Source rock characteristics of the Early Cretaceous Garau and Gadvan formations in the western Zagros Basin–southwest Iran

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Received: 3 November 2016 / Accepted: 29 May 2017 / Published online: 15 June 2017
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Abstract Cretaceous source succession in the Zagros Basin comprises the Garau, Gadvan, and Kazhdumi formations, which have probably generated most of the oil and associated gas in the region. In the following study, the generation potential as well as maturity, molecular, and isotopic characteristics of the Early Cretaceous source rocks (Garau and Gadvan formations) in southwest Iran were investigated. One hundred and forty core and cutting samples of Early Cretaceous sediments were obtained from 24 wells in 12 oil fields from the northern Dezful Embayment and Abadan plain. Geochemical measurements such as Rock–Eval pyrolysis, vitrinite reflectance, GC, GC–MS, and isotopic studies were conducted on selected samples. The results have shown that the Gadvan Formation, with an average TOC of 0.65 wt% and HI values of 122 mgHC/g TOC, can be classified as poor source rock, while the Garau Formation, with TOC and HI values of up to 5.72 wt% and 413 mgHC/g TOC, respectively, can be considered as having good to excellent source potential. Kerogen in the Gadvan Formation belongs to Type III/II, while kerogen in the Garau Formation belongs to Type II. Samples from the Gadvan Formation are at the beginning of oil generation, while the current maturity of the Garau samples is already in the peak oil generation stage. Maturity in the studied samples increases eastward toward the Dezful Embayment. GC, GC–MS and isotopic values for the Gadvan Formation

indicate high land plant contribution, low maturity, and oxic to sub-oxic depositional environment of the organic matter. In contrast, the Garau Formation shows an advanced level of maturity and marine depositional environment. Considering the results of this study, the Garau Formation, with excellent production potential and a high level of maturity, can be regarded as a source of a huge amount of oil and gas in the region.

Keywords Source rock · Production potential · Early Cretaceous · Garau Formation · Gadvan Formation · Zagros Basin

Introduction

The Khami and Bangestan Groups are the main Cretaceous oil producers in southwestern Iran. Among the Cretaceous succession, the Kazhdumi, Gadvan and Garau formations have source rock characteristics and contributed to the generation of most of the oil and associated gas reserves already discovered. The Albian Kazhdumi Formation has been investigated in a number of previous studies (Bordenave and Burwood 1990; Bordenave and Huc 1995; Rabbani and Bagheri Tirtashi 2010; Alizadeh et al. 2012; Mashhadi et al. 2014; Mashhadi and Rabbani 2015). Early Cretaceous source intervals in southern Iran comprise the Gadvan and Garau formations, which are the main subject of this study. There are some previous studies on the Gadvan and Garau formations (or their time equivalent) in the Zagros Basin (Abeed et al. 2011; Rabbani et al. 2013), but all of them have been done outside of the studied area.

The purpose of present study is to investigate the potential source rock characteristics of the Early Cretaceous succession in the oilfields of southwestern Iran. In

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order to characterize the quantity, quality, and maturity of organic matter in the studied intervals, Rock–Eval pyrolysis and vitrinite reflectance were conducted, and additional data, such as GC, GC–MS and isotope analysis, were used to interpret the depositional environment and oil–source correlation.

Geological setting

The available data suggest that the central Iranian block was part of the Arabian Platform and belonged to the Gondwana supercontinent during the Precambrian and early Paleozoic (Stocklin 1974). The breakup between the Arabian platform and the Central Iranian block at the end of the Triassic caused the formation of the Neo-Tethys Ocean, which expanded during the Jurassic and the Early Cretaceous as a result of the seafloor spreading (Stocklin 1974). The northeast margin of the Arabian platform was passive, with the seafloor spreading during the end of the Triassic to end of the Middle Cretaceous period. During the same period, deep marine sediments, i.e., radiolarite or micritic limestone, were deposited at the northeast edge of the Arabian platform (Muris 1980). After the collision of the Arabian and Eurasian plates (including the Iranian block), the Neo-Tethys Ocean shrank as a result of a complex succession of subductions (Sepehr and Cosgrove 2004). This tectonic change caused the area to become active, and compressional tectonic events occurred from the Cenomanian.

The Dezful Embayment, which belongs geologically to the northern part of the Arabian plate is a tectonic feature at the southwestern edge of the Zagros Basin (Fig. 1) and contains Iran's major oil fields. The Dezful Embayment is bounded by three main tectonic elements, namely the E–W trending flexure zone (the Balaroud fault) and a “mountain front” flexure with a NW–SE trend in the northern part. To the east and southeast, the Dezful Embayment is bounded by a complex zone of faults and flexures having a N–S trend (Kazerun–Qatar fault) (Falcon 1967; Motiei 1995; Alavi 2007).

The Abadan Plain is a structural unit limited to the NE by the Susangerd–Ab-e Teymur–Mansuri Zagros trend, to the south by the Persian Gulf, and to the west by the Iran–Iraq border (Fig. 1). The generally N–S trending pre-Zagros anticlines of the Abadan Plain are not exposed in outcrop, but occur in the subsurface. The Abadan Plain was part of the Mesopotamian Depression during the Jurassic and Early Cretaceous (Jassim and Goff 2006; Abeed et al. 2011; Aqrabi et al. 2010).

A global sea-level rise followed the end of Jurassic regression during the Valanginian. As the sea-level rose, shallow-water limestone was widely deposited on the

platform area during the Early Cretaceous, i.e., southwest Lurestan, southern Iraq, the Abadan Plain, and the wide Fars area. The Early Cretaceous morphology of the sedimentary basin was formed after the deposition of the Upper Jurassic evaporites in the Gotnia Formation.

Subsequent to the deposition of these evaporites, the southern part of Khuzestan was covered by a deeper water depression that extended in the Lurestan. In this depression, sedimentation of fine carbonate mud, together with organic matter, prevailed (Fig. 2). Euxinic conditions favorable for the preservation of these organic-rich sediments were also present, making way for the development of a suitable source rock (James and Wynd 1965).

The Garau Formation consists of five units in the Abadan plain area. The bottom unit consists of dark gray to black carbonaceous shale and dark argillaceous pyritic limestone (James and Wynd 1965). Overlying this is dark gray limestone with carbonaceous shale. Above this is gray to brown shale, and above that is limestone with black nodules. The upper part of the formation is alternating gray shale with shaley limestone, and glauconitic sandy limestone and sandy marls in the uppermost part. Almost all of the Garau Formation is considered to have been deposited under a low-energy anoxic environment, and it has excellent source rock potential, mostly in the lower part. The age of the Garau Formation ranges from Valanginian to Coniacian (Fig. 2). Limestone sequences of the Sula'iy and Yamama formations in Saudi Arabia/Iraq, the Minagish Formation in Kuwait are the time equivalents of the Garau Formation (James and Wynd 1965; Aqrabi et al. 2010).

The Gadvan Formation (Fig. 2) was deposited during the Barremian in generally shallow oxic environment (James and Wynd 1965). However, the environment remained dis-oxic in the Lurestan and S–W Dezful Embayment (Bordenave and Huc 1995). In the Abadan Plain and in most of the Dezful Embayment, the Gadvan Formation is dominated by brownish-yellow marl and argillaceous limestone (Kent et al. 1951; Fakour et al. 2010).

Method and materials

During this study, 140 core and cutting samples from Early Cretaceous sediments were obtained from 24 wells in 12 oil fields from northern Dezful Embayment and Abadan Plain (locations are shown in Fig. 1). The samples were selected from the Gadvan (Barremian) and Garau (Early Cretaceous) formations using gamma ray logs and binocular microscopes to avoid caving and contamination (Bordenave and Huc 1995).

The first step in the geochemical study of petroleum systems in an area is to characterize the quantity, quality, and maturity of the source rocks. The most widely used method to identify the generation potential of source rock is Rock-Eval pyrolysis (Espitalié et al. 1977). After some treatment to remove synthetic contamination such as mica, iron junk, nut shell, and drilling mud additives, samples were ground and homogenized.

