source.—The Silurian sediments of northwest Galway were derived from the north. During the Upper Llandovery, the sea transgressed northward over the Ordovician (Piper, 1969, p. 295) so that the feather edge of the Lower Owenduff Group (that is, time equivalents of the Tonalee Formation) just overlaps the South Mayo Trough (Dewey, 1963, p. 334). We conclude that the red material of the Tonalee Formation, which consists of small grains of hematite (Piper, 1972, p. 42), may have been derived from coastal erosion of weathered Dalradian and older rocks to the north of the South Mayo Trough.

D. Deposition.—The Tonalee Formation of Galway is part of a progressively deepening sedimentary sequence. It succeeds the Kilbride Formation, which contains *Eocoelia, Costistricklandia*, and *Clorinda* Communities, and it is followed by the graptolitic Upper Owenduff Group (Laird and McKerrow, 1970, p. 299). It contains a marginal *Clorinda* Community and thus probably accumulated on the deeper parts of the shelf (Piper, 1972, p. 13).

RED BEDS IN ESTONIA AND LATVIA

Marine red shales occur at two horizons in the Silurian of the east Baltic states, one at the base of the Juuru Stage (lower Rhuddanian) and one in the Adavere Stage (lower Telychian). The Estonian geologists have noticed, as we have, that the red beds were deposited in quiet offshore environments and correspond in time to marked transgressions of the source area (H. Nestor, R. Einasto, and M. Rubel, personal commun., 1973). The distribution of the Juuru Stage red beds in southern Estonia and Latvia is outlined by Kaljo (1970, fig. 80). The Adavere Stage red beds have been discovered only recently in boreholes on Saaremaa Island and areas to the southeast on the mainland. The Estonian geologists report that they are of *M. turriculatus* zone age (Velise Beds) and contain a probable *Clorinda* Community.

RED BEDS IN THE NORTHERN APPALACHIANS

The Smyrna Mills Formation of northeastern Maine and adjacent parts of New Brunswick contains "2-3% manganiferous ironstone and red and maroon siltstone and slate" (Pavlides and Berry, 1966, p. B54). This unit is at least 2000 m thick and spans the early Llandovery through early Ludlow time of the Silurian. There are several impersistent red horizons, and these are inferred from graptolitic evidence to range from the Lower Llandovery to a horizon about the Wenlock-Ludlow boundary. The dominant rock types are gray-green and green siltstone, graywacke and slate, and the facies is graptolitic. These rocks accumulated near the axis of the Matapedia Basin at the point where it joins the Fredericton Trough (McKerrow and Ziegler, 1971). There were volcanoes on both sides of the Matapedia Basin during this interval, and the sediments of the Smyrma Mills Formation were presumably derived from these.

