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Source rock characteristics and biostratigraphy of the Lower Silurian (Telychian) organic-rich shales at Akyaka, central Taurus region, Turkey

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Abstract

The Akyaka section in the central Taurus region in the southern part of Turkey includes the organic matter and graptolite-rich black shales which were deposited under dysoxic to anoxic marine conditions in the Early Silurian. A biostratigraphical analysis, based on graptolite assemblages, indicates that the sediments studied may well be referable to the *querichi* Biozone and early Telychian, Llandovery. A total of 15 samples have been subjected to Leco and Rock-Eval pyrolysis and graptolite reflectance measurements for determination of their source rock characteristics and thermal maturity. The total organic carbon content of the graptolite-bearing shales varies from 1.75 to 3.52 wt% with an average value of 2.86 wt%. The present Rock-Eval pyrolytic yields and calculated values of hydrogen and oxygen indexes imply that the recent organic matter type is inert kerogen. The measured maximum graptolite reflectance (G_{Rmax} %) values are between 5.04% and 6.75% corresponding to thermally over maturity. This high maturity suggests a deep burial of the Lower Silurian sediments resulting from overburden rocks of Upper Paleozoic to Mesozoic Upper Cretaceous and Middle-Upper Eocene thrusts occurred in the region.

Keywords: Telychian hot shales; Source rock; Graptolite biostratigraphy; Graptolite reflection measurements; Central Taurus

1. Introduction

Determination of the stratigraphic distribution and controlling depositional factors of the worldwide source rocks indicate that more than 90% of regional hydrocarbon reserves in the world have been generated from Silurian to Oligocene-Miocene sedimentary sequences (Klemme and Ulmishek, 1991). Approximately one-third of the hydrocarbon reserves in the North Africa and Arabian plates are found in regional Silurian to Permian petroleum systems (Cole et al., 1994). The most favourable candidate source rock, identified within the Paleozoic sequence in the region is Lower Silurian "hot shale" unit (Alsharhan and Kendall, 1986; Beydoun, 1991; Mahmoud et al., 1992; Cole et al., 1994). These organic-rich shales were deposited under dysoxic to anoxic, clastic, marine conditions at the beginning of the Silurian as a result of a margin marine transgression following melting of the Gondwana ice (Husseini, 1990; Cole et al., 1994; Loydell, 1998). Rutherford et al. (1997) have demonstrated the distribution of Silurian source rock facies in Middle Eastern and northern African Gondwana based in a plate tectonic perspective. Lüning et al. (2000a) have described a regional distribution and depositional model of the Lower Silurian "hot shales" in North Africa and Arabia leading to a better understanding of the source rock potential of the basal Silurian shales. These hot shales are interpreted as

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having been deposited in paleodepressions displaying lateral discontinuities. Organic matter-rich horizons, corresponding to two anoxic phases, were deposited in the lower Llandoverian (Rhuddanian) as a lower hot shale and in the upper Llandovery and/or lower Wenlock as an upper hot shale (Lüning et al., 1999, 2000a, b). In Jordan, three lower hot shale depocenters also have been identified by Lüning et al. (2005).

The central Taurus region located in the southern Turkey was part of northern Gondwana and lay close to Egypt during the Lower Paleozoic (Keeley, 1989; Beydoun, 1991; Monod et al., 2003). In the Taurus region Silurian black shales were recognized with graptolite faunas by Özgül et al. (1973), above a basal conglomerate which was assigned to the beginning of the Silurian transgression (Özgül et al., 1973; Demirtaşlı, 1984; Dean and Monod, 1990). In southeast Anatolia source-rock potential of the Lower (Tanf Fm., Telhasan-1 well) and Middle-Upper Silurian shales (Dadaş Fm., penetrated in 12 wells, and the thickest sequence is in the Abdülaziz-1 well). These were evaluated by İztan (1991) and Bozdoğan (1992). The studies demonstrated that the Silurian shales are rich in marine algal and amorphous organic matter, indicating that they are thermally mature for hydrocarbon generation.

This paper now has two main objectives,

(1) to describe the deposition of the Lower Silurian graptolitic shales from existing outcrop data in the Akyaka section. This has a well preserved sequence in the central Taurus region, and
(2) to determine their hydrocarbon source rock characteristics and thermal maturity via Rock-Eval pyrolysis, including total organic carbon content (TOC %) and graptolite reflectance measurements.

2. Geological setting

Throughout the Paleozoic, Arabia and southern Turkey (including the Taurus Belt and southeast Anatolia), and central and norhtwest Iran evolved as a continental shelf along the long and wide northern margin of Gondwana (Beydoun, 1991). The study area located in the central Taurus region is bordered by the Kırkkavak Fault in the west and the Ecemiş Fault in the east (Fig. 1a). Fig. 1b illustrates the areal extent of the main lithostratigraphic units in the study area.

Upper Ordovician deposits were recognized in southern Turkey (Sort Tepe Fm., Dean et al., 1981). Göncüoğlu and Kozlu (2000) identified the presence of glacio-eustatic sea-level changes and the formation of periglacial deposits during the Late Ordovician/Early Silurian in the southern part of the Taurides. Several Paleozoic sections in both the Taurus Belt and the Border Folds including a glacial pavement and striations, demonstrate the former presence of an ice sheet in southern and southeastern Turkey (Monod et al., 2003). A Paleozoic sequence in the central Taurus region, from Cambrian to Early Permian, was deposited on the southern flank of the Tauridia highlands (Güvenç and Demirel, 1993). The middle to late middle Cambrian deposition starts with trilobite-bearing nodular and clayey limestones (Dean et al., 1991), indicating a deepening basin to the north of the platform and continues with reddish-greenish micaceous siltstone (Göncüoğlu and Kozlu, 2000). Late Ordovician ice-related deposits rest disconformably on siliciclastic Early Ordovician strata. Uppermost Ordovician units (the lower unit of Monod et al., 2003) consisting of coarse-grained, fining-upwards sandstones of fluvial to shallow marine origin are followed by graptolitic, black, siliceous shales which contain Middle Llandovery (zone) graptolites (Kozlu et al., 2002). Upper Silurian units consist mainly of wackestones-bearing *Orthoceras* sp. (Demirtaşlı, 1984) and gray-green shales. The Devonian formations are composed of carbonates, reefal limestones, quartz arenites and shales (Fig. 2).

3. Material and method

A total of 15 Lower Silurian black shale samples were taken from a measured stratigraphic section (Fig. 2) at Akyaka, where the best identified Lower Silurian sequences in the central Taurus region are found. Samples were analyzed by Humble Geochemical Services (USA) for total organic carbon (TOC %, wt) and Rock-Eval pyrolysis. In order to determine the source rock potential of the samples, the organic richness, the pyrolytic yields (S_1 and S_2 values), and the hydrocarbon proneness from the hydrogen index values were determined based on the method of Espitalie et al. (1985). The interpretive guidelines used here are from Peters (1986) and Peters and Cassa (1994). The results of TOC % and Rock-Eval pyrolysis are shown in Table 1.

Thermal maturity of the samples has been determined by graptolite reflectance and Tmax from pyrolysis (Fig. 4 and Table 2). Graptolite reflectance values were measured on samples that contained visible graptolites on bedding surfaces using a LEITZ MPV II microscope-photometer system (Fossil Fuels Laboratory of Dept. of Geol. Eng. of Hacettepe University). Reflectance measurements were performed on a section parallel to the bedding (Goodarzi and Norford, 1989) because graptolites show true maximum reflectance in this orientation (Goodarzi, 1984) and this maximum reflectance value is similar to that of vitrinite (Davis, 1978). A representative shale sample (AKY-08) which has a lots of graptolites was first polished and prepared parallel to the bedding using standard procedures (Mackowsky, 1982). This sample was then analyzed with SEM-EDX to determine organic matter areas by JEOL-JSM 840 A (Fig. 5).

