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U-Pb Detrital Zircon Dating of Middle Eocene Clastic Rocks from the Gercus Formation, NE Iraq: New Constraints on Their Provenance, and Tectonic Evolution

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Abstract

The provenance of Middle Eocene clastic rock from the Gercus Formation Northeast Iraq was determined by detrital zircon U-Pb geochronology. The DZ U-Pb age spectra from the Gercus Formation suggest that the foreland sediments either influx from multiple provenances or from the result of recycling from the accretionary complex terrane. During pre-accretion, however, the radiolarite basin (Qulqula Radiolarite, 221 Ma) located along the Arabian passive margin likely acted as an intermediate sediment repository for most or all of the detrital zircon. Representative detrital zircon U-Pb measurements revealed that the Gercus clastic rocks fall into several separable age population ranges of 92-102 (Albian-Cenomanian), 221 (Upper Triassic), 395-511 (Cambrian), 570- 645 (Neoproterozoic), 1111 (Mesoproterozoic), and lesser numbers of Paleoproterozoic (1622-1991 Ma) ages. The source of Proterozoic detrital zircons is enigmatic; the age peaks at 1106, 1523, 1639, and 1968 Ma (Proterozoic) does not infer to any ancient rocks in Iraq. The detrital zircons with age populations at 633–982 Ma probably originated from the Arabian-Nubian Shield. The age peak at 557 Ma correlates with Cadomian Magmatism reported from north Gondwana. The age peaks at 401-443 Ma is interpreted to represent Gondwana rifting and the opening of Paleotethys. The youngest ages populations at 93 Ma indicate that fraction of DZ were transported directly from the contemporaneously active magmatic arc (Zagros Ophiolite Segments). The paleogeography and tectonic evolution of the Neogene Zagros foreland basin were reconstructed and divided into two tectonic stages. The early stage is defined by the Campanian accreted terrene (i.e. orogenic wedge), and the late stage is marked by a synchronized modification of the clastic fill of the basin which was sealed by a shallowing upwards depositional sequence ending with the terrestrial Gercus Formation.

Keywords: Gercus; Molasse; Radiolarite; Geochronology; Detrital zircon

1. Introduction

The basin of the Gercus Formation is located in the periphery of Qulqula Rise “accretionary complex terrane” of the Zagros Fold-Thrust belt, marking the transition from passive margin to the accretionary complex terrene– flexural foreland basins setting (Aziz et al. 2011a). In Iraq, the foreland part of Tethys basin is characterized by deep marine Tanjero and Kolosh formations, and encroached southward toward a rapidly subsiding Neogene basin and filled by Molasse clastics (Gercus Formation) in front of the Arabian Plate margin, providing evidence for a long history of subduction, accretion, mélange formation and uplift (Falcon, 1974; Dercourt et al. 1986; Alavi, 1994; Hessami, 2002; Aswad DOI: [10.46717/igj.54.1C.1Ms-2021-03-21](https://doi.org/10.46717/igj.54.1C.1Ms-2021-03-21)

et al. 2011; Aziz et al. 2011a and Koshnaw et al. 2017). Generally, the formation displays lithological variation and is mainly composed of conglomerates, sandstones, and mudstones with alternating carbonate beds (Fig. 1B). It is believed that the Gercus Formation provides the most suitable archive to study the evolution of the foreland system of the Iraqi segment of the north Zagros Thrust Zone (NZTZ) with regards to the transition from passive margin to the accretionary complex terrane-flexural foreland basins setting (Sadiq, 2020). The current study represents the first attempt to determine indices of provenance and tectonics of the source area of the Gercus Formation using detrital zircon (DZ) age data.

Fig. 1. A. Regional tectonic and geological map of the Middle East illustrating key structural divisions of the Zagros Fold-Thrust Belt and foreland basin, including the study area (After Koshnaw et al., 2017); B. Lithological section of the Gercus Formation in Haibat-Sultan