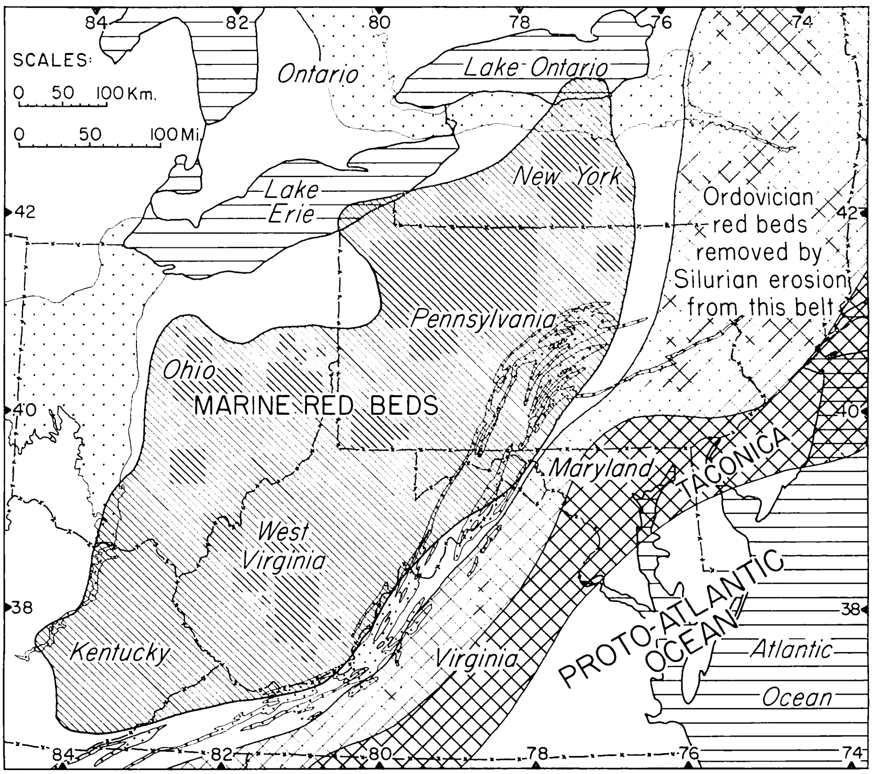

Fig. 7. Fronian and Telychian marine red beds of the Appalachian Basin in their paleographic setting, based on surface and subsurface localities (see table 12). Areas with marine red beds represented by diagonal shading; high land of Taconica heavily crosshatched; uplifted non-marine red Ordovician lightly crosshatched; Silurian outcrops dotted. The marginal numbers refer to latitude and longitude.

RED BEDS IN THE APPALACHIAN BASIN

A. Distribution.—Marine red or grayish red shales of the Clinton Group are widely distributed in the Appalachian Basin (fig. 7, table 12). These are not to be confused with the Clinton iron ores nor with the underlying red sandstones and shales of the Grimsby Formation and equivalents, which are thought to be of deltaic origin (Lumsden and

TABLE 12

Fronian and Telychian red beds in the Appalachian Basin

State	Formation	Age	Community	References
New York surface	Bear Creek and Lower Sodus	Fronian	*Eocoelia*	Gillette, 1947, p. 55, 56, 129, 141, 154, 155, 158, 160, 176, 177, 179, 180.
New York subsurface	Clinton			Fettke, 1961, p. 529, 530, 559, 580; Martens, 1945, p. 763.
Pennsylvania surface	Rose Hill	Fronian-Telychian	*Eocoelia*	Swartz, 1934, p. 89, 90, 96-98, 101, 102.
	Rose Hill			Conlin and Hoskins, 1962, p. 12.
	Rose Hill	Fronian-Telychian	*Eocoelia*	Butts, Swartz, and Willard, 1939, p. 30.
	Rose Hill			Pierce, 1966, p. 30.
	Rose Hill	Fronian-Telychian	*Eocoelia*	Knowles, 1966, p. 28.
Pennsylvania subsurface	Clinton			Fettke, 1961, p. 35, 222, 292, 487-488.
	Rose Hill			Fettke, 1960, p. 11.
Maryland surface	Rose Hill	Fronian-Telychian	*Eocoelia*	Prouty and Swartz, 1923, p. 71, 80, 85, 103.
Virginia surface	Clinton	Fronian-Telychian	*Eocoelia*	Cooper, 1939, p. 39.
West Virginia surface	Rose Hill			Woodward, 1941, p. 61, 69.
	Clinton			Price and Heck, 1939, p. 338.
West Virginia subsurface	Clinton			Martens, 1945, p. 60, 61, 68, 276, 278, 344, 345, 437, 579; Freeman, 1951, p. 9, 11.
	Rose Hill			Woodward, 1941, p. 83.
	Keefer			Woodward, 1941, p. 83.
Kentucky surface	Estill	Telychian		Rexroad and others, 1965, p. 14, 16, 17, 24.
	Noland	Fronian		Rexroad and others, 1965, p. 16.
Kentucky subsurface	Clinton			Martens, 1945, p. 737, 746, 747; Freeman, 1951, p. 9, 11.
Ohio surface	Estill	Telychian		Rexroad and others, 1965, p. 22, 24.
Ohio subsurface	Clinton			Fettke, 1961, p. 653. Martens, 1945, p. 779, 783, 787, 806, 807, 810, 814, 815, 819; Freeman, 1951, p. 9, 11.

Pelletier, 1969). The marine red or grayish red shales are characteristically interbedded with greenish gray shales (Hunter, 1970, p. 112). A total of up to a 100 m of red or grayish red shales may be present in any one section. Analysis of a typical grayish red shale showed 4.16 percent Fe_2O_3 and 3.68 percent FeO, whereas a typical greenish gray shale showed 2.36 percent Fe_2O_3 and 4.07 percent FeO (Hunter, 1970, p. 113); thus, as in Norway, the red beds have more ferric iron than the green/gray beds.