Twenty-eight samples were selected for measuring vitrinite reflectance according to the Rock-Eval pyrolysis results. Reflectance was measured using Zeiss Axioplan II

Fig. 2 Stratigraphic chart of the studied area in southwest Iran. The main sources are indicated by *two stars* and the marginal ones by *one star*. After Bordenave and Hegre (2010)

Table 1 Rock–Eval pyrolysis result of the studied samples

Field name	Formation	Depth (m)	Sample type	TOC (wt%)	S1 (mg HC/g rock)	S2 (mg HC/g rock)	S3 (mg HC/g rock)	$T_{\max}$ (°C)	HI (mg HC/g TOC)	OI	PI
Arvand	Gadvan	3650	Cutting	0.33	0.11	0.23	1.06	431	69	325	0.32
Arvand	Gadvan	3680	Cutting	0.24	0.04	0.14	0.6	431	58	247	0.24
Arvand	Gadvan	3710	Cutting	0.54	0.14	0.58	1.72	437	107	318	0.2
Arvand	Gadvan	3820	Cutting	0.63	0.14	0.46	1.9	435	74	301	0.23
Azadegan	Gadvan	3725	Cutting	1.31	8.53	6.48	0.9	434	495	69	0.57
Azadegan	Gadvan	3755	Cutting	1.84	8.78	3.6	0.81	431	196	44	0.71
Azadegan	Gadvan	3895	Cutting	1.39	3.16	3.14	0.93	429	226	67	0.5
Azadegan	Gadvan	3915	Cutting	1.66	5.17	4.97	0.92	432	299	56	0.51
Azadegan	Gadvan	4055	Cutting	2.54	13.19	6.6	1.17	430	260	46	0.67
Azadegan	Gadvan	4085	Cutting	2.18	9.39	5.95	0.7	437	273	32	0.61
Azadegan	Gadvan	3562	Core	0.86	0.4	1.23	1.52	434	143	177	0.25
Azadegan	Gadvan	3790	Core	0.9	0.36	1.05	2	433	117	222	0.26
Azadegan	Gadvan	3855	Core	0.87	0.4	0.62	2.39	429	71	275	0.4
Azadegan	Gadvan	3930	Core	0.91	0.37	0.81	2.32	432	89	255	0.31
Azadegan	Gadvan	3980	Core	0.43	0.21	0.42	1.95	429	98	453	0.33
Azadegan	Gadvan	3780	Cutting	1.57	1.03	3.19	2.83	434	203	180	0.24
Azadegan	Gadvan	3860	Cutting	0.68	0.29	0.38	2	431	56	294	0.44
Azadegan	Gadvan	3930	Cutting	0.66	0.27	0.47	2.02	429	71	306	0.37
Azadegan	Gadvan	3820	Cutting	0.63	0.21	1.29	0.84	429	205	133	0.14
Azadegan	Gadvan	3842	Cutting	0.48	0.18	0.52	1.84	431	108	383	0.25
Azadegan	Gadvan	3890	Cutting	0.59	0.13	1.07	0.72	432	181	122	0.11
Azadegan	Gadvan	3950	Cutting	0.6	0.28	0.63	1.62	428	105	270	0.3
Azadegan	Gadvan	3725	Core	0.43	0.06	0.22	0.96	432	51	223	0.2
Azadegan	Gadvan	3855	Core	0.61	0.13	0.5	1.99	431	82	326	0.21
Azadegan	Gadvan	3900	Core	0.44	0.1	0.35	2.17	433	80	493	0.22
Ahwaz	Gadvan	3690	Core	0.62	0.2	0.52	3.31	430	84	534	0.27
Ahwaz	Gadvan	3750	Core	1.35	0.32	2	2.12	440	148	157	0.14
Ahwaz	Gadvan	3770	Core	0.73	0.23	0.67	2.5	434	92	342	0.25
Darquain	Gadvan	3814	Cutting	0.43	0.1	0.38	0.51	436	88	119	0.22
Darquain	Gadvan	3848	Cutting	0.45	0.08	0.32	0.48	438	71	107	0.2
Darquain	Gadvan	3887	Cutting	0.29	0.04	0.15	0.55	438	52	190	0.21
Darquain	Gadvan	3915	Cutting	0.35	0.07	0.25	0.48	437	71	137	0.23
Darquain	Gadvan	3933	Cutting	0.38	0.09	0.29	0.65	436	76	171	0.23
Darquain	Gadvan	3966	Cutting	0.56	0.14	0.49	0.73	441	88	130	0.22
Darquain	Gadvan	4018	Cutting	0.38	0.4	0.45	0.68	433	118	179	0.47
Darquain	Gadvan	4079	Cutting	0.32	0.11	0.26	0.58	437	81	181	0.29
Darquain	Gadvan	3955	Cutting	0.79	0.6	0.81	1.4	434	103	177	0.43
Darquain	Gadvan	4205	Cutting	1.92	4.52	6.8	0.76	435	355	40	0.4
Darquain	Gadvan	3621	Core	0.28	0.18	0.66	0.59	430	236	211	0.21
Darquain	Gadvan	3650	Core	0.22	0.21	0.46	0.56	431	209	255	0.31
Hendijan	Gadvan	3435	Cutting	1.6	0.15	2.68	2.14	431	168	134	0.05
Hendijan	Gadvan	3510	Cutting	0.61	0.04	0.59	0.83	429	97	136	0.06
Hosseiniéh	Gadvan	3750	Cutting	0.37	0.06	0.26	1	437	70	270	0.19
Hosseiniéh	Gadvan	3790	Cutting	0.46	0.1	0.18	1.06	434	40	229	0.35
Hosseiniéh	Gadvan	3820	Cutting	0.56	0.08	0.25	2.43	433	45	432	0.23
Hosseiniéh	Gadvan	3840	Cutting	0.26	0.05	0.13	0.94	430	48	360	0.29
Hosseiniéh	Gadvan	3865	Cutting	1.32	0.72	3.73	0.53	436	283	40	0.16