2. Geological Setting

The Gercus Formation forms a part of the Paleogene successions, northern Iraq (Fig. 2B), represented by a thick section of Middle-Late Eocene clastic sediments. A complete section of these rocks forms an outcrop in the northeastern side of Jabal Hiabat Sultan, in the Unstable Folded zone (Al-Rawi, 1980; Al-Qayim, 1994; Jassim and Goff, 2006). The Gercus Formation is characterized by predominant red continental clastic sediments such as conglomerates, sandstones and mudstones with interbedded carbonate beds and evaporites with a possibility of shallow marine influence near the bottom of the section (Fig. 2). In north-eastern Iraq, the formation crops mainly several kilometres north of the boundary between High and Low Folded Zones. It extends along a relatively narrow belt in the northwest-southeast direction from eastern to northern Iraq (Buday, 1980; Al-Rawi, 1983; Buday and Jassim, 1987; Jassim and Goff, 2006; Hussain and Aghwan, 2015) and continues northwest into southeast Turkey (Tasman, 1949). Toward the southeast, it is correlative with the Kashkan Formation in Iran (James and Wynd, 1965) seems to be similar, in most aspects, to the Gercus Formation, including its age. A detailed sedimentological study reveals that this rock accumulated in three main distinct facies associations: aeolian, fluvial and lacustrine (Hussain and Aghwan, 2015). Al-Qayim and Al-Shaibani (1991) suggested that sediments in the Gercus Formation are deposited in a clastic-dominated tidal flat.

Base on the main lithological distribution, the formation was divided by Ameen (1998) into three parts (lower, middle, upper). Al-Mashaikie and Mohammed (2017) classified four facies based on facies types, sedimentary structures, and facies successions in the Gercus formation for the first time suggesting the marine environment of the Formation. All previous investigations of the Middle Eocene Gercus formation included the study of sedimentology and palaeontology.

Fig. 2. Field photograph of a-Differently colored beds of the Gercus Formation along road cut in Jabal Habiab-Sultan, Koya area; b- Red sandstone layer within the Gercus Formation; c- sandstone beds of the Gercus in Qaradagh section; d- View of the Gercus Formation in Qaradagh

3. Materials and Methods

Ten samples of sandstones from the Gercus Formation were collected from klka-smaq, Hiabat Sultan, and Qaradqgh (Wazyara) stratigraphic sections (Table 1). In the present study, Ten thin sections of representative samples were examined to achieve the classification of the sandstones from the Gercus Formation at original analytical Ltd in Welshpool, United Kingdom, using high resolution petrography approach, in which all of the particles are carefully and forensically classified and the analysis includes full descriptions, determination of mineralogical abundances based on traditional or Gazzi-Dickinson's point counting approaches which was described by Ingersoll and Suczek, (1979) and involved counting of 300 points per slide (300 points at 0.04 mm intervals on each sample). This method puts fine-grained lithic fragments that do not have individual crystals larger than 0.0625 mm in the lithic fragment pole. Each sample was then analyzed using the Zeiss EVO MA10 SEM, coupled with an Oxford Instruments 80mm² EDS detector with Aztec software. Heavy mineral identification used the "Feature" module of Aztec, whereby around 1000 grains were imaged and a semi-quantitative major element analysis undertaken. Mineral identification was then undertaken using propriety thresholds for chemical composition. Zircon grains were separated using conventional density and magnetic separation techniques. This was repeated several times due to the low zircon content in the samples. Analytical parameters and standardization approach followed that detailed in Papapavlou et al. (2017), Precambrian Research. Zircon U-Pb dating was determined by use of an Analytik Jena PQ Elite ICP-MS coupled with an ASI resolution 193-nm excimer laser ablation system. Zircon analyses were normalized to the

BB9 zircon RM, with Plesovice and Temora 2 run as secondary standards (Plesovice reference Age 337Ma and Temora 2 reference Age 416 Ma).

Table 1. The latitude, longitude and location of the selected sections for the sandstones from the Gercus Formation

Sample	Section	Locality	Latitude	longitude
G1-G5	Hiabat Sultan (HS)	klka-smaq and Hiabat Sultan	N 35° 55' 28'' N 35° 29' 32''	E 44° 54' 58'' E 44° 11' 58''
G16-G10	Qaradagh (QS)	Qaradagh and Wazyara	N 35° 16' 02'' N35° 16' 33''	E 45° 21' 21'' E 45° 21' 38''

4. Results

4.1. Petrography

The texture and mineralogy of the Gercus Formation were highly variable between locations due, in part, to the formation's length of more than 1,000 km along the Zagros and Taurus belts inside Iran, Iraq and Turkey. Due to textural and mineralogical diversity, the Gercus sandstone shows several classifications by numerous authors, including, most commonly, chert-carbonate and quartz-chert lithic wacke and, less commonly, chert-carbonate and Quartz-chert lithic arenite (Al-Mashaikie et al. 2014). In the current study, the samples of the Gercus sandstones in both Haibat-Sultan and Qaradagh sections were classified as litharenite using QRF diagram (Fig. 3).