B. Age.—Deposition of the marine red or grayish red shales took place during the Late Llandovery (table 12), but the detailed correlation of many of the sections has yet to be determined. In New York State, the Bear Creek Shales and Lower Sodus Formation contain *Eocoelia hemisphaerica* and *E. intermedia*, respectively (Ziegler, unpub. data) indicating a Fronian age. However, further south, red shale deposition continued at least until late Telychian times, as *E. sulcata* is reported from red beds in Pennsylvania and Maryland. Both Fronian and Telychian red shales occur along the east flank of the Cincinnati Arch in Kentucky and Ohio, the correlation of these units being established on the basis of conodonts, but paleontologic evidence for the correlation of the subsurface Clinton beds is lacking. Presumably they are all of Late Llandovery or possibly early Wenlock age.

C. Source.—To the south and east the Clinton red and green shales grade into coarse clastics derived from Taconica (Rodgers, 1971, p. 1154), and to the west they grade into the shallow carbonate facies of the platform. These Clinton sediments were thus most probably derived from the terrestrial Queenston and Juniata red shales and sandstones to the east and south (Freeman, 1951, p. 9). These late Ordovician nonmarine clastics are the depositional counterpart of the Taconic Orogeny and prograded from the east and south across much of the Appalachian Basin (Bretsky, 1970, p. 18). During the Silurian, however, hundreds of meters of these red beds were eroded from a belt varying from 50 to 200 km wide and extending from eastern New York State to southwestern Virginia (fig. 7). Apparently the whole eastern margin of the platform was tilted up, as Silurian rocks rest on progressively older Ordovician units to the south and east. During Late Llandovery time alone, the sea transgressed approximately 300 km to the east in New York State (Ziegler and Boucot, 1970, figs. 8 and 9). We conclude that erosion of the thoroughly oxidized and presumably loosely consolidated Queenston and Juniata sediments produced the red shales of the Upper Llandovery.

D. Deposition.—The Silurian marine red beds of the Appalachian Basin apparently differ from their European counterparts in having been deposited in relatively shallow water. Where the community is known, it is always the *Eocoelia* Community. The European occurrences are associated with the *Costistricklandia* and deeper communities. Apart from depth, however, the physical characteristics of the environment may have been effectively the same in both cases. Detailed comparisons are being worked out, but our initial interpretation is that the coastal environment at this time in the broad shallow Appalachian Basin was less subject to strong tidal currents than the open shelf environments bordering the Proto-Atlantic Ocean (Ziegler, 1970). For instance, very little sand from the immediate coastal environment was carried into the *Eocoelia* Community area of the Appalachian Basin, whereas in the Welsh Borderland this community is typically developed in sandstone sequences (Ziegler, 1965, p. 271). We conclude tentatively that lack of physical, and possibly biological, reworking of the inshore sediments of the Appalachian Basin resulted in the unreduced state of the iron minerals in the relatively shallow, but fully marine environment.

PRE-SILURIAN RED BEDS

The Silurian Period is not unique in containing marine red beds. We believe that marine red beds are more common in the Silurian than in the Ordovician of the Caledonides and the Appalachians, because there were few Ordovician marine transgressions in these areas. But there is evidence of an Upper Caradocian transgression at Girvan, in southwest Scotland; south of this area, red shales are abundant in the Tappins Group (Williams, 1962, p. 41-45).

The eastward transgression of the Cambrian sea from Wales over the Welsh Borderland is associated with widespread marine red beds. In North Wales, red and purple slates occur in the Lower Cambrian of the Harlech Dome and Caernarvonshire (George, 1961, p. 16, 21, 23; Wood, 1969, p. 50, 54, 61, 62). In Caernarvonshire, they appear in the first deep marine environments after the Glog Grit (and its equivalents), which rest on the subaerial ignimbrites of the Padarn Volcanic Group (Crimes, 1970, p. 119-120). The Red Shales of the Caerfai Series in South Wales were also deposited in the deeper parts of a transgressive Lower Cambrian sequence (Crimes, 1970, p. 119; George, 1970, p. 17). In Shropshire, where the Cambrian rests unconformably on folded Precambrian, the basal Wrekin Quartzite and the Lower Comley Sandstone are followed by fossiliferous Lower Cambrian limestones, several of which are red (Pocock and others, 1938, p. 65; Greig and others, 1968, p. 96). Further east, in the Nuneaton area, a red limestone is present near the top of the Lower Cambrian Hartshill Quartzite, and the early Middle Cambrian Purley Shales are purple (Edmunds and Oakley, 1958, p. 11).