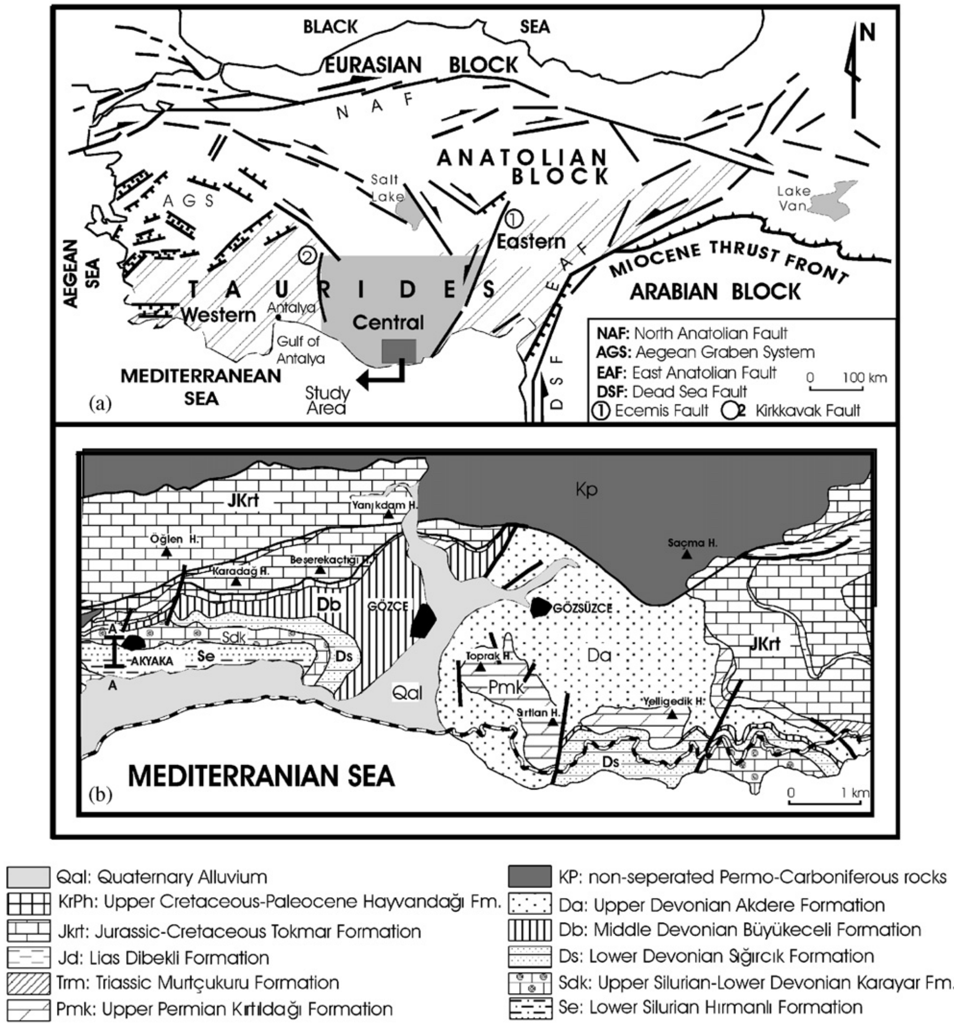

Fig. 1. (a) Location of the study area within the Taurus Belt region. (b) Map showing generalized geological units of the central Taurus region.

4. Results

4.1. Akyaka section

The Lower Silurian graptolite-bearing strata of the Hırmanlı(?) formation (Demirtaşlı, 1984) at Akyaka have only recently been sampled for determination of their source rock characteristics and graptolite taxonomy (Fig. 2). The Akyaka section is located 30 km east of Anamur (Fig. 1) (Silifke P30 sheet, between UTM coordinates 40.00.000N/5.11.750 E and 40.00.500N/5.11.750E).

The section is 96.5 m thick and consists mainly of organic-rich black shales with plenty of graptolites and with thin, silicious mudstone and interbedded cherts, nodular limestone and quartz sandstones. Based on the lithologies, the sequence is subdivided into three parts from bottom to top.

1. The lower part of the section is characterized by gray shale, limestone-sandstone lenses, graptolite and pyrite-bearing dark gray-black laminated shales which are 30 m thick. A gray chert band, 20 cm thick, overlies these shales.
2. Between 45.0 and 65.5 m there is an alternation of black shale, reddish silicious mudstone, and light gray shale that contains little organic matter together with chert bands.
3. The upper part of the section from 65.5 to 86.5 m contains nodular limestone, gray shale and sandstone alternations. The overlying deposits from 86.5 to 96.5 m are characterized by thick-bedded brownish-greenish gray quartz sandstone and cherts.

4.2. Systematic description of graptolites

4.2.1. Graptolite biostratigraphy of the Akyaka section

Fig. 3 gives the logged section and the four collecting levels AKY-06 to AKY-09. The faunas at each horizon are as follows:

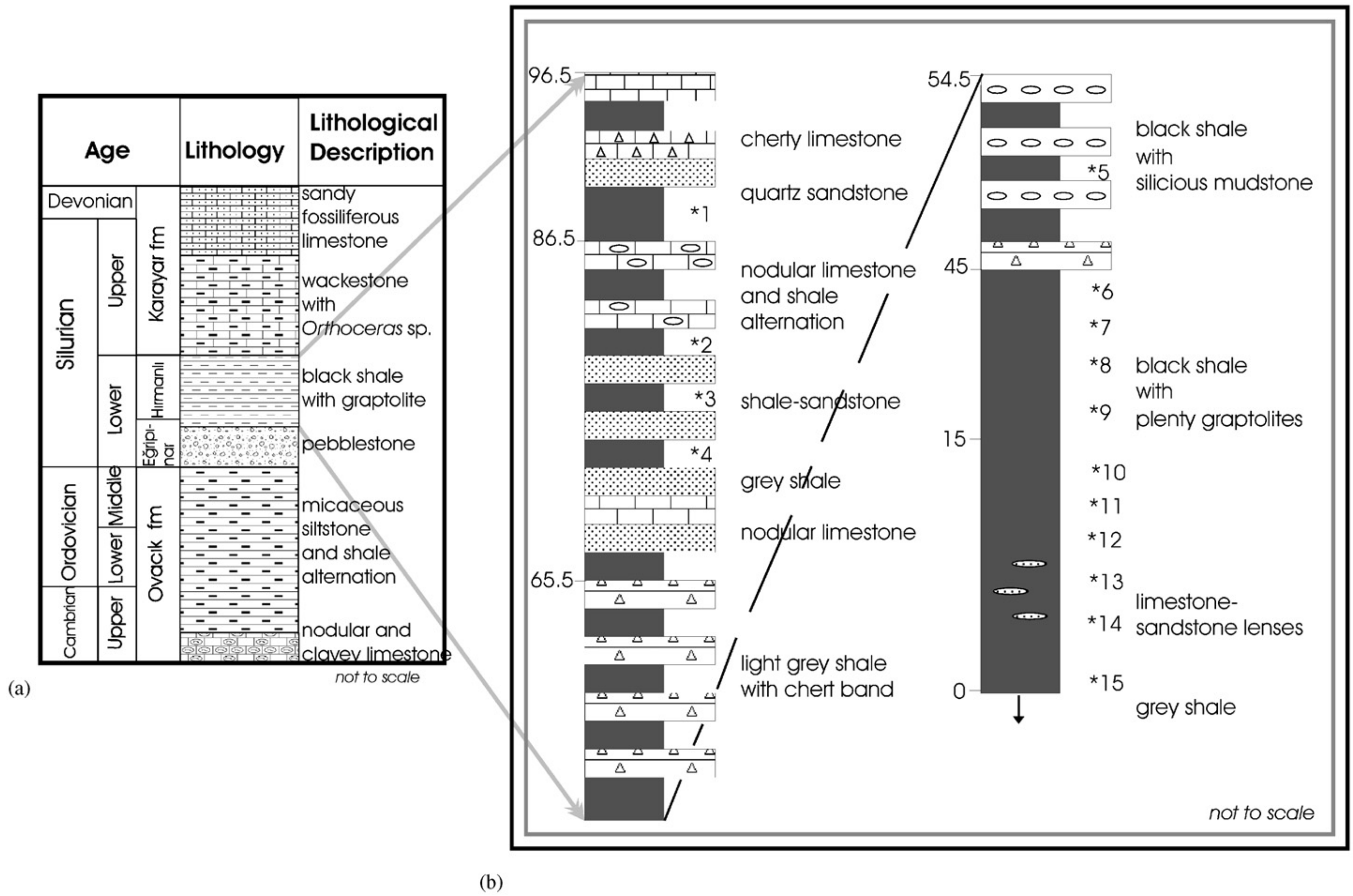

Fig. 2. (a) Summary of the stratigraphic units of the Lower Palaeozoic autochthomous units of central Taurus region (not to scale, after Demirtaşlı, 1984). (b) Lithology and sample locations in Akyaka measured section.

AKY-06	*Spirograptus* cf. *guerichi* Loydell; *Rastrites linnaei* Barrande; *Glyptograptus* aff. *fastigatus* Haberfelner; *Pristiograptus regularis* Törnquist s.l.
AKY-07	*Stimulograptus sedgwickii* (Portlock).
AKY-08	*Stimulograptus sedgwickii* (Portlock); *Glyptograptus incertus* Elles and Wood; *Parapetalolithus dignis* Koren' and Rickards; *Rastrites linnaei* Barrande; *Streptograptus*? *storchi* Loydell.
AKY-09	*Rastrites linnaei* Barrande; *Streptograptus*? *storchi* Loydell; *Glyptograptus incertus* Elles and Wood.

All four collecting levels may well be referable to the *guerichi* Biozone (approximately the equivalent of the *maximus* Biozone of some works or the lowest part of the *turriculatus* Biozone of others). It is unquestionably early Telychian, Llandovery in age. Some species need a little further comment. For example *S. sedgwickii* is not restricted to the eponymous biozone but ranges up into the top of the *guerichi* Biozone (see for example Loydell, 1993, p. 151). All the other species are typical of the *guerichi* Biozone although the assemblage as a whole is not very diverse. *P. dignis* is recorded outside Kazakhstan for the first time (see Koren' and Rickards, 1996, p. 59).

4.2.2. *Graptolite preservation in the Akyaka section*

Some of the specimens are three dimensional, partly in pyrite, partly weathered pyrite, but generally preservation is not good. There is a tectonic deformation and a clear lineation on the bedding planes of most of the specimens: this is marked on the illustrations of the specimens because it does affect measurements of dorsoventral width and thecal spacing in particular. *P. dignis, R. linnaei,* and *Pr. regularis s.l.* are relatively well preserved. The bedding surfaces also have a number of very badly preserved fragments, which could not be identified.

4.3. *Total organic carbon and rock-eval pyrolysis data*

Organic geochemical analyses were performed on a total of 15 outcrop shale samples at Akyaka section (Fig. 2). These shales are dark gray to black, fissile and exhibit fine lamination on a milimeter-scale. Moderate to good organic-rich (TOC > 1%, Peters and Cassa, 1994) intervals occur in the basal graptolitic shales (between 0 and 45 m of

Table 1
Total organic carbon (TOC %, wt) values and results of Rock-Eval pyrolysis for the sample from the Akyaka section

Sample	TOC (wt%)	S1 mgHC/g rock	S2 mgHC/g rock	S3 mgCO$_2$/g rock	S4 mgC/g rock	RC mgC/g rock	Tmax (°C)	HI mgHC/g TOC	OI mgCO$_2$/g TOC	S2/S3	PI
AKY-01	0.07	0.01	0.00	0.20	0.69	0.07	–1	0	286	0.00	
AKY-02	0.22	0.01	0.00	0.17	2.19	0.22	–1	0	77	0.00	
AKY-03	0.17	0.01	0.00	0.15	1.69	0.17	–1	0	88	0.00	
AKY-04	0.22	0.01	0.00	0.25	2.19	0.22	–1	0	114	0.00	
AKY-05	0.08	0.01	0.00	0.29	0.79	0.08	–1	0	362	0.00	
AKY-06	3.40	0.01	0.03	0.10	33.97	3.40	454	1	3	0.30	0.25
AKY-07	2.53	0.01	0.00	0.06	25.29	2.53	–1	0	2	0.00	
AKY-08	1.75	0.01	0.00	0.02	17.49	1.75	–1	0	1	0.00	
AKY-09	1.77	0.01	0.01	0.05	17.68	1.77	346	1	3	0.20	0.50
AKY-10	2.79	0.02	0.05	0.07	27.84	2.78	405	2	3	0.71	0.29
AKY-11	3.05	0.03	0.02	0.10	30.46	3.05	374	1	3	0.20	0.60
AKY-12	3.55	0.02	0.01	0.14	35.48	3.55	342	0	4	0.07	0.67
AKY-13	3.43	0.03	0.04	0.23	34.24	3.42	365	1	7	0.17	0.43
AKY-14	3.43	0.03	0.08	0.25	34.21	3.42	545	2	7	0.32	0.27
AKY-15	0.35	0.02	0.00	0.27	3.48	0.35	–1	0	77	0.00	