Fig. 3. Mineralogical classification of the clastic rocks in the Gercus sandstone samples (after Pettijohn, 1975).
Q: total quartz; F: total feldspar; RF: total rock fragments

The sandstones clasts were poorly sorted and angular to subrounded grain morphology. Matrix-supported, 'chaotically' sorted wacke demonstrated possible rare lamellar fenestral voids, suggestive of some degree of lamination. Detrital grain mineralogy was characterized primarily as monocrystalline quartz and rarely as polycrystalline quartz or feldspar (both k-feldspar and plagioclase) (Table 2). Plagioclase grains shows deformation phenomenon (Fig 4c). Very common lithic rock fragments were predominantly chert (including silicified limestone clasts) (Fig. 4b) and dolostone rock fragments (Fig. 4d). Additional lithic grains included rare fragments of limestone, siliciclastic mudstone, phyllite/schist, and plutonic and volcanic fragments (Figs. 4d and f). Phyllosilicate grains occurred as rare biotite mica, rare chlorite and rare muscovite mica. Accessory grains are detrital opaque grains.

Table 2. Modal analyses of the Gercus sandstone samples; Fld (Feldspar); Sed (Sedimentary); Meta (Metamorphic); Ign (Igneous); RF (Rock Fragment)

Sample	Quartz%		Fld	Rock fragment					Phyllosilicate and Accessories	Matrix	Cement	Clays	Porosity
	Mono	Poly		Sed	Meta	Ign	Chert	RF					
G2	8.3	2.3	4.3	35.2	1.3	9.4	8.2	54.1	2	9.4	18.43	0.8	0.33
G4	11.3	1.42	5.1	33.4	2.5	8.3	8.5	52.7	2.3	6.1	17.68	0.9	2.5
G6	10.5	2.9	4.2	40.2	3.3	8.1	10.4	62	1.8	5.5	11.95	0.82	2.33
G5	17.8	4.3	3.8	30.7	2.7	7.2	9.7	50.3	1.12	6.8	13.16	0.31	2.41
G10	13.9	4	5.6	35.5	2.4	7.5	8.38	53.8	2.2	7.2	10.89	0.43	2
G12	9.4	4	3.6	34.9	3.2	5.5	8.6	52.2	3.3	7.5	15.84	0.93	2.83
G14	10.1	2.2	5.3	41.4	2.5	7.4	12.6	63.9	1.1	6.9	8.56	0.44	3.5
G16	9.9	5.8	4.9	37.9	4.8	8.5	7.7	58.9	1.9	6.7	9.27	0.51	2.12
G18	7.9	1	4.5	38.9	2	4.7	9.2	54.8	1.6	7.4	19.59	0.55	2.66
G19	8.3	3.3	3.9	43.4	2.6	9.9	9.5	65.4	2.4	6.1	7.74	0.96	1.9
Av.	10.74	3.12	4.5	37.2	2.73	7.7	9.28		1.972	6.96	13.31	0.67	2.26

4.2. Heavy Minerals

Heavy minerals are powerful tools for assessing the provenance and reconstruct paleogeography of clastic rock deposition. Each heavy mineral grain is a unique messenger, bearing the details of its origin and the development of its sedimentary history (Mange and Wright, 2007). Thus, the analysis of heavy minerals in the Iraqi foreland basin sequences can prove valuable in defining the depositional histories of both extra and intra-basin processes that influence the formation of clastic rocks (Dill, 1998). Accessory grains of detrital opaque minerals were common, forming > 90% of the heavy mineral suite. These minerals included magnetite, Cr-spinel and ilmenite. The heavy mineral contents in the Gercus Formation include Zircon (0.10%) which are considered as ultra-stable, non-opaque minerals, rutile (0.16%; Fig. 5A) is widespread in the Gercus clastic samples. Titanite (0.30-0.35%) and Apatite minerals (Fig. 5C) are relatively high. Garnet (metastable non-opaque minerals) derived from dynamothermal metamorphic source rocks are rare. Epidote, sub-rounded and pitted, was a dominant non-opaque component (Fig. 5D). The unstable heavy minerals pyroxene (hypersthene) occurs as sub-rounded grains with visible cleavages (Fig. 5D) and probably sorted from nearby mafic igneous rocks. Chlorite with yellowish-green lamellae was common. The heavy mineral suites from the Gercus clastic samples were dominated by opaque grains (magnetite), epidote, pyroxene, amphibole and chlorite, all of which were derived from ultrabasic to basic igneous successions of the Iraqi ophiolite terrains. Microcrystalline-cryptocrystalline hematite is also abundant as an authigenic phase, occurring intimately intermixed with detrital clays or it could be as transported grains. It is also possibly replacive of some organic matter within the matrix. Minor pyrite is also very finely disseminated throughout the matrix.