In eastern Newfoundland and coastal New England, Cambrian marine red beds occur in areas that were situated on the same side of the Proto-Atlantic Ocean as England and Wales. McCartney (1969, p. 117) records red shales and limestones in the transgressive Lower Cambrian sequences of eastern Newfoundland, and Skehan (1969, p. 798) compares these with very similar beds of the same age in eastern Massachusetts. Red and purple Lower Cambrian shales are also present in Cape Breton Island and coastal New Brunswick (North, 1971, p. 241-243).

On the other side of the Proto-Atlantic Ocean, the Canadian Shield was also transgressed during the Early Cambrian. Red or purple argillites, possibly associated with this transgression, occur in the Lower Cambrian Charney Formation of Quebec (North, 1971, p. 248), in the Mettawee Slates of the Bull Formation on the western margin of the Taconic klippe (Theokritoff, 1968, p. 15; Palmer, 1971, p. 180-181), and in the Rome and Waynesboro Formations of the Central and Southern Appalachians (Palmer, 1971, p. 193-194).

Marine red shales also occur in the Precambrian; for example, the Torridonian rocks of northwest Scotland (Williams, 1968) and the Longmyndian rocks of the Welsh Borderland (James, 1956). We believe that there would have been more examples if the iron oxides in many older beds had not been altered during metamorphism. The evidence strongly suggests that red sediments were deposited in pre-Devonian marine environments whenever a local transgression occurred over oxidized terrane.

CONCLUSIONS

Red shales and mudstones are not uncommon in marine sequences of the Early Paleozoic. They were particularly widespread during the Llandovery and early Wenlock and can be found in clastic deposits that accumulated on the Baltic and Canadian Shields and in the intervening oceanic areas. Their occurrence is correlated with four effects directly observable in the stratigraphic record: (1) transgressive pulses; (2) high rates of sedimentation; (3) quiet outer shelf and deeper marine environments, and, in the case of the Appalachian Basin, a shallow but quiet epicontinental sea; and (4) availability of a suitably oxidized source area. In addition, the amount of organic productivity can be inferred to be low in the areas of red bed accumulation. Some of the above factors are summarized in table 5.

The recent suggestion that the "red mudstones could have resulted from a slightly restricted sea . . . permitting the development of a suitable geochemical environment" (Piper, 1972, p. 43) can be rejected because seas were generally transgressive at this time which would have led to the opposite effect. Moreover, there is no suggestion in the diversity or distribution of the faunas that there was anything unusual about the geochemical environment. We conclude that the sediments are red because they were derived from oxidized source material and were buried rapidly in quiet marine environments before they could be reduced. Coastal erosion and transportation associated with storms during periods of transgression probably facilitated the direct incorporation of the oxidized sediments in the marine record.

ACKNOWLEDGMENTS

We are grateful to M. Kastner for comments and advice on the geochemistry of iron minerals. R. K. Bambach, L. R. M. Cocks, B. W. Sellwood, J. M. Hurst, G. Newall, A. J. Boucot, and R. M. Weinburg read the manuscript and made helpful suggestions. We are grateful to R. B. Rickards and J. Hutt for comments and advice on the Howgill Fells, the Lake District, and Ireland. McKerrow is indebted to the Department of the Geophysical Sciences, University of Chicago for hospitality during the preparation of this paper. The research was supported in part by NSF grants GB 17655 and GA 35073 to Ziegler.

REFERENCES

Andrew, G., 1925, The Llandovery rocks of Garth, Breconshire: Geol. Soc. London Quart. Jour., v. 81, p. 389-406.

Bassett, D. A., 1955, The Silurian rocks of the Talerddig district Montgomeryshire: Geol. Soc. London Quart. Jour., v. 3, p. 239-267.

Berner, R. A., 1971, Principles of chemical sedimentology: New York, McGraw-Hill, 240 p.

Bretsky, P. W., 1970, Upper Ordovician ecology of the central Appalachians: Yale Univ., Peabody Museum Nat. History Bull. 34, 150 p.

Burgess, I. C., Rickards, R. B., and Strachan, I., 1970, The Silurian strata of the Cross Fell area: Great Britain Geol. Survey Bull., v. 32, p. 167-182.