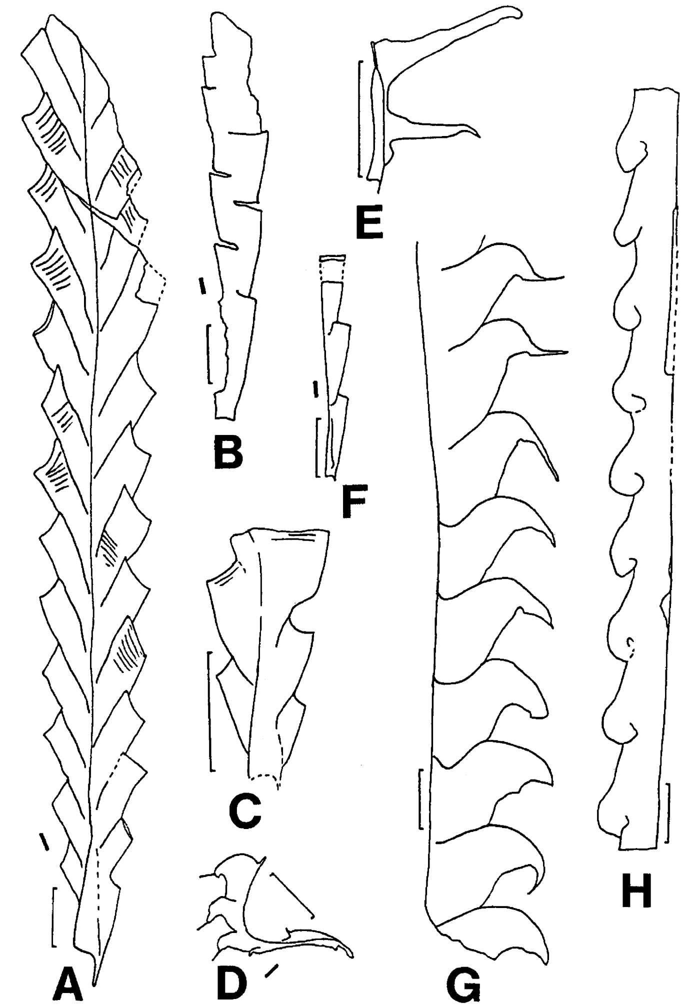

Fig. 3. Graptolites from the Akyaka section. (A) Parapetalolithus dignis Koren' and Rickards, AKY-08/1; (B) Glyptograptus aff. fastigatus Haberfelner, AKY-06/3; (C) *Glyptograptus incertus* (Elles and Wood), AKY-08/4; (D) Spirograptus cf. geurichi Loydell, AKY-06/1; (E) Rastrites linnaei Barrande, AKY-08/3; (F) Pristiograptus regularis Törnquist s.l. AKY-06/2; (G) Stimulograptus sedgwickii (Portlock), AKY-07/1; (H) Streptograptus? storchi Loydell, AKY-08/2, Scale bars 1 mm; short, heavy bar indicates tectonic stretching direction, where appropriate.

the Akyaka sequence, Fig. 2), except one sample (AKY-15) which contains TOC value of less than 0.5%. The TOC contents of these shales vary from 1.75 (AKY-08) to 3.55 (AKY-12) with an average of 2.86% (Table 1). The TOC values of five samples (AKY-01-05) obtained from upper part of the sequence (between 45 and 86 m, Fig. 2) are between 0.07 and 0.22, indicating very poor organic-richness. All samples have very low hydrogen index values (0–2 mgHC/g TOC) and pyrolysis S_1+S_2 yields (0.01–0.11 mgHC/g-rock). These results imply that the measured Tmax values ranging from 342 to 545 °C are not reliable (Table 1). A crossplot of hydrogen index against oxygen index values (Fig. 4) (Espitalie et al., 1985) illustrate that the organic matter type of the Lower Silurian black shales in the region inert carbon and is thermally spent. However, comparable Lower Silurian

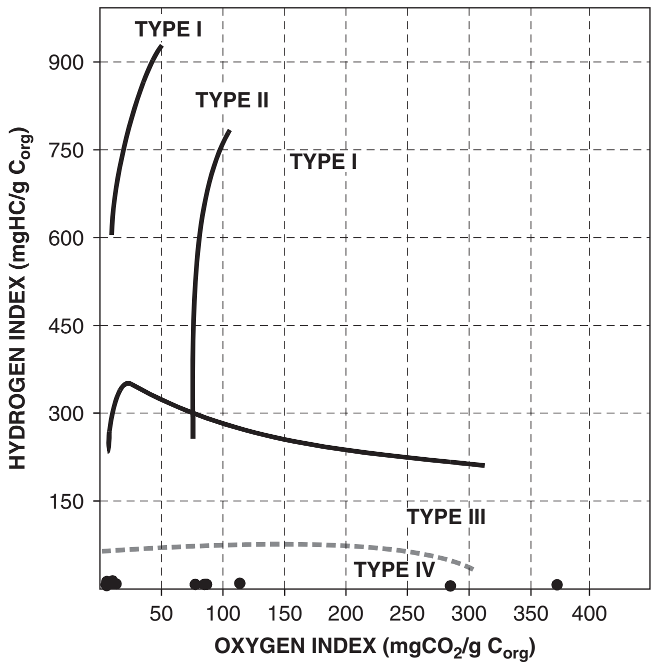

Fig. 4. Results of Rock-Eval pyrolysis for the Telychian sediments of the Akyaka section plotted on a Hydrogen Index (HI) vs. Oxygen Index (OI) kerogen classification diagram (Espitalie et al., 1985).

Table 2
Results of graptolite reflectance measurements of Akyaka-08

$\%G_{\mathrm{Rmin}}$	$\%G_{\mathrm{Rmax}}$
1.50	6.75
2.25	6.45
3.31	5.04
2.53	6.43

graptolite-bearing sediments occurring elsewhere (e.g. North Africa and Arabia) appear to possess significant potential in respect of both petroleum and/or gas generation (Alsharhan and Kendall, 1986; Husseini, 1991; Mahmoud et al., 1992; Cole et al., 1994; Lüning et al., 1999, 2000a, b, 2005).

4.4. Thermal maturity

Graptolite reflectance as an alternative to vitrinite reflectance has been evaluated by numerous studies (Kurylowicz et al., 1976; Goodarzi, 1984, 1985; Goodarzi and Norford, 1987, 1989; Bustin et al., 1989; Link et al., 1990; Cole, 1994; Suchy et al., 2002) in assessing the level of thermal maturity in Ordovician and Silurian strata because of the absence of higher-plant remains in pre-Devonian age sedimentary units. Correlation between the reflectance of pyrobitumen, vitrinite, graptolite and amorphous organic matter has been documented in Bertrand and Heroux (1987), Goodarzi and Norford (1989), Bertrand, 1990; Yang and Hesse (1993), Cole, (1994), and Geintzis et al. (1996).

In the present study, the reflectance of graptolites was used to assess the maturation level of the Lower Silurian shales. After analyzing organic matter by SEM-EDX (see Fig. 5), maximum graptolite reflectance values were measured on a representative sample (AKY-08) which contains well preserved graptolite specimens. Maximum graptolite reflectance (G_{Rmax} %) values are between 5.04% and 6.75% corresponding to thermally over maturity, while the minimum reflectance (G_{Rmin} %) values are measured as ranging from 1.50% to 2.53%. These reflectance and high illite crystallinity values that range from 0.3 to 0.4 (Varol, 2005) indicate ankizone (for minerals) and metagenesis (for organic constituents)

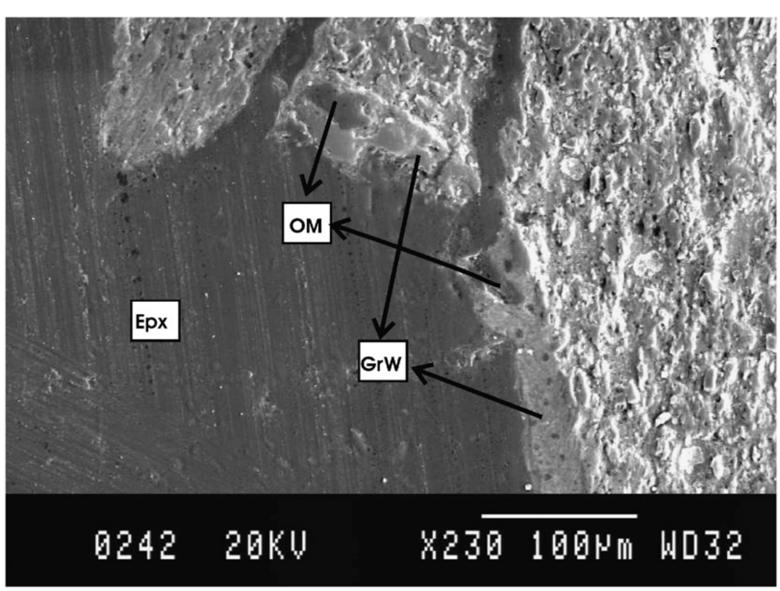

Fig. 5. SEM-EDX image of graptolites within sample Akyaka-08 (E: Epofix resin, OM: Organic matter, GrW: Graptolite shell).

paleotemperatures, generally between 200 and 350 °C (Dunoyer de Segonzac, 1970). This high thermal maturity suggests a deep burial of the Lower Silurian units resulting from overburden of the Paleozoic succession (from Middle Silurian to Lower Carboniferous). Later Upper Cretaceous and Middle-Upper Eocene thrusts occurred in the region. In southeast Anatolia, the Lower Silurian shales equivalent to the Tanf Formation of Syria, are currently thermally early mature to mature for oil generation (İztan, 1991; Bozdoğan, 1992). This significant difference between in the central Taurus region and southeast Anatolia can be attributed to regional variations in the original depth of burial.