Fig. 4. Photomicrographs of Gercus sandstones; A. lithic-arenite rocks were poorly sorted and angular to subrounded grain morphology (PPL); B. chert fragment (PPL); C. deformed plagioclase (XL); D. dolostone RF (XL); E&F. plutonic rock fragment (PPL)

Fig. 5. Photomicrographs (PPL) of selected heavy minerals in the Gercus clastic formation, 1. Prismatic rutile, B- Hypersthene, C- Euhedral apatite, D- Subrounded epidote

4.3. U-Pb dating Data

Detrital zircon U-Pb geochronology is a widespread and powerful technique and has been used in most subsequent studies to identify the provenance of sedimentary unit (Haas et al. 1999; Fedo et al. 2003). It has been successfully employed in clastic sediments for recording reservoirs in the basins, finding sedimentary pathways, recording denudation histories, and dating volcano-magmatic events (e.g. Andersen, 2005). The zircon grains extracted from the mixed five samples of the Gercus sandstones reveals different morphology. The oldest grains show rounded and destroyed texture due to metamictization (Fig. 6d). The other zircon grains display typical zoning with subhedral to euhedral morphology suggesting igneous origin (Figs. 6 a, b and d).

Fig. 6. Backscattered image of dated detrital zircons in the Gercus clastic rocks. (a, b and c): Zircon grains display typical zoning with subhedral to euhedral morphology; d: Zircon grain shows rounded and destroyed texture

Recently, there have been DZ (detrital zircon) geochronological studies of the post-collisional Neogene foreland basins, including the Injana (Upper Fars), Mukdadiya (Lower Bakhtiari) and Bai-Hasan (Upper Bakhtiari) formations in the Kirkuk embayment (Koshnaw et al. 2017). Thus far, no attempt has been made to apply the DZ U-Pb geochronology to assess the Middle Eocene age active syn-orogenic sedimentation records within foreland basins. DZ U-Pb isotope data are studied from thirty-five zircon grains extracted from the Gercus Formation (Table 3). Concordia and probability density plots (Figs. 7 and 8). Complex U-Pb age data (i.e. multiple age components) are preserved from the studied samples. This can prove challenging for the forward reconstructions of the paleogeography and tectonic evolution of northeastern Iraq. These complex DZ age spectra are attributed to tectonically active terranes occurring to the east of the study area. The U-Pb age distributions of Gercus sediments indicate an influx of detrital material of Qulqula parautochthonous sediment within this formation (Fig. 8). This probably reflects not only the cratonic influence of an Arabian passive margin but also the denudation of an arc built upon a mid-oceanic crust of about 100 Ma. In addition to later ages, Gercus sediments has pronounced 92-102 Ma (Albian-Cenomanian), 221 Ma (Upper Triassic), 395-511 Ma (Cambrian), 570-645 Ma (Neoproterozoic), 1,111 Ma (Mesoproterozoic) and 1,622-1,991 Ma

(Paleoproterozoic) ages, highlighting the cratonic influence of the Proterozoic ages. Therefore, the zircon age populations of the Gercus clastic units studied here can be definitely correlated with those of the source-rock distribution of the Qulqula Rise that shows recycled DZ age contributions from erodible Arabian craton sources.

Fig. 7. Concordia diagram of dated detrital zircons from Gercus clastic rocks shows different concordant points indicates a wide spectrum of Concordia age (Ma)