Butts, C., Swartz, F. M., and Willard, B., 1939, Tyrone Quadrangle: Pennsylvania Geol. Survey, 4th Ser., Atlas 96, 116 p.

Charlesworth, H. A. K., 1960, The Lower Paleozoic inlier of the Curlew Mountains Anticline: Royal Irish Acad. Proc., v. 61B, p. 37-50.

Cocks, L. R. M., 1971, Facies relationships in the European Lower Silurian, *in* Babin, C., ed., Colloque Ordovicien-Silurien, Brest, Sept. 1971: Bur. Recherches Geol. et Min., no. 73, p. 223-227.

Cocks, L. R. M., and Rickards, R. B., 1969, Five boreholes in Shropshire and the relationships of shelly and graptolite facies in the Lower Silurian: Geol. Soc. London Quart. Jour., v. 124, p. 213-238.

Cocks, L. R. M., and Toghill, P., 1973, The biostratigraphy of the Silurian rocks of the Girvan District, Scotland: Geol. Soc. London Jour., v. 129, p. 209-243.

Conlin, R. R., and Hoskins, D. M., 1962, Mifflintown quadrangle: Pennsylvania Geol. Survey, 4th Ser., Atlas 126, 46 p.

Cooper, B. N., 1939, Geology of the Draper Mountain Area, Va.: Virginia Geol. Survey, Bull. 55, 98 p.

Craig, G. Y., and Walton, E. K., 1959, Sequence and structure in the Silurian rocks of Kirkcudbrightshire: Geol. Mag., v. 96, p. 209-220.

Crimes, T. P., 1970, A facies analysis of the Cambrian of Wales: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 7, p. 113-170.

Curtis, M. L. K., 1972, The Silurian rocks of the Tortworth Inlier, Gloucestershire: Geol. Assoc. Proc., v. 83, p. 1-35.

Davies, K. A., 1933, The geology of the country between Abergwesyn (Breconshire) and Pumpsaint (Carmarthenshire): Geol. Soc. London Quart. Jour., v. 89, p. 172-200.

Dewey, J. F., 1963, The Lower Palaeozoic stratigraphy of central Murrisk, County Mayo, Ireland, and the evolution of the South Mayo Trough: Geol. Soc. London Quart. Jour., v. 119, p. 313-344.

Dewey, J. F., McKerrow, W. S., and Moorbath, S., 1970, The relationships between isotopic ages, uplift and sedimentation during Ordovician times in western Ireland: Scottish Jour. Geology, v. 6, p. 133-145.

Dewey, J. F., and Pankhurst, R. J., 1970, The evolution of the Scottish Caledonides in relation to their isotopic age pattern: Royal Soc. Edinburgh Trans., v. 68, p. 361-389.

Edmunds, F. H., and Oakley, K. P., 1958, The Central England District: British Regional Geology, 80 p.

Fettke, C. R., 1960, Jesse B. Miller No. 1 Well, Napier Township, Bedford County: Pennsylvania Geol. Survey Well-Sample Rec. 56, 43 p.

——— 1961, Well-sample descriptions in northwestern Pennsylvania and adjacent states: Pennsylvania Topog. and Geol. Survey Bull. M40, 691 p.

Freeman, L. B., 1951, Regional aspects of Silurian and Devonian subsurface stratigraphy in Kentucky: Am. Assoc. Petroleum Geologists Bull., v. 35, p. 1-61.

George, T. N., 1961, North Wales: London, Her Majesty's Stationery Office, British Regional Geology, 152 p.

——— 1970, South Wales: London, Her Majesty's Stationery Office, British Regional Geology, 152 p.

Gillette, T., 1947, The Clinton of western and central New York: New York State Mus. Bull. 341, 191 p.

Greig, D. C., Wright, J. E., Hains, B. A., and Mitchell, G. H., 1968, Geology of the country around Church Stretton, Craven Arms, Wenlock Edge and Brown Clee: Great Britain Geol. Survey Mem., Sheet 166, 379 p.

Grim, R. E., 1951, The depositional environment of red and green shale: Jour. Sed. Petrology, v. 21, p. 226-232.

Hagemann, F., 1957, On the petrography of the Silurian shales from Hadeland, Norway: Norsk geol. tidssk., v. 37, p. 229-246.