Table 1 continued

Field name	Formation	Depth (m)	Sample type	TOC (wt%)	S1 (mg HC/g rock)	S2 (mg HC/g rock)	S3 (mg HC/g rock)	$T_{\max}$ (°C)	HI (mg HC/g TOC)	OI	PI
Hosseinih	Gadvan	4010	Cutting	0.46	0.15	0.31	2.44	431	67	528	0.32
Hosseinih	Gadvan	4130	Cutting	0.74	0.17	0.37	2.54	428	49	341	0.31
Hosseinih	Gadvan	3910	Cutting	0.92	0.94	1.46	2.27	431	159	247	0.39
Hosseinih	Gadvan	3931	Cutting	1.26	1.44	1.74	2.42	432	138	192	0.45
Juffair	Gadvan	4200	Core	0.64	0.3	1.06	0.9	429	165	139	0.22
Juffair	Gadvan	4285	Core	0.72	0.14	1.26	0.58	436	175	81	0.1
Juffair	Gadvan	4320	Core	0.91	0.21	2.24	1.77	431	246	194	0.08
Khorramshahr	Gadvan	3523	Cutting	0.28	0.14	0.42	0.61	436	150	218	0.25
Khorramshahr	Gadvan	3539	Cutting	0.56	0.19	0.82	0.73	438	146	130	0.18
Khorramshahr	Gadvan	3568	Cutting	0.5	0.24	0.52	1	430	104	200	0.31
Khorramshahr	Gadvan	3597	Cutting	0.71	0.19	0.74	0.88	436	104	124	0.2
Khorramshahr	Gadvan	3627	Cutting	0.44	0.24	0.68	0.7	437	155	159	0.26
Khorramshahr	Gadvan	3651	Cutting	0.72	0.18	0.89	1.44	436	124	200	0.17
Khorramshahr	Gadvan	3694	Cutting	0.47	0.16	0.51	1.35	433	109	287	0.25
Khorramshahr	Gadvan	3725	Cutting	0.63	0.26	0.49	1.66	430	78	263	0.35
Khorramshahr	Gadvan	3749	Cutting	0.52	0.16	0.81	1.07	437	156	206	0.17
Khorramshahr	Gadvan	3813	Cutting	0.83	0.19	1.14	1	438	137	120	0.14
Kushk	Gadvan	3925	Cutting	0.44	0.33	0.64	1.4	436	145	318	0.34
Kushk	Gadvan	3950	Cutting	0.69	0.23	0.69	1.35	434	100	196	0.25
Omid	Gadvan	4430	Cutting	0.34	0.32	0.31	0.68	431	91	200	0.5
Omid	Gadvan	4525	Cutting	1.23	0.83	1.42	3.04	430	115	247	0.37
Azadegan	Garau	3835	Cutting	1.09	0.63	1.35	3.4	433	124	312	0.32
Azadegan	Garau	3905	Cutting	2.16	8.91	7.03	1.01	435	325	47	0.56
Azadegan	Garau	4033	Cutting	0.73	0.2	0.44	2.38	424	60	326	0.32
Azadegan	Garau	4095	Cutting	0.27	0.16	0.34	1.1	416	126	407	0.31
Azadegan	Garau	4135	Cutting	0.6	1.1	1.48	1.55	434	247	258	0.43
Azadegan	Garau	4215	Cutting	0.31	0.24	0.34	0.94	424	110	303	0.42
Azadegan	Garau	4346	Cutting	0.76	1.91	3.6	1.76	432	474	232	0.35
Juffair	Garau	4170	Cutting	0.69	1.13	0.84	1.92	434	122	278	0.57
Juffair	Garau	4664	Cutting	1.26	0.91	2.86	0.73	434	227	58	0.24
Juffair	Garau	4666	Cutting	2.4	0.8	9.33	1.24	442	389	52	0.08
Juffair	Garau	4706	Cutting	3.24	1.15	8.23	1.88	443	254	58	0.12
Juffair	Garau	4714	Cutting	3.17	5.03	4.71	1.03	434	149	32	0.52
Juffair	Garau	4756	Cutting	2.98	2.4	5.09	1.17	433	171	39	0.32
Juffair	Garau	4776	Cutting	2.48	1.07	5.55	1.17	442	224	47	0.16
Juffair	Garau	4860	Cutting	1.52	4.08	4.64	0.76	442	305	50	0.47
Juffair	Garau	4895	Cutting	1.11	4.58	3.68	0.73	444	331	66	0.55
Juffair	Garau	4906	Cutting	3.85	7.98	8.95	1.63	440	232	42	0.47
Juffair	Garau	4920	Cutting	0.76	3	2.18	0.72	443	287	95	0.58
Juffair	Garau	4935	Cutting	0.42	1.21	1.16	0.58	441	276	139	0.51
Juffair	Garau	4980	Cutting	0.43	1.18	1.08	0.39	443	253	92	0.52
Juffair	Garau	4990	Cutting	0.66	2.18	1.5	0.83	442	227	126	0.59
Juffair	Garau	5015	Cutting	0.64	2.44	2.05	0.5	443	321	78	0.54
Juffair	Garau	5105	Cutting	2.46	9.15	6.69	1.61	445	272	66	0.58
Juffair	Garau	5120	Cutting	2.56	7.24	8.22	1.69	453	321	66	0.47
Juffair	Garau	5200	Cutting	4.16	9.85	8.53	1.55	449	205	37	0.54
Juffair	Garau	5345	Cutting	1.91	6.97	5.62	2.32	445	294	121	0.55

Table 1 continued

Field name	Formation	Depth (m)	Sample type	TOC (wt%)	S1 (mg HC/g rock)	S2 (mg HC/g rock)	S3 (mg HC/g rock)	$T_{\max}$ (°C)	HI (mg HC/g TOC)	OI	PI
Juffair	Garau	5360	Cutting	1.78	8.11	4.49	2.25	437	252	126	0.64
Juffair	Garau	5375	Cutting	1.2	5.1	3.83	1.48	442	320	124	0.57
Mahshahr	Garau	4510	Cutting	1.56	9.91	3.53	0.72	441	226	46	0.74
Mahshahr	Garau	4680	Cutting	0.97	6.11	2.19	0.61	445	226	63	0.74
Mahshahr	Garau	5020	Cutting	1.63	8.92	3.6	0.93	434	221	57	0.71
Mahshahr	Garau	5080	Cutting	1.45	7.89	4.23	0.75	440	292	52	0.65
Darquain	Garau	3960	Cutting	0.49	1.84	1.08	0.34	438	220	69	0.63
Darquain	Garau	3985	Cutting	1.02	4.75	2.87	0.64	440	281	63	0.62
Darquain	Garau	4638	Cutting	0.72	1.95	3.21	0.37	433	445	52	0.38
Darquain	Garau	4650	Cutting	1.1	1.07	2.58	0.47	438	234	43	0.29
Darquain	Garau	4656	Cutting	1.25	2.18	4.22	0.64	438	337	51	0.34
Darquain	Garau	4700	Cutting	2.1	1.7	2.99	0.61	439	142	29	0.36
Darquain	Garau	4750	Cutting	1.87	1.22	3.15	0.77	440	168	41	0.28
Darquain	Garau	4765	Cutting	0.86	3.21	1.72	0.59	441	200	69	0.65
Darquain	Garau	4830	Cutting	1.52	1.92	4.21	0.79	440	277	52	0.31
Darquain	Garau	4880	Cutting	1.82	2.22	3.93	0.71	439	217	39	0.36
Darquain	Garau	4905	Cutting	2.22	2.18	5.85	0.62	440	263	28	0.27
Darquain	Garau	4950	Cutting	0.58	0.63	0.94	0.41	438	162	70	0.4
Darquain	Garau	4970	Cutting	0.62	0.1	2.25	0.72	442	360	116	0.04
Dehloran	Garau	5117	Cutting	0.63	0.57	1.19	0.40	437	189	63	0.32
Dehloran	Garau	5165	Cutting	0.44	0.48	1.2	0.15	440	273	34	0.29
Dehloran	Garau	5190	Cutting	0.69	0.72	2.85	0.21	438	413	30	0.20
Dehloran	Garau	5239	Cutting	0.73	0.84	1.86	0.16	439	255	22	0.31
Haftkel	Garau	3300	Cutting	1	1.2	1.47	0.25	440	147	25	0.45
Haftkel	Garau	3450	Cutting	0.98	0.82	0.99	0.44	441	101	45	0.45
Haftkel	Garau	3580	Cutting	1.15	0.77	1.25	0.82	443	108	71	0.38
Haftkel	Garau	3600	Cutting	1.97	1.2	2.42	1.04	444	123	53	0.33
Haftkel	Garau	3700	Cutting	2.75	1.11	1.89	1.16	444	68	42	0.37
Haftkel	Garau	3800	Cutting	1.42	0.87	1.25	0.88	445	88	62	0.41
Haftkel	Garau	4050	Cutting	2.22	0.43	0.97	0.95	446	43	43	0.31
Haftkel	Garau	4150	Cutting	1.1	0.65	1.71	0.62	448	155	56	0.28
Haftkel	Garau	4250	Cutting	1.25	0.88	1.92	0.95	447	153	76	0.31
Kushk	Garau	4502	Cutting	0.92	4.74	3.77	0.35	440	410	38	0.56
Kushk	Garau	4550	Cutting	6.42	14.4	5.33	0.51	438	83	8	0.73
Kushk	Garau	4624	Cutting	6.02	6.09	3.11	0.48	438	52	8	0.66
Kushk	Garau	4655	Cutting	3.88	1.86	2.74	0.31	442	71	8	0.40
Kushk	Garau	4695	Cutting	5.72	1.22	3.85	1.43	441	67	25	0.24
Kushk	Garau	4750	Cutting	0.61	1.51	2.05	0.32	442	336	53	0.42
Kushk	Garau	4810	Cutting	3.56	2.85	3.92	0.53	442	110	15	0.42
Kushk	Garau	4850	Cutting	10.8	10.7	13.05	0.54	442	121	5	0.45
Kushk	Garau	5100	Cutting	2.3	1.05	3.7	0.69	443	161	30	0.22
Kushk	Garau	5116	Cutting	4.21	1.15	3.27	0.51	441	77	12	0.26
Kushk	Garau	5152	Cutting	1.53	4.81	3.99	0.60	442	261	39	0.55
Kushk	Garau	5170	Cutting	1.48	5.65	4.01	0.55	445	271	37	0.58
Khorramshahr	Garau	4080	Cutting	0.33	0.29	0.69	0.9	441	209	273	0.3

microscope in oil immersion following the method described by Taylor et al. (1998) and Alizadeh et al. (2012). The results are exhibited in Table 2.