Fig. 8. Age probability distribution diagram depicting detrital zircon U-Pb ages

Table 3. DZ U–Pb isotopes of the Gercus Formation, NE Iraq

Analysis	U ppm	Th ppm	U/Th	$^{207}\text{Pb}/^{206}\text{Pb}$	$\pm 2 \sigma$ Ma	$^{206}\text{Pb}/^{238}\text{U}$	$\pm 2 \sigma$ Ma	$^{207}\text{Pb}/^{235}\text{U}$ Age Ma	$\pm 2 \sigma$ Ma	$^{206}\text{Pb}/^{238}\text{U}$ Age Ma	$\pm 2 \sigma$ Ma
G 1	190	99.2	0.52	20	190	92	3	93	9	92	3
G 2	175	125	0.71	630	188	93	3	88	9	93	3
G 3	260	257	0.99	0	110	95	3	91	5	95	3
G 4	G 20	93	242	2.60	30	93	96	2	95	96	6
G 5	83	328	3.95	47	83	97	2	98	4	97	2
G 6	120	138	1.15	130	120	98	2	103	6	98	2
G 7	98	212	2.16	202	98	100	2	108	5	99	2
G 8	130	173	1.33	160	130	102	3	109	8	101	3
G 9	85	237	2.79	67	85	101	2	101	4	101	2
G 10	53	950	17.92	65	53	102	3	103	4	102	3
G 11	62	277	4.47	174	62	221	5	223	7	221	5
G 12	92	388	4.21	680	93	389	40	440	30	395	4
G 13	31	1395	45.0	438	28	400	6	405	7	400	10
G 14	49	392	8.00	368	49	415	8	412	10	415	8
G 15	66	135	2.04	542	65	445	10	465	15	444	3
G 16	38	2540	66.84	738	38	516	11	560	11	511	14
G 17	25	1950	78.0	610	25	550	10	565	10	550	10
G 18	68	109	1.60	440	68	565	11	540	15	570	10
G 19	41	1150	28.04	605	40	640	20	625	15	645	3
G 20	82	112	1.37	880	82	678	19	737	23	672	19
G 21	58	394	6.79	690	58	695	29	691	23	697	30
G22	50	340	6.8	1012	45	785	20	845	20	780	10
G23	40	495	12.37	975	40	880	20	900	20	875	4
G24	34	315	9.26	971	34	944	18	966	16	943	19
G25	30	765	25.5	985	25	975	20	975	15	975	7
G26	58	75	1.29	1021	58	995	20	1005	20	996	9
G27	44	298	6.77	1050	40	1110	26	1112	20	1100	10
G28	29	308	10.62	1111	29	1152	21	1152	18	1111	29
G29	48	241	5.02	1120	45	1048	25	1060	20	1120	10
G30	40	309	7.73	1125	40	1158	24	1151	21	1125	40
G31	28	498	17.79	1181	28	1224	23	1225	17	1181	28
G32	28	175	6.25	1504	28	1551	29	1543	20	1504	28
G33	22	422	19.18	1622	22	1653	30	1657	19	1622	22
G34	36	134	3.72	1865	36	1978	43	1946	26	1865	36
G35	30	141	4.70	1991	30	2072	48	2046	30	1991	30

5. Discussion

5.1.U-Pb Zircon Ages and its Tectonic Implications

To better constrain on the evolution of the flexural foreland basin, DZ U-Pb age spectra suggests that the foreland sediments either influx from multiple provenances or are the result of recycling from the accretionary complex terrane, which likely acted as an intermediate sediment repository. The active accretionary prism composed of Pliensbachian-Turonian Qulqula radiolarite (Gharib and De Wever, 2010) and serpentinite-matrix mélange of mixed ages (150 and 200 Ma) (Aziz et al. 2011b). During pre-accretion, however, the radiolarite basin, located along the Arabian passive margin, likely acted as an intermediate sediment repository of mostly Neoproterozoic DZ. It also hosted a significant fraction of the DZ transported directly from the contemporaneously active magmatic arc. In contrast, the serpentinite-matrix mélange was largely composed of post-Cenomanian mantle exhumation (Wrobel-Daveau et al. 2010). Varying volumes of exotic blocks detached and drifted from the Palaeoproterozoic crystalline basement fragment as well as exhumed oceanic crustal sequence, assigning it approximately to the Late Triassic age (Aziz et al. 2011b). It has been noted that the DZ U-Pb age spectra in the underlying Tanjero Formation show nearly exclusive derivation from the uplift Qulqula Formation (i.e. Qulqula Rise) (Aziz and Sadiq, 2020). Our results indicate that a feasible paleogeographic (provenance) reconstruction of the time of Gercus sedimentation (Middle Eocene) would include a biased distribution of detrital materials in the Gercus clastic sediments. Here, the serpentinite-matrix mélange underwent

pervasive pre-Middle Eocene erosion in which the serpentinite matrix was substantially removed by erosion, leaving exotic blocks of different sources amenable to DZ U-Pb dating.