Henningsmoen, G., 1960, Cambro-Silurian deposits of the Oslo region, *in* Holtedahl, O., ed., Geology of Norway: Norske geol. undersøkelse Nr. 208, p. 130-150.

Hunter, R. E., 1970, Facies of iron sedimentation of the Clinton Group, *in* Fisher, G. W., Pettijohn, F. J., Meeb, J. C., and Weaver, K. N., eds., Studies of Appalachian Geology: Central and Southern: New York, Interscience Pub., p. 101-121.

James, J. H., 1956, The structure and stratigraphy of part of the Pre-Cambrian outcrops between Church Stretton and Linley, Shropshire: Geol. Soc. London Quart. Jour., v. 112, p. 315-335.

Jones, O. T., 1947, The geology of the Silurian rocks west and south of the Carneddau Range, Radnorshire: Geol. Soc. London Quart. Jour., v. 103, p. 1-36.

Jones, W. D. V., 1945, The Valentian succession around Llanidloes, Montgomeryshire: Geol. Soc. London Quart. Jour., v. 100, p. 309-332.

Kaljo, D., 1970, The Silurian of Estonia: Inst. Geol., Tallinn, 344 p.

Kelling, G., 1962, The petrology and sedimentation of Upper Ordovician rocks in the Rhinns of Galloway, southwest Scotland: Royal Soc. Edinburgh Trans., v. 65, p. 107-137.

Kiaer, J., 1908, Das Obersilur im Kristianiagebiete: Vidensk selsk. Skr., I Math-Naturv. Kl., 1906, B. II, 596 p.

King, W. B. R., and Wilcockson, W. H., 1934, The Lower Palaeozoic rocks of Austwick and Horton-in-Ribblesdale: Geol. Soc. London Quart. Jour., v. 90, p. 7-31.

Knowles, R. R., 1966, Geology of a portion of the Everett fifteen minute Quadrangle, Bedford County, Pennsylvania: Pennsylvania Geol. Survey Prog. Rept. 170, 90 p.

Laird, M. G., and McKerrow, W. S., 1970, The Wenlock sediments of northwest Galway, Ireland: Geol. Mag., v. 107, p. 297-317.

La Joie, J., and Chagnon, A., 1973, Origin of red beds in a Cambrian flysch sequence, Canadian Appalachians, Quebec: Sedimentology, v. 20, p. 91-103.

Lange, H., 1971, Sedimentation in the Persian Gulf: Colors in the clay fraction: Internat. Sedimentology Cong., 8th, Heidelberg 1971, Abs., p. 56-57.

Lapworth, C., 1878, The Moffat Series: Geol. Soc. London Quart. Jour., v. 34, p. 240-346.

Lapworth, H., 1900, The Silurian sequence of Rhayader: Geol. Soc. London Quart. Jour., v. 56, p. 67-137.

Lumsden, D. N., and Pelletier, B. R., 1969, Petrology of the Grimsby Sandstone (Lower Silurian) of Ontario and New York: Jour. Sed. Petrology, v. 39, p. 521-530.

Lumsden, G. I., Tulloch, W., Howells, M. F., and Davies, A., 1967, The geology of the neighbourhood of Langholm: Scotland Geol. Survey Mem., Sheet 11, 255 p.

Marr, J. E., and Nicholson, H. A., 1888, The Stockdale Shales: Geol. Soc. London Quart. Jour., v. 44, p. 654-732.

Martens, J. H. C., 1945, Well-Sample Records: West Virginia Geol. Survey, v. 17, 888 p.

McCartney, W. D., 1969, Geology of Avalon Peninsula, southeast Newfoundland, *in* Kay, Marshall, ed. North Atlantic-Geology and continental drift: Am. Assoc. Petroleum Geologists Mem. 12, p. 115-129.

McKerrow, W. S., and Campbell, C. J., 1960, The stratigraphy and structure of the Lower Palaeozoic rocks of northwest Galway: Royal Dublin Soc. Sci. Proc., ser. A, v. 1, p. 27-51.

McKerrow, W. S., and Ziegler, A. M., 1971, The Lower Silurian paleogeography of New Brunswick and adjacent areas: Jour. Geology, v. 79, p. 635-646.

Mitchell, G. H., and Mykura, W., 1962, The geology of the neighbourhood of Edinburgh: Scotland Geol. Survey Mem., 145 p.