Complementary analysis

According to the Rock–Eval pyrolysis results, 25 rock samples were selected for extraction, liquid and gas chromatography experiments. Gas chromatography mass spectrometry (GC–MS) and isotopic analyses were performed on 14 and 11 of the selected samples, respectively. Compound-specific isotope measurement (GC–IRMS) was carried out on four samples from both the Gadvan and Garau formations.

Ground rock samples were extracted by Soxhlet using dichloromethane (DCM) for 24 h; the solvent was removed by centrifuge evaporator. To fractionate the extract, a liquid column of silica gel activated by alumina was employed. Saturate, aromatic, and polar compounds were fractionated by n-hexane, benzene, and chloroform, respectively.

Gas chromatography (GC) analysis was performed by an instrument equipped with a 30 m DB-1 fused silica capillary column (i.d. 0.25 mm; 0.25 μ m film thickness). For mass spectrometry analysis, the GC was coupled to a Finigan MAT GCQ ion trap mass spectrometer. The oven temperature was programmed from 70 to 300 °C at a rate of 4 °C/min, in which 15 min was considered as the isothermal period. The injection temperature was 275 °C in split-less mode, and the carrier gas was helium. For calculating GC and GC–MS, a biomarker ratio peak area for each compound was considered.

For GC–IRMS analysis, in which carbon isotopic ratio is measured for specific saturated hydrocarbon, a trace GC was coupled to a Delta V isotope ratio mass spectrometer via a combustion interface, and a ComFlow IV unit, all ThermoFisher. At the beginning and end of each analysis, CO₂ was injected for calibration. Isotopic ratios are reported with respect to the Vienna Pee Dee Belemnite (VPDB) standard.

Table 2 Vitrinite reflectance measurement results of studied samples

Field name	Formation	Depth	Ro _{min}	Ro _{max}	Ro _{mean}	Comment
Azadegan	Gadvan	3940	0.28	1.29	0.6	Core
Azadegan	Gadvan	4129	0.37	1.35	0.7	Cutting
Azadegan	Gadvan	3757	0.56	1.11	0.89	Cutting
Azadegan	Gadvan	3940	0.28	1.29	0.6	Cutting
Azadegan	Gadvan	4128	0.37	1.35	0.7	Cutting
Mahshahr	Gadvan	4400	0.61	0.73	?	Caving samples
Mahshahr	Gadvan	4500	0.45	1.46	0.9	Cutting
Kushk	Gadvan	3946	0.48	0.8	0.7	Cutting
Kushk	Gadvan	4020	0.48	0.48	0.53	Caving samples
Hosseinih	Gadvan	3931	0.57	0.57	0.67	Cutting
Hosseinih	Gadvan	3982	0.55	0.55	0.66	Cutting
Hosseinih	Gadvan	3903	0.52	1	0.66	Cutting
Omid	Gadvan	4481	0.48	0.98	0.67	Cutting
Juffair	Gadvan	4256	0.61	1.2	0.83	Cutting
Juffair	Gadvan	4188	0.44	0.44	0.51	Caving samples
Darquain	Gadvan	3844	0.32	0.32	0.40	Caving samples
Yadavaran	Gadvan	3918	0.53	0.80	0.65	Cutting
Azadegan	Garau	4430	?	?	0.7–0.9	Cutting
Azadegan	Garau	4470	0.85	0.9	0.7–0.9	Cutting
Azadegan	Garau	4552	?	?	0.7–0.9	Cutting
Mahshahr	Garau	5100	0.52	0.59	?	Caving samples
Mahshahr	Garau	4900	0.54	1.21	?	Caving samples
Kushk	Garau	4850	0.845	1.441	1.013	Cutting
Ahwaz	Garau	4370	0.39	0.39	0.47	Caving samples
Darquain	Garau	4700	0.875	1.231	1.011	Cutting
Darquain	Garau	4470	0.71	0.71	0.80	Cutting
Darquain	Garau	4790	0.70	0.70	0.81	Cutting
Darquain	Garau	4810	0.72	0.72	0.84	Cutting

Fig. 3 Plot of S1 + S2 versus TOC, showing production potential of the samples

Fig. 4 Plot of HI versus $T_{\max}$ (left) and OI (right), showing maturity and kerogen type of studied samples

Result and discussion

Rock-Eval and vitrinite reflectance

The total organic carbon content of the Gadvan Formation varies from 0.25 to 1.6 wt%. The average TOC in this formation is 0.65 wt% (Table 1) which is considered as poor

potential source rock (Hunt 1996). Cutting samples from Azadegan show significant pollution from migrating hydrocarbons, as shown by their S1 values which are higher than their S2 values, for a maturity lower than 430 °C $T_{\max}$. A similar conclusion can be made for the Darquain 4205 m sample. Therefore, the results of Rock-Eval analyses of these polluted samples are not discussed further.

Fig. 5 Plot of PI versus T_{max} , showing maturity of the studied samples

Fig. 6 Depositional environment and average TOC contour map of the Gadvan (left) and Garau (right) formations. Average T_{max} in the well location are indicated for each field. After Bordenave and Huc (1995)

In the Garau Formation, present time TOC ranges from 0.27 up to 5.72%, with an average of 1.76% (Table 1). This value is consistent with good to very good source potential (Peters and Cassa 1994). According to paleogeographic maps, the depocenter of the Garau Formation is located in the Dezful Embayment (east of the Ahwaz oilfield) and in the Lurestan Basin (Bordenave and Hegre 2010).

The S2 peak in Rock–Eval indicates the current ability of the sample to produce hydrocarbon. In the studied samples, the present time S2 values of the Gadvan and Garau formations range 0.13–3.75 and 0.97–9.33 mgHC/g Rock, respectively. The average values of the present time hydrogen index (HI) are 122 and 213 mgHC/g TOC in the Gadvan and Garau formations, respectively. Regarding the

Fig. 7 GC-SAT chromatograms for the selected studied sample of the Gadvan and Garau formations indicate n-alkanes as well as Pr and Ph. GC profile of the Gadvan Formation shows a binary envelope while in the Garau Formation, an unimodal profile can be seen

plot in Fig. 3, it can be concluded that the Gadvan is a marginal source rock. In contrast, it is noteworthy that Garau samples are already close to the peak of oil expulsion window ($T_{\max}$ in the 440–450 °C range). Therefore, initial values of both S2 and HI of Garau samples could have been much higher, even double the current values. Then the Garau Formation could be classified as very good to excellent source rock.

The hydrogen index (HI) is plotted versus the oxygen index (OI) and $T_{\max}$ values in Fig. 4 in order to identify the kerogen type of the studied samples. According to these diagrams, the kerogen of the Gadvan Formation is Type III, and in contrast, the Garau Formation contains kerogen belonging to Type II. Abeed et al. (2011), using visual kerogen studies together with the elemental analysis, reported kerogen Type II-S for the Sulaiy Formation (time equivalent of Garau Formation).