5. Conclusions

This paper has attempted to describe source rock potential and graptolite taxonomy of the Lower Silurian black shales in the Akyaka section of the central Taurus region. These units were deposited under dysoxic to anoxic conditions at the beginning of Silurian following the late Ordovician glaciation. Although there are many geological records of Telychian-Wenlockian hot shales from the Ghadames basin, Algeria (ESR-1 well), Iraq (Akkaş-1 well) (Demaison, 1993; Tyson, 1995; Tyson, 1996), Wadi Tamrerhout (Morocco) (Lüning et al., 2000b, 2004), and Dyfed and Buttington region of Wales (Loydell and Cave, 1993), hitherto no data have been presented from Turkey. The Akyaka Telychian hot shales (central Taurus region of Turkey) contain biozones which are suitable for comparison with most of the areas where the biozone (approximately the equivalent of the maximus biozone of others) has been described. This graptolite-bearing horizon attains thicknesses about 45 m in the study area and has an organic richness exceeding 2.86% on average. However, source rock quality is poor considering that it has low pyrolytic yields (S_1+S_2) less than 2 mg HC/ g rock and 0–2 mg HC/ TOC of hydrogen index values. The high maximum graptolite reflectance, in combination with illite crystallinity values (Varol, 2005), can be explained by the greater depth of burial and higher temperatures experienced by the Lower Silurian strata in the central Taurus region.

The source potential and graptolite biozones identified may contribute to less-explored region of North Gondwana including western and eastern Taurus regions of Turkey where Silurian deposits exist.

Acknowledgments

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Appendix A. Systematic descriptions

Order Graptoloidea Lapworth, 1875

Family Glyptograptidae Mitchell, 1987

Genus *Glyptograptus* Lapworth, 1873 (emend Koren' and Rickards, 1996)

Type species: By original designation, *Diplograptus tamariscus* Nicholson, 1868 from southern Scotland.

Glyptograptus incertus (Elles and Wood, 1901)

Fig. 3C

1907 *Diplograptus (Glyptograptus) tamariscus* var *incertus* var. nov.; Elles and Wood, p. 249, pl. 30, Figs. 9a–d, text-Fig. 168a.

(A full synonymy can be found in Loydell (1992) and Koren' and Rickards (1996).)

Material: One specimen AKY-08/4 and other possible fragments.

Remarks: In dimensions, including thecal style and spacing, the best Akyaka specimen closely resembles the recent detailed description given by Koren' and Rickards (1996) of specimens from the *gregarius* and *convolutus* biozones of western Kazakhstan.

Glyptograptus aff. fastigatus Haberfelner, 1931

Fig. 3B

aff. 1931 *Glyptograptus tamariscus* mut. *Fastigatus* nov. mut.; Haberfelner, pp. 105–610, pl. 3, Figs. 17a–e.

aff. 1992 *Glyptograptus fastigatus* Haberfelner, 1931; Loydell, pp. 30–31, pl. 1, Figs. 4,5, text-Fig. 11, Figs. 2–4, 11,12, 22. (A fuller synonymy can be found in Loydell (1992).)

Material: One specimen AKY-06/3 and other fragments, none showing the biprofile view of the thecae.

Descriptions: The proximal end is quite drawn out and it is not clear whether a theca is missing or whether the apparent sicular base (Fig. 3B) has been correctly identified. The thecae are not in full profile and this may explain the odd appearance of the extreme proximal end. The thecae are clearly strongly alternating, have glyptograptid overall aspect and are spaced at 7 in 10 mm (2TRD 2.85). The dorsoventral width is about 1 mm at the level of th 3–4.

Remarks: The specimen has a slightly lower thecal spacing than given by Loydell (1992) in his redescription of well-preserved specimens from Wales and the proximal end may well be more drawn out and pointed. Haberfelner's originals have this aspect too. The dorsoventral width at the level of th 3th 4 is about correct. More material is needed of this form.

Genus *Parapetalolithus* Koren' and Rickards, 1996

Type species: By original designation *P. dignis* Koren' and Rickards, 1996, from the *guerichi* Biozone of the southern Ural Mountains, western Kazakhstan.

Parapetalolithus dignis Koren' and Rickards, 1996

Fig. 3A.

1996 *Parapetalolithus dignis* gen. et sp. nov.; Koren' and Rickards, pp. 59,61, pl. 9, Figs. 7,10, text-Figs. 11i–k

Material: A single unusually wellpreserved specimen, AKY-08/1 showing all details of thecae including growth fuselli.

Description: The rhabdosome has a length of more than 16 mm and a maximum dorsoventral width (low relief) of a little over 2 mm. Thecal spacing proximally is 10 in 10 mm, and most distally 9 in 10 mm (2TRD 2.0–2.5) and are about 0.50 mm wide, angled at 20° to the axis and with an overlap of approximately one half. The median septum is complete in obverse view but cannot be seen in reverse view: it could only begin after the second thecal pair on the reverse side. At $th1^1$ the dorsoventral width is 0.85 mm so the increase in width distally is very gradual. The sicula is almost 2 mm long.

Remarks: This species is close to *P. tenuis* but is smaller, widens more gradually and has a lower thecal spacing value. It is smaller than all other Telychian parapetalolithids. Fig. 3A is schematic at the proximal end with the proximal part of $th1^2$ removed (it is preserved as powdery, weathered pyrite) to show the sicula. *P. dignis* has not previously been recorded outside Kazakhstan.

Family Monograptidae Lapworth, 1873

Genus *Pristiograptus* Jackel, 1889

Type species: *Pristiograptus frequens* Jackel (1889) by original designation from the Silurian of Germany.

Pristiograptus regularis (Törnquist, 1899) sensu lato

Fig. 3F.

1899 *Monograptus regularis* n.sp.; Törnquist, p. 7, pl. 1 Figs. 9–14.

[Further references can be found in Hutt (1975); And discussion of the relationship of p. regularis to wandograptus rickards and jell can be found in Rickards and Jell, 2002]

Material: One good proximal end, Fig. 3F, and a few more proximal fragments.

Remarks: We have too few specimens to effect a description but the proximal end of Fig. 3F. F is clearly very close to previous descriptions of the proximal end of *P. regularis*, having the same small sicula (approximately 1 mm long), its apex just below the level of the aperture of th1, and with a thecal spacing value of about 8 in 10 mm (2TRD 2.5). The proximal end of *P. renaudi* Philippot is slightly curved rather than straight. *P. huttae* Loydell is similar but may have a higher thecal spacing.

Genus *Stimulograptus* Přibyl and Štorch 1983

Type species: *Graptolithus halli* Barrande (1850), by original designation, from the *Linnaei* Biozone, Želkovice, Bohemia.