North, F. K., 1971, The Cambrian of Canada and Alaska, *in* Holland, C. H., ed., Cambrian of the New World: London, Wiley-Interscience, p. 219-324.

Palmer, A. R., 1971, The Cambrian of the Appalachian and eastern New England regions, eastern United States, *in* Holland, C. H., ed., Cambrian of the New World: London, Wiley-Interscience, p. 169-217.

Peach, B. N., and Horne, J., 1899, The Silurian rocks of Britain, v. 1: Scotland: United Kingdom Geol. Survey Mem., 749 p.

Pavlides, L., and Berry, W. B. N., 1966, Graptolite-bearing Silurian rocks of the Houlton-Smyrma Mills area, Aroostook County, Maine: U.S. Geol. Survey Prof. Paper 550-B, p. B51-B61.

Pettijohn, F. J., 1957, Sedimentary rocks, 2d ed.: New York, Harper & Brothers, 718 p.

Phipps, C. B., and Reeve, F. A. E., 1967, Stratigraphy and geological history of the Malvern, Abberley and Ledbury Hills: Geol. Jour., v. 5, p. 339-368.

Pierce, K. L., 1966, Bedrock and surficial geology of the McConellsburg Quadrangle, Pennsylvania: Pennsylvania Geol. Survey, Atlas 109a, 111 p.

Piper, D. J. W., 1967, A new interpretation of the Llandovery sequence of North Connemara, Eire: Geol. Mag., v. 104, p. 253-267.

——— 1969, Geosyncline-margin sedimentary rocks in Silurian of West Connacht, Ireland, *in* Kay, Marshall, ed., North Atlantic—Geology and continental drift: Am. Assoc. Petroleum Geologists Mem. 12, p. 289-297.

——— 1972, Sedimentary environments and palaeogeography of the late Llandovery and earliest Wenlock of North Connemara, Ireland: Geol. Soc. London Jour., v. 128, p. 33-51.

Pocock, R. W., Whitehead, T. H., Wedd., C. B., and Robertson, T., 1938, Shrewsbury District, including the Hanwood Coalfield: Great Britain Geol. Survey Mem., sheet 152, 297 p.

Price, P. H., and Heck, E. T., 1939, Detailed County Geologic Report of Greenbriar County: West Virginia Geol. Survey, 846 p.

Prouty, W. F., and Swartz, C. K., 1923, Sections of the Rose Hill and McKenzie Formations: Maryland Geol. Survey, Silurian V., p. 53-104.

Rexroad, C. B., Branson, E. R., Smith, M. O., Summerson, C., and Boucot, A. J., 1965, The Silurian formations of east-central Kentucky and adjacent Ohio: Kentucky Geol. Survey, ser. X, Bull. 2, 34 p.

Rickards, R. B., 1964, The graptolitic mudstone and associated facies in the Silurian strata of the Howgill Fells: Geol. Mag., v. 101, p. 435-451.

——— 1973, On some highest Llandovery red beds and graptolite assemblages in Britain and Eire: Geol. Mag., v. 110, p. 70-72.

Rickards, R. B., Burns, V., and Archer, J., 1973, The Silurian sequence at Balbriggan, County Dublin: Royal Irish Acad. Proc., v. 73, sec. B, p. 303-316.

Roberts, R. O., 1929, The geology of the district around Abbey-Cwmhir, Radnorshire: Geol. Soc. London Quart. Jour., v. 85, p. 651-676.

Rodgers, John, 1971, The Taconic Orogeny: Geol. Soc. America Bull., v. 82, p. 1141-1178.

Rust, B. R., 1965a, The stratigraphy and structure of the Whithorn area of Wigtownshire, Scotland: Scottish Jour. Geology, v. 1, p. 101-133.

——— 1965b, The sedimentology and diagenesis of Silurian turbidites in south-east Wigtownshire, Scotland: Scottish Jour. Geology, v. 1, p. 231-246.

Shotton, F. W., 1935, The stratigraphy and tectonics of the Cross Fell Inlier: Geol. Soc. London Quart. Jour., v. 91, p. 639-704.

Skehan, J. W., 1969, Tectonic framework of southern New England and eastern New York, *in* Kay, Marshall, ed., North Atlantic—Geology and continental drift: Am. Assoc. Petroleum Geologists Mem. 12, p. 793-814.