Rock sample maturities were determined on the basis of $T_{\max}$, PI, and vitrinite reflectance. In the Gadvan Formation, $T_{\max}$ values range between 430 and 441 °C, with an average of 433 °C. Vitrinite reflectance was measured for 17 samples and yielded approximately 0.67%. According to plot of PI versus $T_{\max}$ in Fig. 5, as well as vitrinite reflectance measurements, the maturity of the organic matter in the Gadvan Formation can be regarded as being, at the most, at the beginning stage of oil generation. In the studied area, toward the northeast and the Dezful Embayment, the $T_{\max}$ values and maturity of the Gadvan Formation increase from 430 °C in the Abadan Plain to more than 440 °C in the northern Dezful Embayment, which is consistent with the increasing depth (Fig. 6). It should be considered that maturity measurements have been done on the samples from exploration wells which are drilled at the

Table 3 Result of liquid chromatography and GC-FID for Gadvan and Garau formations

Field name	Formation	Depth	Sat%	Aro%	Pol%	Pr/Ph	Pr/nC ₁₇	Ph/nC ₁₈	CPI	nC ₁₇ /(nC ₁₇ + nC ₂₇)	nC ₁₈ /(nC ₁₈ + nC ₂₈)	TAR
Juffair	Gadvan	4200	31.29	21.79	27.93	0.74	0.35	0.51	0.99	0.82	0.55	0.31
Khorramshahr	Gadvan	3815	39.31	8.42	52.27	1.02	0.47	0.63	1.10	0.89	0.63	0.12
Azadegan	Gadvan	3785	30.56	13.1	56.34	0.46	0.42	0.82	1.01	0.94	0.53	0.07
Azadegan	Gadvan	3795	33.02	9.11	57.87	1.45	0.55	0.62	1.09	0.95	0.63	?
Azadegan	Gadvan	3935	19.66	13.11	67.23	0.95	0.50	0.63	1.14	0.95	0.62	?
Azadegan	Gadvan	3755	53.91	8.71	37.38	0.86	0.43	0.62	1.08	0.99	0.60	0.15
Azadegan	Gadvan	3805	55.48	9.44	35.08	1.12	2.22	1.37	1.12	0.92	0.44	0.09
Azadegan	Gadvan	4085	50.7	9.45	39.85	0.68	0.29	0.47	1.03	0.96	0.61	0.07
Azadegan	Gadvan	4170	30.27	19.44	50.29	0.89	0.51	0.57	1.15	0.71	0.45	0.45
Azadegan	Gadvan	3755	25.22	18.5	56.28	1.58	0.99	0.91	1.12	0.70	0.55	0.65
Ahwaz	Gadvan	3710	12.88	10.02	77.1	0.49	0.37	0.40	1.03	0.58	0.48	0.09
Omid	Gadvan	4530	25.75	5.52	68.73	0.71	0.45	0.53	1.02	0.92	0.56	0.30
Hendijan	Gadvan	3440	23.29	15.19	61.52	0.64	0.79	1.00	1.18	0.70	0.50	0.69
Darquain	Gadvan	3955	26.34	13.63	60.03	1.12	0.65	0.75	0.96	0.98	0.57	0.04
Kushk	Gadvan	3950	28.2	12.9	58.9	0.91	0.7	0.8	0.95	0.8	0.53	0.15
Dehloran	Garau	5190	57.5	15.5	27	0.41	0.7	0.8	1.01	0.9	0.6	0.35
Dehloran	Garau	4905	46	8.5	45.5	0.43	0.4	0.8	1.05	0.88	0.55	0.09
Masjed Soleyman	Garau	3732	61	12	27	0.5	0.49	0.62	1.06	0.96	0.61	0.14
Haftkel	Garau	3800	52	16	32	0.68	0.31	0.68	1.01	0.89	0.63	0.35
Kushk	Garau	4810	46.5	16.5	37	0.8	0.4	0.63	1.08	0.91	0.68	0.15
Juffair	Garau	5120	55.49	7.88	36.63	0.68	0.44	0.77	1.01	0.94	0.56	0.09
Hendijan	Garau	3990	23.29	15.19	61.52	0.42	0.39	0.50	1.08	0.48	0.43	0.37
Omid	Garau	5345	35.18	2.24	62.58	0.50	0.51	0.44	1.12	0.95	0.66	0.07
Azadegan	Garau	4405	20.57	10.54	68.89	0.50	0.41	0.44	1.09	0.53	0.48	0.40
Azadegan	Garau	4525	49.24	11.36	39.4	0.78	0.39	0.66	1.08	0.97	0.66	0.04

CPI = $2(nC_{23} + C_{25} + C_{27} + C_{29})/[C_{22} + 2(nC_{24} + C_{26} + C_{28}) + nC_{30}]$; TAR = $(nC_{27} + C_{29} + C_{31})/(nC_{15} + C_{17} + C_{19})$

Fig. 8 Plot of Pr/nC₁₇ versus Ph/nC₁₈ from GC-FID, showing maturation, depositional environment, and kerogen type of organic matter

Fig. 9 Typical saturate GC-MS fragmentograms of the selected studied samples. *Labeled peaks* are identified in Table 4

tops (apexes) of anticlines, so in the neighboring synclines the maturity of this formation will be higher.

The Garau Formation samples are characterized by $T_{\max}$ values that range up to 453 °C. Average vitrinite reflectance was measured at approximately 0.82%. The plot in Fig. 5 and vitrinite reflectance measurements in Table 2 indicate organic matter maturities equal to peak oil generation in the Garau Formation, as is obvious in the $T_{\max}$ values in Fig. 6. The maturity of the Garau Formation increases toward the east of the northern part of the studied area which is consistent with the reported maturity values of its time equivalent Sulaiy Formation in southern Iraq (Abeed et al. 2011). Again it should be mentioned that the maturity of Garau Formation will be higher in the synclines and kitchen areas, because measurements are derived from samples from wells on the top of anticlines.

Most of the studied samples of the Gadvan Formation are located in the Abadan Plain. However, as shown in Fig. 6, samples located toward the Dezful Embayment show a slight increase in their TOC. Abeed et al. (2011) reported that the TOC content of the Zubair Formation (time equivalent of Gadvan) varies between 0.4 and 1%. Hence, regionally, the organic matter content of the

Gadvan Formation decreases from the Dezful Embayment in Iran to the Mesopotamian Basin in Iraq.

The present time TOC content of the Garau Formation increases eastward, as indicated in the average TOC contour map in Fig. 6. In the Mesopotamian Basin west of the studied area, the TOC of the Sulaiy Formation (time equivalent of Garau) has been reported at up to 10%, which means an increasing TOC westward (Abeed et al. 2011).

Gas chromatography

Two typical gas chromatograms for the Gadvan and Garau formations are shown in Fig. 7, and corresponding concentration ratios can be found in Table 3.

The concentration of long and short chain n-alkane is significant in the Gadvan Formation, as shown in Fig. 7 (Peters and Moldowan 1993). The carbon preference index (CPI) for long chain n-alkanes and Pristane/Phytane ratios is more than 1; Pr/nC_{17} and Ph/nC_{18} are less than 1 (Table 3; Fig. 8). Regarding these parameters, the high land plant contribution, low maturity, absences of biodegradation, and anoxic to sub-oxic depositional