Stimulograptus sedgwickii (Portlock, 1843)

Fig. 3G.

1843 *Graptolithus sedgwickii*—(Portlock); Portlock pp. 318–319, pl. 19, Figs. 1–3

1993 *Graptolithus sedgwickii*—(Portlock, 1843); Loydell pp. 79–81, text-Fig. 15, Figs. 3–4, 17–20. [A full synonymy is given in Loydell (1993)]

Material: Three well preserved mesial/distal fragments in three dimensions, originally pyritized but with the pyrite now altered to a dark powdery material.

Remarks: These specimens conform with earlier descriptions of the species, in particular a pair of long, robust spines have been detected on several thecae, despite this form of preservation which may hide the spine, and the dorsal thecal wall is fully retroverted and hence fully hook-shaped. The dorsoventral width exceeds 2 mm on one specimen and the thecal spacing can be as low as 7 in 10 mm. Thecal overlap is very low.

Genus *Spirograptus* Gurich, 1908

Type species. Graptolithus turriculatus Barrande (1850) subsequently designated by Bulman (1929) from the Llandovery of Bohemia

Spirograptus cf. *guerichi* Loydell, Štorch and Melchin 1993.

Fig. 3D.

Cf. 1993 *Spirograptus guerichi* sp. nov.; Loydell, Štorch and Melchin pl. 1 Figs. 1,3 5 pl. 2, Figs. 1–6, 8–10, text Figs. 3B, 6C–H. [The full history of this species is outlined in Loydell (1993, pp. 82–4)]

Material: Three specimens, one with three trochospiral coils, the others as Fig. 3D. There are also a few curved siculae on the slabs which may be referable to this form.

Remarks: We do not have quite enough material to effect certain identification. For example, we have been unable to determine the number of thecal spines on the proximal thecae. On the other hand all thecal rhabdosomal measurements are very close to the original of *S. guerichi* and the dorsoventral width of the specimen with three coils is closer to *S. guerichi* than it is to *S. turriculatus* Barrande.

Genus Streptograptus Yin, 1937

Type species: *Graptolithus plumosus* Baily (1871), pp. 22–23, subsequently designated Loydell and Chen (1991) from the Llandovery of Northern Ireland.

Streptograptus ? storchí Loydell, 1991

Fig. 3H.

Material: Several specimens, with two distal fragments such as Fig. 3H, and some more slender though exceedingly badly preserved proximal region.

Remarks: Unfortunately no thecal apertural details are available with these specimens, but it is clear that the initial prothecal position is broad, and that the free ventral wall then slopes inwards towards the next thecal apertural region. This is the case in several streptograptids but our forms seem closest to *S. storchí* especially in the distal dorsoventral width and thecal spacing which are identical (respectively 1 mm and more; and 7 thecae in 10 mm, 2TRD up to 2.8). The badly preserved proximal regions have a higher thecal count of 10–12 in 10 mm (2TRD 1.645–2.0) and dorsoventral widths as low as 0.40 mm.

Genus *Rastrites* Barrande, 1850

Type species: *R. peregrinus* Barrande (1850) subsequently designate (Hopkinson, 1869) from the Llandovery of Bohemia.

Rastrites linnaei Barrande, 1850

Fig. 3E.

1850 *Rastr. linnaei* Barr.; Barrande, pp. 65–66, pl. 4, Figs. 2,4 (non 3)

1993 *Rastrites linnaei* Barrande, 1850; Loydell, pp. 134–137, text-Figs. 23, 1–5,9; 25, 9, 10, 12, 13,26,13.

Material: The proximal end figured as Fig. 3E, and other more doubtful or less complete fragments.

Remarks: A full review of this species is given in Loydell (1993) and the well-preserved proximal end illustrated here fits his redescribed material perfectly. Other species, except perhaps *R. schauri,* seem to achieve a much greater length to th2, that is the rhabdosome widens very quickly. In *R. schauri* the sicular details are not know so a comparison with our best specimen cannot be made at present.

References

Alsharhan, A.S., Kendall, C.G.S.C., 1986. Precambrian to Jurassic rocks of Arabian Gulf and adjacent areas—their facies, depositional setting, and hydrocarbon habitat. American Association Petroleum Geologists Bulletin 70 (8), 977–1002.

Baily, W.H., 1871. Palaeontological remarks. In: Traill, W.A., Egan, F.W. (Eds.), Explanatory Memoir to Accompany Sheets 49,50 and Part of 61 of the Maps of the Geological Survey of Ireland Including the Country Around Downpatrick, and the Shores of Dundrum Bay and Strangford Lough, County of Down. Alexander Thom. Dublin and London, 71pp.

Barrande, J., 1850. Graptolites de Bôheme. Prague, pp. 1–74

Bertrand, R., 1990. Correlations among the reflectances of vitrinite, chitinozoans, graptolites and scoledonts. Organic Geochemistry 15, 565–574.

Bertrand, R., Heroux, H., 1987. Chitinozoan, graptolite and scolecodont reflectance as an alternative to vitrinite and pyrobitumen reflectance in Ordovician and Silurian strata, Anticosti Island, Quebec, Canada. American Association Petroleum Geologists Bulletin 71, 951–957.

Beydoun, Z.R., 1991. Arabian Plate Hydrocarbon Geology and Potential–A Plate tectonic Approach. American Association of Petroleum Geology Studies in Geology. No. 33. The American Association of Petroleum Geologists Tulsa, Oklahoma, USA, 77pp.

Bozdoğan, N., 1992. Lower Silurian deposition in the southeastern Anatolia. In Proceedings of the Ninth Petroleum Congress and Exhibition of Turkiye. February 17–21, 1992. Ankara, pp. 207–223.

Bulman, O.M.B., 1929. The genotypes of the genera of graptolites. Annals and Magazine of Natural History 4, 169–185.

Bustin, R.M., Link, C., Goodarzi, F., 1989. Optical properties and chemistry of graptolite periderms following laboratory simulated maturation. Organic Geochemistry 14, 355–364.

Cole, G.A., 1994. Graptolite-Chitinozoan reflectance and its relationship to other geochemical maturity indicators in the Silurian Qusaiba Shale, Saudi Arabia. Energy & Fuels 8, 1443–1459.

Cole, G.A., Abu-Ali, M.A., Aoudeh, S.M., Carrigan, W.J., Chen, H.H., Colling, E.L., Gwathney, W.J., Al-Hajji, A.A., Halpern, H.I., Jones, D.J., Al-Sharidi, S.H., Tobey, M.H., 1994. Organic geochemistry of the Paleozoic Petroleum system of Saudi Arabia. Energy & Fuels 8, 1425–1442.

Davis, A., 1978. The reflectance of coal. In: Karr, C. (Ed.), Analytical Methods for Coal and Coal Products, vol. 1. Academic Press, London, pp. 27–28.

Dean, W.T., Monod, O., Perinçek, D., 1981. Correlation of Cambrian and Ordovician rocks in southeastern Turkey. Petroleum Activities at the 100th year. Türkiye Cumhuriyeti Petrol İşleri Dergisi, Ankara 25, 269–291 (English) [pp. 292–300 (Turkish)].

Dean, W.T., Monod, O., 1990. Revised stratigraphy and relationships of Lower Paleozoic rocks. eastern Taurus Mountains, south central Turkey. Geological Magazine 127, 333–347.

Dean, W.T., Martin, F., Monod, O., Gül, M.A., Bozdoğan, N., Özgül, N., 1991. Early paleozoic evolution of the Gondwanaland margin in the western and central Taurides. In: Turgut, S. (Ed.), Tectonics and Hydrocarbon Potential of Anatolia and Surrounding Regions. Ozan Sungurlu Foundation, Ankara, pp. 262–273.