Strahan, A., Cantrill, T. C., Dixon, E. E. L., Thomas, H. H., and Jones, O. T., 1914, Geology of the South Wales coalfield, Part 11, The country around Haverfordwest: Great Britain Geol. Survey Mem., sheet 228, 262 p.

Swartz, F. M., 1934, Silurian sections near Mount Union, central Pennsylvania: Geol. Soc. America Bull., v. 45, p. 81-134.

Theokritoff, G., 1968, Cambrian biogeography and biostratigraphy in New England, *in* Zen, E-an, White, W. S., Hadley, J. B., and Thompson, J. B., eds., Studies in Appalachian geology: New York, Interscience, p. 9-22.

Toghill, P., 1968, The graptolite assemblages and zones of the Birkhill Shales (Lower Silurian) at Dobb's Linn: Palaeontology, v. 11, p. 654-668.

Toghill, P., and Strachan, I., 1970, The graptolite fauna of Grieston Quarry, near Innerleithen, Peebleshire: Palaeontology, v. 13, p. 511-521.

Van Houten, F. B., 1968, Iron oxides in red beds: Geol. Soc. America Bull., v. 79, p. 399-416.

——— 1973, Origin of red beds: A review—1961-1972: Earth and Planetary Sci. Ann. Rev., v. 1, p. 39-61.

Walton, E. K., 1955, Silurian greywackes in Peebleshire: Royal Soc. Edinburgh Proc., ser. B, v. 65, p. 327-357.

Warren, P. T., 1963, The petrography, sedimentation, and provenance of the Wenlock rocks near Hawick, Roxburghshire: Edinburgh Geol. Soc. Trans., v. 19, p. 225-255.

——— 1964, The stratigraphy and structure of the Silurian (Wenlock) rocks southeast of Hawick, Roxburghshire, Scotland: Geol. Soc. London Quart. Jour., v. 120, p. 193-222.

Whittard, W. F., 1928, The stratigraphy of the Valentian rocks of Shropshire—The main outcrop: Geol. Soc. London Quart. Jour., v. 83, p. 737-759.

Williams, A., 1962, The Barr and Lower Ardmillan series (Caradoc) of the Girvan District, southwest Ayrshire, with descriptions of the Brachiopoda: Geol. Soc. London Mem. 3, 267 p.

Williams, G. E., 1968, Torridonian weathering and its bearing on Torridonian palaeoclimate and source: Scottish Jour. Geology, v. 4, p. 91-190.

Wills, L. J., and Laurie, W. H., 1938, Deep sewer trench along the Bristol road from Ashill road near the Longbridge Hotel to the city boundary at Rubery: Birmingham Nat. History Philos. Soc. Proc., v. 16, p. 175-180.

Wills, L. J., and Smith, B., 1922, The Lower Palaeozoic rocks of the Llangollen District with special reference to the tectonics: Geol. Soc. London Quart. Jour., v. 78, p. 176-226.

Wood, D. S., 1969, The base and correlation of the Cambrian rocks of North Wales, *in* Wood, A., ed., The Pre-Cambrian and Lower Palaeozoic rocks of Wales: Cardiff, University Wales Press, p. 47-66.

Wood, E. M. R., 1906, On the Tarannon Series of Tarannon: Geol. Soc. London Quart. Jour., v. 62, p. 644-701.

Woodward, H. P., 1941, Silurian system of West Virginia: West Virginia Geol. Survey, v. 14, 326 p.

Ziegler, A. M., 1965, Silurian marine communities and their environmental significance: Nature, v. 207, p. 270-272.

——— 1970, Geosynclinal development of the British Isles during the Silurian Period: Jour. Geology, v. 78, p. 445-479.

——— 1972, Some points of interest concerning the Silurian in tiers of southwest central Ireland in their geosynclinal context: Geol. Soc. London Jour., v. 128, p. 263-266.

Ziegler, A. M., and Boucot, A. J., 1970, North American Silurian animal communities, *in* Berry, W. B. N. and Boucot, A. J., eds., Correlation of the North American Silurian rocks: Geol. Soc. America Spec. Paper 102, p. 95-106.

Ziegler, A. M,. Cocks, L. R. M., and Bambach, R. K., 1968, The composition and structure of Lower Silurian marine communities: Lethaia, v. 1, p. 1-27.

Ziegler, A. M., Cocks, L. R. M., and McKerrow, W. S., 1968, The Llandovery transgression of the Welsh Borderland: Palaeontology, v. 11, p. 736-782.