Table 4 GC–MS fragmentograms peaks identification, peaks are shown in Fig. 9

Peak	<i>m/z</i>	Compound	Peak	<i>m/z</i>	Compound
1	191	C ₁₉ tricyclic terpane	1	217	C ₂₁ H ₃₆ pregnane
2	191	C ₂₀ tricyclic terpane	2	217	C ₂₂ H ₃₈ bisnorcholeane
3	191	C ₂₁ tricyclic terpane	3	217	C ₂₇ H ₄₈ -β-α-diacholestane (S)
4	191	C ₂₂ tricyclic terpane	4	217	C ₂₇ H ₄₈ -β-α-diacholestane (R)
5	191	C ₂₃ tricyclic terpane	5	217	C ₂₇ H ₄₈ -α-β-diacholestane (S)
8	191	C ₂₄ tetracyclic terpane	6	217	C ₂₇ H ₄₈ -α-β-diacholestane (R)
12	191	C ₂₇ -18a(H),21b(H)-22,29,30-trisnorhopane (<i>T_s</i>)	7	217	C ₂₈ H ₅₀ -β-α-diacholestane (S)
13	191	C ₂₇ -17a(H),21b(H)-22,29,30-trisnorhopane (<i>T_m</i>)	8	217	C ₂₈ H ₅₀ -β-α-diacholestane (R)
15	191	C ₂₉ -17a(H),21b(H)-30-norhopane	9	217	C ₂₈ H ₅₀ -β-α-diacholestane (S)
17	191	C ₃₀ -17a(H),21a(H) hopane	15	217	C ₂₈ H ₅₀ -β-β-cholestane (S)
18	191	C ₃₀ -17b(H),21a(H) hopane (mortane)	16	217	C ₂₉ H ₅₂ -β-β-cholestane (R)
19	191	C ₃₁ -17a(H),21b(H)-30 homohopane (22S)	21	217	C ₂₉ H ₅₂ -β-β-cholestane (S)
20	191	C ₃₁ -17a(H),21b(H)-30 homohopane (22R)	22	217	C ₂₉ H ₅₂ -α-α-cholestane (R)
21	191	C ₃₀ -Gammacerane	5	218	C ₂₈ H ₅₀ -β-(R)
1	218	C ₂₁ -pregnane	6	218	C ₂₈ H ₅₀ -β-(S)
2	218	C ₂₂ -pregnane	7	218	C ₂₉ H ₅₂ -β-(R)
3	218	C ₂₇ H ₄₈ -β-(R)	8	218	C ₂₉ H ₅₂ -β-(S)
4	218	C ₂₇ H ₄₈ -β-(S)			

Table 5 Result isotope analysis in the studied samples

Field name	Formation	Whole oil δ ¹³ C extracted HC	Saturated HC δ ¹³ C (PDB)	Aromatic HC δ ¹³ C (PDB)	CV
Kushk	Gadvan	−27.8	−28.6	−27.5	−0.2
Darquain	Gadvan	−28.02	−28.8	−27.3	0.8
Azadegan	Gadvan	−28.1	−29.2	−27.5	1.2
Azadegan	Gadvan	−27.05	−28.8	−26.5	2.5
Ahwaz	Gadvan	−26.9	−28.1	−26.8	0.2
Hendijan	Gadvan	−25.8	−27.4	−25.1	2.0
Yadavaran	Gadvan	−26.7	−27.5	−26.0	0.1
Yadavaran	Gadvan	−26.4	−26.7	−26.1	−2.0
Azadegan	Garau	−28.8	−29.2	−28.0	0.3
Azadegan	Garau	−28.1	−29.0	−27.9	−0.1
Hendijan	Garau	−26.8	−27.2	−26.1	−0.6

environment for organic matter in the Gadvan Formation can be inferred (Tissot and Welte 1984; Moldowan et al. 1985).

In the Garau Formation, the unimodal GC chromatogram values as well as a high concentration of short chain n-alkanes show an advanced level of maturity. CPI values are close to 1, the Pristane concentration is much lower than the Phytane, and, as Fig. 8 shows, the Pr/nC₁₇ and Ph/nC₁₈ are less than 1. According to the GC parameters, high maturity, lack of biodegradation, and Type II organic matter, a strongly anoxic depositional marine

environment for the Garau Formation can be inferred (Tissot and Welte 1984; Moldowan et al. 1985; Peters and Moldowan 1993).

Biomarker study

Because biomarkers are derived from biological precursor molecules in specific organisms, and because each of these organisms lives only under certain environmental conditions, it is logical to use biomarkers as indicators of those conditions (Bjørøy et al. 1992). However, any application

Table 6 Result of GC–MS analysis for Gadvan and Garau formations

Field name	Formation	Depth (m)	$T_s/(T_s + T_m)$	C_{29}/C_{30} Hopane	C_{31} Hop 22S/(22S + 22R)	Str 29 20S/(20S + 20R)	Str29 $\beta\beta/(\beta\beta + \alpha\alpha)$	Regular steranes			DBT/Phen	MPI1
								$C_{27}\%$	$C_{28}\%$	$C_{29}\%$		
Kushk	Gadvan	3950	0.3	0.95	0.58	0.41	0.50	27	34.00	39.0	0.7	0.69
Darquain	Gadvan	3960	0.2	1.10	0.60	0.52	0.45	44	24.00	31.0	0.65	0.66
Azadegan	Gadvan	4170	0.36	1.00	0.57	0.53	0.53	27	26.00	47.0	1.14	0.68
Azadegan	Gadvan	3755	0.22	1.10	0.56	0.25	0.47	36	29.00	38.0	0.71	0.71
Arvand	Gadvan	3715	0.14	1.05	0.58	0.46	0.43	42	24.00	35.0	0.15	0.51
Hendijan	Gadvan	3442	0.3	1.00	0.48	0.25	0.30	37	27.00	36.0	0.71	0.62
Masjed Soleyman	Garau	3732	0.57	0.87	0.59	0.5	0.51	45	28	27	1.77	0.71
Haftkel	Garau	3800	0.5	1.16	0.59	0.38	0.48	30	35	35	3.44	0.64
Kushk	Garau	4810	0.58	1.13	0.59	0.42	0.53	44	29	27	3.25	0.25
Azadegan	Garau	4405	0.67	1.08	0.54	0.40	0.52	49	22	29	0.76	0.52
Azadegan	Garau	4525	0.31	1.10	0.57	0.53	0.53	27	26.00	47.0	0.81	0.6
Hendijan	Garau	3990	0.45	1.00	0.59	0.52	0.46	40	24.00	36.0	0.15	1.08
Dehloran	Garau	5190	0.60	1.12	0.65	0.48	0.63	39	28	33	1.91	0.77
Darquain	Garau	4905	0.59	0.92	0.39	0.4	0.5	42	26	32	1.25	0.97

Fig. 10 Plot of MPI-1 versus calculated vitrinite reflectance in the studied samples (Peters et al. 2005) showing maturity of organic matter in the studied formations

of biomarkers for organic-facies interpretation should be made with a full awareness that organic facies (and hence biomarker distributions) can change rapidly, both vertically and laterally (Moldowan et al. 1986; Bjorøy et al. 1992). If

one is working with a typical sample of cuttings material, the biomarker signature will be an average for all facies present in the sample, and thus, it will be much harder to interpret (Tables 4, 5).

In this study, GC–MS analysis was done on saturates and aromatics fractions in 14 samples in both the Garau and Gadvan formations. Biomarker parameters for the studied samples are shown in Fig. 9 and are summarized in Table 6. Terpanes, steranes, and aromatic parameters were used to investigate the geochemical characteristics of the formations under consideration.

First, the biomarkers related to the maturity of the samples will be examined. The value of C_{31} homohopane $22S/(22S + 22R)$ increases with maturity, from 0 to 0.61 (Peters et al. 2005). This ratio for the Gadvan and Garau formations ranges between 0.48–0.6 and 0.54–0.65, suggesting an early oil window and peak oil generation, respectively (Table 6). The $T_s/(T_s + T_m)$ ratio in the Gadvan Formation changes from 0.14 to 0.36, while in the Garau Formation this ratio ranges between 0.36 and 0.67, which shows again a low level of maturity in the Gadvan Formation and high level of maturity in the Garau (Peters and Moldowan 1993). In addition to maturity, the lithology of the studied samples can influence the $T_s/(T_s + T_m)$ ratio;

for the same maturity, the argillaceous content of the source rocks generally increases the $T_s/(T_s + T_m)$ ratio (Peters et al. 2005). As most of the Garau samples are richer in carbonate, the high $T_s/(T_s + T_m)$ ratios correlate to higher thermal maturity.

The $C_{29} \beta\beta/(\beta\beta + \alpha\alpha)$ sterane ratio increases from zero to nearly 0.7 (0.61–0.71 equilibrium) (Peters and Moldowan 1993). In the studied samples of the Gadvan and Garau formations, this ratio ranges between 0.3–0.53 and 0.46–0.63, which implies early and peak oil generation window, respectively (Table 6; Fig. 9). The average ratio of $5\alpha(H), 14\alpha(H), 17\alpha(H)$ C_{29} and steranes $20S/(20S + 20R)$ is 0.4 and 0.45 in the Gadvan and Garau formations, respectively.