Demirtaşlı, E., 1984. Stratigraphy and tectonic of the area between Silifke and Anamur. In: Tekeli, O., Göncüoğlu, M.C. (Eds.), Geology of the Taurus Belt, 1983. Ankara, Turkey, MTA, pp. 101–141.

Dunoyer de Segonzac, G., 1970. The transformation of clay minerals during diagenesis and low grade metamorphism: a review. Sedimentology 15, 281–346.

Elles, G.L., Wood, E.M.R., 1901–18. Monograph of British Graptolites. Palaeontographical Society, Monograph Parts I–II, pp. 1–539.

Espitalie, J., Deroo, G., Marquis, F., 1985. La pyrolyse Rock Eval et ses applications. Review Institute Français Petroleum 10, 755–784.

Geintzis, T., deFreitas, T., Goodarzi, F., Melchin, M., Lenz, A., 1996. Thermal maturity of lower Paleozoic successions in Arctic Canada. American Association Petroleum Geologists Bulletin 80, 1065–1084.

Goodarzi, F., 1984. Organic petrography of graptolite fragments from Turkey. Marine and Petroleum Geology 1, 202–210.

Goodarzi, F., 1985. Dispersion of optical properties of graptolites with increased maturity in early Palaozoic organic-rich sediments. Fuel 64, 1735–1740.

Goodarzi, F., Norford, B.S., 1987. Optical properties of graptolite epiderm—a review. Bulletin of the Geological Society of Denmark 35, 141–147.

Goodarzi, F., Norford, B.S., 1989. Variation of graptolite reflectance with depth of burial. International Journal of Coal Geology 11, 127–141.

Göncüoğlu, M.C., Kozlu, H., 2000. Early Paleozoic evolution of the NW Gondwanaland Data from southern Turkey and surrounding regions. Gondwana Research 3 (3), 315–324.

Gurich, G., 1908. Leitfossilien (Kambrium bis Silur). Lief Berlin 1, 1–95.

Güvenç, T., Demirel, I.H., 1993. Permian in western Asia. Permophiles 22, 8–10.

Haberfelner, E., 1931. Graptolithen aus dem Obersilur der Karnischen Alpen. ITeil. Hochuipfel, Nordseite, Sitzungbrerichte Akademie der Wissenschaftenin Wien 140, 89–168.

Hopkinson, J., 1869. On British graptolites. Journal of the Quekett Microscopical Club 1, 151–166.

Husseini, M.I., 1990. The Cambro-Ordovician Arabian and adjoining plates-A glacioeustatic model. Journal of Petroleum Geology 13 (3), 267–287.

Husseini, M.I., 1991. Tectonic and depositional model of the Arabian and Adjoining Plates during the Silurian-Devonian. American Association Petroleum Geologists Bulletin 75 (1), 108–120.

Hutt, J.E., 1975. The Llandovery graptolites of the English Lake District Part 2. Palaeontographical Society (Monographs) London 129, 57–137.

İztan, H., 1991. Telhasan-1 kuyusunda kesilen Kaş ve Tanf formasyonlarının jeokimyasal değerlendirilmesi, TPAO Araştırma raporu no: 1991.

Jackel, O., 1889. Ueber das Alter des sogen, Deutsch. Geologischen Gesellschrafen Zeitschrift 41, 653–716.

Keeley, M.L., 1989. The Paleozoic history of the Western Desert of Egypt. Basin Research 2, 35–48.

Klemme, H.D., Ulmishek, D., 1991. Effective petroleum source rocks of the World: stratigraphic distribution and controlling depositional factors. AAPG 75 (12), 1809–1851.

Koren', T.N., Rickards, R.B., 1996. Taxonomy and evolution of Llandovery biserial graptoloids from the Southern Urals, Western Kazakhstan. Special Papers in Palaeontology 54, 1–103.

Kozlu, H., Günay, Y., Sachanski, V., 2002. Stratigraphy and graptolite biostratigraphy of the Lower Silurian succession in SE Anatolia and the Taurus Belt. Turkish Petroleum Corporation Exploration Group Report, Ankara.

Kurylowicz, L.E., Ozimic, S., McKirdy, D.M., Kantsler, A.J., Cook, A.C., 1976. Reservoir and source rock potential of the Larapinta Group, Amadeus Basin, Central Australia. Australian Petroleum Exploration Association Journal 16, 49–65.

Lapworth, C., 1873. On an improved classification of the Rhabdophora. Geological Magazine 10, 500–504, 555–560.

Lapworth, C., 1875. Descriptions of graptolites of the Arenig and Llandeilo rocks of St. Davids. Quarterly Journal of the Geological Society of London 31, 631–672.

Link, C.M., Bustin, R.M., Goodarzi, F., 1990. Petrology of graptolites and their utility as indices of thermal maturity in lower Paleozoic strata in Northern Yukon, Canada. International Journal of Coal Geology 15, 113–135.

Loydell, D.K., 1991. The biostratigraphy and formational relationships of the upper Aeronian and lower Telychian (Llandovery, Silurian) formations of western mid-Wales. Geological Journal 26, 209–244.

Loydell, D.K., Chen, X., 1991. (Graptolithina), proposed designation of Graptolithus plumosus Baily, 1871 as the type species. Bulletin of Zoological Nomenclature 48, 236–237.

Loydell, D.K., 1992. Upper Aeronian and Lower Telychian (Llandovery) graptolites from Western mid-Wales. Part 1. The Palaeontographical Society, (Monograph) London, pp. 1–55.

Loydell, D.K., 1993. Upper aeronian and Lower telychian (Llandovery) graptolites from Western mid-Wales. Monograph of the Palaeontographical Society 147, 55–180.

Loydell, D.K., Cave, R., 1993. The Telychian (Upper Llandovery) stratigraphy of Buttington Brick Pit, Wales. Newsletters on Stratigraphy 29 (2), 91–103.

Loydell, D.K., 1998. Early Silurian sea-level changes. Geological Magazine 135 (4), 447–471.

Lüning, S., Craig, J., Fitches, B., Mayouf, J., Busrewil, A., El Dieb, M., Gammudi, A., Loydell, D.K., McIlroy, D., 1999. Re-evaluation of the petroleum potential of the Kufra Basin (SE Libya, NE Chad): does the source rock barrier fall? Marine and Petroleum Geology 16 (7), 693–718.

Lüning, S., Craig, J., Loydell, D.K., Storch, P., Fitches, W.R., 2000a. Lowermost Silurian 'Hot Shales' in North Africa and Arabia: regional distribution and depositional Model. Earth Science Reviews 49, 121–200.

Lüning, S., Loydell, D.K., Sutcliffe, O., Salem, A.A., Zarella, E., Craig, J., Harper, D.A.T., 2000b. Silurian-lower devonian black shales in Morocco: which are the organically richest horizons. Journal of Petroleum Geology 23 (3), 293–311.

Lüning, S., Wendt, J., Belka, Z., Kaufmann, B., 2004. Temporal-spatial reconstruction of the Early Frasnian (Late Devonian) anoxia in NW Africa: new field data from the Ahnet Basin (Algeria). Sedimentary Geology 163 (3–4), 237–264.

Lüning, S., Shahin, Y.M., Loydell, D.K., Al-Rabi, H.T., Masri, A., Tarawneh, B., Kolonic, S., 2005. Anatomy of a world-class source rock. Distribution and depositional model of Silurian organic rich shales in Jordan and implications for hydrocarbon potential. American Association Petroleum Geologists Bulletin 89 (10), 1397–1427.