Aromatic biomarkers are more resistive to temperature than are saturate ones (Peters et al. 2005). In this study, MPI-1 was measured for the rock samples (Table 6). Peters et al. (2005) proposed a formula for calculating the equivalent vitrinite reflectance of a special sample using MPI-1 (Fig. 10). According to Table 6 and Peter's formula,

Fig. 11 Plot of DBP/Phen versus Pr/Ph, showing a depositional environment of organic matter in the studied samples

Fig. 12 Plot of $\delta^{13}\text{C}$ aromatic versus saturate values to investigate organic matter depositional environment (Sofer 1984)

Fig. 13 Plot of n-alkanes GC-IRMS profile for four samples in the Gadvan and Garau formations; two different profiles are obvious. Also, Garau profiles are lighter in n-alkane isotope value

Table 7 Result of GC-MS analysis for Gadvan and Garau formations (see Fig. 13 for n-alkane isotope profile)

Field name	Formation	nC ₁₅	nC ₁₆	nC ₁₇	nC ₁₈	nC ₁₉	nC ₂₀	nC ₂₁	nC ₂₂	nC ₂₃	nC ₂₄	nC ₂₅	nC ₂₆	nC ₂₇	nC ₂₈	nC ₂₉	nC ₃₀	Pri	Phy
Kushk	Gadvan				−27.9	−28.1	−28.3	−29.1	−29.0	−28.9	−29.2	−29.1	−29.5	−30.7	−31.2			−29.4	−29.6
Azadegan	Gadvan	−27.2	−27.8	−28.2	−28.4	−28.7	−28.7	−28.3	−28.9	−29.1	−29.5	−29.5	−29.8	−30.1	−30.1	−31.2	−30.4	−29.4	−30.1
Azadegan	Garau		−28.5	−28.6	−28.9	−29.1	−29.7	−30.3	−29.7	−29.9	−30.3	−30.5	−30.7	−30.8	−31.3	−31.6	−31.9	−29.8	−30.2
Azadegan	Garau	−28.3	−28.6	−29.2	−29.5	−29.7	−30.2	−30.0	−29.8	−29.6	−30.3							−29.9	−30.8

the average calculated vitrinite reflectance in the Gadvan and Garau formations are 0.75 and 0.84%, respectively.

Regarding biomarkers more specifically related to the environment of deposition, Table 6 shows the relative proportion of the C₂₇–C₂₈ and C₂₉ regular steranes. Higher C₂₇ values for the Garau samples indicate a marine depositional environment. By contrast, higher C₂₈ values for the Gadvan Formation mean the input of terrestrial organic matter (Hunt 1996; Mackenzie et al. 1983). Total/NIOC (2003) in a joint study showed that, with the increasing age of source rock, the amount of C₂₈ regular steranes in the samples decreases. They introduced a table to use the amount of C₂₈ regular steranes as indicators of the age of an specific oil in the Persian Gulf. In this study, the C₂₈ regular sterane content of both the Gadvan and the Garau has the similar average values, 27.33 and 27.25%, respectively, which can be used to further source–oil correlation.

A cross-plot of DBT/Phen versus Pr/Ph can be used to detect the depositional environment of organic matter (Hughes et al. 1995). As indicated in Fig. 11, the Gadvan Formation is located in a mixed shale/carbonate environment, and the Garau Formation is located in a marine carbonate depositional environment.

Abeed et al. (2011), using visual kerogen interpretation and biomarker data, reported kerogen Type II-S for the Sula'iy Formation (time equivalent of the Garau Formation), which is in agreement with the high concentration of dibenzothiophene (strongly anoxic marine environment) compound in the Garau Formation.

Isotope study

In this study, bulk composition stable carbon isotope analysis was applied to determine the depositional environment of the Gadvan and Garau formations (Table 5). Moreover, individual n-alkanes GC-IRMS were measured to differentiate the source rock for future oil–source correlation. As Fig. 12 shows with a plot of $\delta^{13}\text{C}$ aromatic versus $\delta^{13}\text{C}$ saturates (Sofer 1984), the Gadvan samples originated in a marine environment with terrestrial influences, while the Garau samples derived from a marine environment.

Regarding Table 5, the canonical variable (CV) confirms the result because, for all the Garau Formation samples, the CV is less than 0.47, while of the 8 analyzed samples from the Gadvan Formation, 5 have CV values more than 0.47 (Sofer 1984).

GC-IRMS analysis, in which carbon isotopic ratios were measured on specific saturated hydrocarbons, is shown in Table 7. As illustrated in Fig. 13, two different n-alkane isotope profiles for the Gadvan and Garau formations emerged, in which the Garau Formation profile is more

negative and $\delta^{13}\text{C}$ for individual n-alkanes is systematically lower than in the Gadvan samples. This obvious difference in the isotope value was not seen in bulk isotope data in Table 5 and Fig. 12. Hayes (1993) stated that more negative isotope values indicate more planktonic algae.

Conclusion

Results of Rock–Eval analysis indicate that the Gadvan Formation, with an average TOC of 0.65% and HI values of 122 mgHC/g TOC, can be classified as marginal source rock; by contrast, the Garau Formation, with TOC and HI current values up to 5.72% and 413 mgHC/g TOC, respectively, should be considered as having good to excellent source potential. Moreover, it should be recalled that the initial TOC and HI values of the Garau samples were both significantly higher than the current values. The kerogen type in the Gadvan Formation is mainly Type III with some input of Type II, and, as Fig. 4 shows, the kerogen is of Type II in the Garau Formation.

Gadvan samples are situated between 3510 and 4525 m depth. These samples are immature or at the beginning of the oil window, but have not yet reached the expulsion window (average $T_{\text{max}} = 433\text{ }^{\circ}\text{C}$, average $\text{VR}_0 = 0.67\%$). It is understood that in the synclinal part of the Abadan plain, the Gadvan may have reached the expulsion window. However, as the Gadvan Formation contains a limited amount of Type III kerogen, the contribution of the Gadvan on the charge of Abadan Plain hydrocarbon reserves is deemed negligible. By contrast, Garau samples came from a current burial ranging from 4250 to 5239 m (with the exception of Haftkel oil field, where more than 1000 m of Aghajari layers were eroded prior to the Zagros Folding) and are already in the peak of oil expulsion, or already at the beginning of the gas and condensate stage (average $T_{\text{max}} = 441\text{ }^{\circ}\text{C}$, average $\text{VR}_0 = 0.82\%$). Again, maturity is higher in the deeper part of the Abadan Plain. At Haftkel, Garau is shallower, 3300–4250 m, and no vitrinite reflectance were measured. However, the average T_{max} of 441 $^{\circ}\text{C}$ confirms the importance of the erosion of the Aghajari Formation.

GC parameters for the Gadvan Formation indicate high land plant contribution, low maturity, and an oxic to sub-oxic depositional environment of organic matter. In the Garau Formation, an advanced level of thermal maturity, Type II (likely II-S) organic matter, and a marine depositional environment under anoxic condition have been recognized.

Saturate and aromatic biomarker parameters, as well as isotopic analysis, confirm the Rock–Eval and GC results. In the Gadvan Formation, a maturity level of early oil generation (MPI-1 suggests equivalent $\text{VR}_0 \approx 0.75$) and

mixed shale/carbonate with terrigenous input depositional environment ($\text{CV} > 0.47$) has been established, while, for the Garau Formation, a high level of maturity (MPI-1 suggests equivalent $\text{VR}_0 \approx 0.84$) and marine carbonate depositional environment ($\text{CV} < 0.47$) has been determined.

GC-IRMS analysis results show two different n-alkane isotope profiles where the Garau Formation profile is more negative, which shows more planktonic algae and higher maturity. These n-alkane isotope profiles can be used for further oil–source correlation in ongoing studies.

The excellent, mature Garau source rocks in the Abadan Plain area have generated huge amounts of oil, and possibly gas and condensate, which were ready to be trapped in the large N–S oriented anticlines, such as Azadegan, Hosseinih, Darquain and Mahshahr, which were formed well before the Zagros Folding.

Acknowledgements The author would like to offer sincere thanks to the National Iranian Oil Company-Exploration Directorate (NIOC-EXP) for providing samples, data and financial support of geochemical analysis. We also are grateful to the Geochemistry Department of NIOC-EXP, especially for helpful discussions and comments which improved the original manuscript.

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References

- Abdollahie Fard I, Braathen A, Mokhtari M, Alavi SM (2006) Interaction of the Zagros Fold-Trust Belt and the Arabian-type, deep seated folds in the Abadan Plain and the Dezful Embayment, SW Iran. *Pet Geosci* 46:347–362
- Abeed Q, Alkhafaji A, Littke R (2011) Source rock potential of the upper Jurassic–Lower Cretaceous succession in the southern Mesopotamian basin, southern Iraq. *J Pet Geol* 34(2):117–134
- Alavi M (2007) Structures of the Zagros fold thrust belt in Iran. *Am J Sci* 307:1064–1095
- Alizadeh B, Sarafdokht H, Rajabi M, Opera A, Janbaz M (2012) Organic geochemistry and petrography of Kazhdumi (Albian–Cenomanian) and Pabdeh (Paleogene) potential source rocks in southern part of the Dezful Embayment, Iran. *Org Geochem* 49:36–46
- Aqrabi AAM, Goff JC, Horbury AD, Sadooni FN (2010) The petroleum geology of Iraq. Scientific press, Beaconsfield
- Bjørøy M, Hall K, Hall PB, Leplat P (1992) Detailed hydrocarbon analyser for well site and laboratory use. *Mar Pet Geol* 9:648–665
- Bordenave ML, Burwood R (1990) Source rock distribution and maturation in the Zagros orogenic belt, provenance of the Asmari and Sarvak reservoirs oil accumulations. *Org Geochem* 16:369–387

- Bordenave ML, Hegre JA (2010) Current distribution of oil and gas fields in the Zagros Fold Belt of Iran and contiguous offshore as the result of the petroleum systems. *Geol Soc Lond Spec Publ* 330:291–353
- Bordenave ML, Huc AY (1995) The Cretaceous source rocks in the Zagros foothills of Iran: an example of a large size intra-cratonic basin. *Revue de l'Institut Français du Pétrole* 50:527–753
- Espitalié J, Bordenave ML (1993) Screening techniques for source rocks evaluation; tools for source rocks routine analysis; Rock-Eval pyrolysis. In: Bordenave ML (ed) *Applied Petroleum Geochemistry*, Editions Technip, Paris, France, pp 273–261
- Espitalié J, Laporte JL, Madec M, Marquis F, Leplat P, Paulet J (1977) Méthode rapide de caractérisation des roches mères, de leur potentiel pétrolier et de leur degré d'évolution. *Revue de l'Institut Français du Pétrole* 32:23–45
- Fakour I, Jahani D, Asilian Mahabadi H (2010) Facies, Depositional environment and sequence stratigraphy of the Gadvan and Dariyan formations in north of Dezful Embayment in Izeh Zone–Zagros Basin. In: *The 1st international applied geological congress*, Mashhad, Iran
- Falcon NL (1967) The geology of the northeast margin of the Arabian basement shield. *Adv Sci* 24:31–42
- Hayes JM (1993) Factors controlling the ^{13}C content of sedimentary organic compounds; principle and evidence. *Mar Geol* 113:111–125
- Hughes WB, Holba AG, Dzou LIP (1995) The ratio of dibenzothiophene to phenanthrene and pristane to phytane as indicator of depositional environment and lithology of petroleum source rock. *Org Geochem* 17:3581–3598
- Hunt JM (1996) *Petroleum geochemistry and geology*, 2nd edn. W.H. Freeman and Company, New York
- James GA, Wynd JG (1965) Stratigraphic nomenclature of Iranian oil consortium agreement area. *AAPG Bull* 49(12):2182–2245
- Jassim SZ, Goff HC (2006) *Geology of Iraq*. Dolin, Prague and Moravian Museum, Brno
- Kent P, Slinger FCP, Thomas AN (1951) Stratigraphical exploration surveys in the Persia. In: *Third petroleum congress*. The Hague, section 1, pp 141–161
- Mackenzie AS, Li RW, Maxwell JR, Moldowan JM, Seifert WK (1983) Molecular measurement of thermal maturation of Cretaceous shales from the Overthrust belt Wyoming, USA. In: Bjoroy M et al (eds) *Advanced in organic geochemistry 1981*. Wiley, New York, pp 496–503
- Mashhadi ZS, Rabbani AR (2015) Organic geochemistry of crude oils and Cretaceous source rock in the Iranian sector of the Persian Gulf; an oil–oil and oil–source rock correlation study. *Int J Coal Geol* 146:118–144
- Mashhadi ZS, Kamali MR, Rabbani AR (2014) Source rock evaluation and geochemical characterization of Albian Kazhdumi Formation offshore SW Iran. In: *Third EAGE exploration workshop*, 6–9 April 2014, Abu Dhabi, UAE
- Moldowan JM, Seifert WK, Gallegos EJ (1985) Relationship between petroleum composition and depositional environment of petroleum source rock. *AAPG Bull* 69(8):1255–1268
- Moldowan JM, Sundararaman P, Schoell M (1986) Sensitivity of biomarker properties to depositional environment and/or source input in the Lower Toarcian of S.W. Germany. *Org Geochem* 10:915–926
- Motiei H (1995) *Petroleum geology of Zagros*. Publication of the Geological Survey of Iran (**in Persian**)
- Muris RJ (1980) Middle East stratigraphic evolution and oil habitat. *Am Assoc Pet Geol Bull* 64:597–618
- Peters KE, Cassa MR (1994) Applied source rock geochemistry. In: Magoon LB, Dow WG (eds) *The petroleum system—from source to trap*, vol 60. American Association of Petroleum Geologists Memoir, Tulsa, pp 93–120
- Peters KE, Moldowan JM (1993) *The biomarker guide*. Interpreting molecular fossils in petroleum and ancient sediments. Prentice Hall, Upper Saddle River
- Peters KE, Walters CC, Moldowan JM (2005) *The biomarker guide*. Biomarker and isotope in petroleum exploration and earth history, vol 2. University of Cambridge Press, Cambridge, pp 475–1155
- Rabbani AR, Bagheri Tirtashi R (2010) Hydrocarbon source rock evaluation of the super-giant Ahwaz oilfield, SW Iran. *Aust J Basic Appl Sci* 4:673–686
- Rabbani AR, Mashhadi ZS, Rezaei Z (2013) Source rock of the Barremian to Early Aptian Gadvan Formation in the Persian Gulf. *Applied Geolgy* 1(9):21–30 (**in Persian**)
- Sepehr M, Cosgrove JW (2004) Structural framework of the Zagros Fold–Thrust Belt, Iran. *Mar Pet Geol* 21:829–843
- Sofer Z (1984) Stable carbon isotope composition of crude oils; application to source depositional environment and petroleum alteration. *AAPG Bull* 68:31–49
- Stocklin J (1974) Possible ancient continental margins in Iran. In: Burk CA, Drake CL (eds) *The geology of continental margins*. Springer, New York, pp 873–887
- Taylor GH, Teichmüller M, Davis A, Diessel CFK, Littke R, Robert P (1998) *Organic petrology*. Gebrüder Borntraeger, Berlin
- Tissot BP, Welte DH (1984) *Petroleum formation and occurrence*, 2nd edn. Springer, New York
- Zeinalzadeh A, Moussavi-Harami R, Mahboubi A, Sajjadian VA (2015) Basin and petroleum system modeling of the Cretaceous and Jurassic source rock of the gas and oil reservoirs in Darquain field, south west Iran. *J Nat Gas Sci Eng* 26:419–426