Mackowsky, M.-T., 1982. Methods and tools of examination. In: Stach, E., et al. (Eds.), Stach's Textbook of Coal Petrology. Gebruder Borntraeger, Berlin, pp. 295–299.

Mahmoud, M.D., Vaslet, D., Husseini, M.I., 1992. The lower Silurian Qalibah Formation of Saudi Arabia—an important hydrocarbon source rock. American Association Petroleum Geologists Bulletin 76 (10), 1491–1506.

Mitchell, C.E., 1987. Evolution and Plylogenetic Classification of the Diplograptacea. Palaeontology 30, 353–405.

Monod, O., Kozlu, H., Ghienne, J.F., Dean, W.T., Günay, Y., Herisse, A.L., Paris, F., Roberdet, M., 2003. Late Ordovician glaciation in southern Turkey. Terra Nova 15 (4), 249–257.

Nicholson, H.A., 1868. On the graptolites of the Coniston Flags; with notes on the British species of the genus graptolites. Quarterly Journal of the Geological Society, London 24, 521–545.

Özgül, N., Metin, S., Erdoğan, B., Göger, E., Bingöl, O., 1973. Cambrian-Tertiary rocks of the Tufanbeyli region, eastern Taurus. Bulletin of the Geological Society of Turkey 16, 82–100 (in Turkish).

Peters, K.E., 1986. Guidelines for evaluating petroleum source rocks using programmed pyrolysis. American Association Petroleum Geologists Bulletin 70, 318–329.

Peters, K.E., Cassa, M.R., 1994. Applied source rock geochemistry. In: Magoon, L.B., Dow, W.G. (Eds.), The Petroleum System—from source to trap. The American Association of Petroleum Geologists, Memoir 60, pp. 93–120.

Portlock, J.E., 1843. Report on the geology of the county of Londonderry and parts of Tyrone and Fermanagh. Dublin, 1–784.

Rickards, R.B., Jell, J.S., 2002. New graptolite faunas from the llandovery Lower silurian of the graveyard creek subprovince, Broken river region, Queensland, Australia. Proceedings of the Geologists' Association 113, 111–120.

Rutherford, E., Walker, H., Yücel, F., 1997. Distribution of Silurian source rock facies in middle eastern and northern African Gondwana: a plate tectonic perspective. In: Göncüoğlu, M.C., Derman, A.S., (Eds.), Early Paleozoic evolution of NW Gondwana, vol. 3. Turkish Association of Petroleum Geology Special Publication, pp. 158–164.

Suchy, V., Sykorova, I., Stejskal, M., Safanda, J., Machovic, V., Novotna, M., 2002. Dispersed organic matter from Silurian shales of the Barrandian Basin, Czech Republic: optical properties, chemical composition and thermal maturity. International Journal of Coal Geology 53, 1–25.

Törnquist, S.L., 1899. Researches into the Monograptidae of the Scanian Rastrites Beds. Lunds Universitets Arsskrifter 26, 1–33.

Tyson, R.V., 1995. Sedimentary Organic Matter. Organic Facies and Palynofacies. Chapman & Hall, London, 615pp.

Tyson, R.V., 1996. Sequence-stratigraphical interpretation of organic facies variations in marine siliciclastic systems. General principle and application to the onshore Kimmeridge Clay Formation, UK.

In: Hesselbo, S.P., Parkinson, D.N. (Eds.), Sequence Stratigraphy in British Geology, vol. 103. Geological Society of London, Special Publication, pp. 75–96.

Varol, N.Ö., 2005. Batı-Orta Toroslar Bölgesindeki Paleozoyik Birimlerin Hidrokarbon Potansiyelinin Araştırılması. Hacettepe Üniversitesi, Fen Bilimleri Enst. Doktora Tezi, 2005D 2781, 175pp.

Yang, C., Hesse, R., 1993. Diagenesis and anchimetamorphism in an overthrust belt, external domain of the Taconian Orogen, southern Canadian Appalachians-II. Paleogeothermal gradients derived from maturation of different types of organic matter. Organic Geochemistry 20 (3), 381–403.

Yin, T.H., 1937. Brief description of the Ordovician and Silurian fossils from Shihtien. Bulletin of the Geological Society of China 16, 281–302.

Further reading

Bassler, R., 1915. Bibliographic index of American Ordovician and Silurian fossils. Bulletin of the United States National Museum 92, 1–718.

Bronn, H.G., 1835. Lethaea geognostica, 1–544, Stuttgart.

Carruthers, W., 1868. Graptolites: their structure and position. Intellectual Observer 11, 283–292, 365–374.

Chopey-Jones, A., Williams, M., Zalasiewicz, J., 2003. Biostratigraphy, palaeobiogeography and morphology of the Llandovery (Silurian) graptolites *Campograptus lobiferus* (McCoy) and *Campograptus harpago* (Törnquist). Scottish Journal of Geology 39, 71–85.

Davies, K.A., 1929. Notes on the graptolite faunas of the Upper Ordovician and Lower Silurian. Geological Magazine 66, 1–27.

Demaison, G., 1973. Contributions of geochemistry to explorations strategy. In: Bordenave, M.L. (Ed.), Applied Petroleum Geochemistry. Edition Technip, Paris, pp. 489–503.

Hundt, R., 1942. Beiträge zur Kenntris des Mitteldeutschen Graptolithenmeeres. Beiträge Geologischen Thüringen 6, 205–231.

Hutt, J.E., 1974. The Llandovery graptolites of the English Lake District Part 1. Palaeontographical Society (Monograph) London 128, 1–56.

Jones, W.D.V., Rickards, R.B., 1967. *Diplograptus penna* Hopkinson 1869 and its bearing on vesicular structures. Paläontologische Zeitschrift 41, 173–185.

Lapworth, C., 1876. On Scottish Monograptidae. Geological Magazine 3 (2), 308–321, 350–360, 499–507, 541–552.

Lapworth, C., 1877. The graptolites of County Down. Belfast Naturalists Field Club, 125–144.

Legrand, P., 1987. Modo de desarollo del Suborden Diplograptina (Graptolitina) en el Ordovicio Superior y en Silurico. Implicaciones taxonomicas [Mode of development of the Suborder Diplograptina in the Upper Ordovician and Silurian Taxonomic implications]. Revista Espanola de Paleontologia 2, 59–64.

Loydell, D.K., Štorch, P., Melchin, M., 1993. *Spirograptus turriculatus* and related *Llandovery* graptolites. Palaeontology 36, 909–926.

McCoy, F., 1850. On some new genera and species of Silurian Radiata in the collection of the University of Cambridge. Annals and Magazine of Natural History 6, 270–290.

Nicholson, H.A., 1869. On some new species of graptolites. Annals and Magazine of Natural History 4, 231–242.

Packham, G.H., 1962. Some Diplograptids from the British Lower Silurian. Palaeontology 5, 498–526.

Perner, J., 1895. Études sur les Graptolites de Bohême pt II. Prague.

Perner, J., 1897. Studie, o ™eských graptolitech. Rozpravy Ceske Akademie Vedy Slovesn, Umeni 2, 3–41.

Přibyl, A., Storch, P., 1983. 1 subgen. n. (Graptolites) from the lower Silurian of Bohemia. Vestnik ústředního ústavu Geologického 58, 221–226.

Rickards, R.B., 1988. Graptolite faunas at the base of the Silurian. Bulletin of the British Museum Natural History 43, 345–349.