5.2. Provenance of Middle Eocene Cercus

Present-day outcrops of the serpentinite-matrix *mélange* can only be traced to the base of 'Lower Allochthon' (i.e. Walash-Naopurdan nappe) (Aziz, 2008; Aziz et al., 2011a) of age-dated 43-24 Ma (Ali et al., 2013 and Aswad et al., 2014). It demonstrates a block-in-matrix aspect, with exotic blocks of various sizes (centimetric to hectometric) and types (meta-igneous and meta-sedimentary) locally found within the serpentinite matrix (Aziz, 2008). However, the exhumed ophiolitic mantle and associated oceanic crustal of the Late Triassic (219 Ma, see Fig. 9) as well as the crystalline basement sequences of the Palaeoproterozoic (1200-1968 Ma) have been dismembered and occur as fragments enclosed in the chaotic serpentinite-matrix *mélange* (consists of heterogeneous exotic blocks of rock units display mixed age). Unlike the Harsin *mélange* at the southern Iraq-Iran border (Wrobel-Daveau et al., 2010), the accreted serpentinite-matrix *mélange* of the Iraqi segment of the NZTZ underwent pervasive pre-Middle Eocene erosion, where a substantial portion of the serpentinite matrix was removed. These left exotic blocks of the different sources amenable to DZ U-Pb dating. Aziz et al. 2011b analyzed three rock samples for Sr-Nd isotope collected from the locations furthest apart (i.e. Mawat, Galalah, Halsho) and revealed Sr-Nd isotopic heterogeneity. The ages obtained from these samples were 150, 200 and 770 Ma, respectively (Aziz et al. 2011b). The value of $\epsilon_{\text{Nd}} = -30.0$ (Mawat sample, MB) would correspond to a $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of 0.5111 and refer to the Palaeoproterozoic crystalline basement. It is apparent that the U-Pb ages from DZ in Gercus clastic sediments can provide key information on the serpentinite-matrix *mélange*. Specifically, the Late Triassic oceanic domains 219 Ma of the GQR (Galalah, Qalander and Rayat) serpentinite-matrix *mélange* oceanic domains are observed through zircon age population in Gercus clastics, as the mantle floor of the Qulqula radiolarite basin between the Arabian and the Avroman block. The age peaks at ~ 0.4 Ga is interpreted to represent Gondwana rifting and the opening of Paleotethys. Some authors suggest that the formation of Devonian (372-364 Ma) A-type granites in NE Iraq (W Iran) may be connected to the subduction of Paleo Tethys ocean beneath the eastern margins of the Cimmerian blocks (Abdulzahra et al. 2016). The youngest zircon age population in Gercus sandstone rocks (93 Ma) is presumably the age of the uppermost sequence of Qulqula radiolarite basin. This approximates the age of the contemporaneously active magmatic arc (i.e. 106-92; Ma, Aswad & Elias, 1988). We believe that Gercus Formation provides the most suitable archive to study the evolution of the foreland system of the Iraqi segment of the NZTZ with regards to the transition from passive margin to the accretionary complex terrene-flexural foreland basins setting.

5.3. Tectonic Evolution

Flexural tectonics and dynamic loading during the evolution of the foreland system can be recognized through flattening the top Gercus Formation and bending of pre-Tanjero strata (e.g. Turonian-Santonian Kometan Formation). The Maastrichtian-Middle Eocene foreland cycle can be divided into two stages, early stage and late stage. The early stage is defined by the Campanian-accreted terrene (i.e. orogenic wedge) form loads sufficient to produce flexural basin with the deepest part situated next to the tip of the loads. This flexural basin is filled by the flysch clastics of the Maastrichtian-Early Eocene (i.e. referred to by the Tanjero-Kolosh flysch sequence), mainly formed by silty marls, siltstones and sandstones. A paleogeographic reconstruction shows that the flysch clastics grains of Tanjero-Kolosh sequence, incorporated within the deepest part of the flexural basin, were derived from the advancing orogenic wedge. The late stage is marked by a synchronized modification of the clastics fill of the basin and changes in dip directions to compensate for the reduction of the load by both erosion and extension. The basin, therefore, was sealed by a shallowing upwards depositional sequence ending

with the terrestrial Gercus Formation. The development of the latter must be interpreted in the context of Neo-Tethys tectonics and, therefore, in relation to the development of the Paleogene intraoceanic arc volcanicity of Walash, to the northeast of the advancing orogenic wedge. This is documented, for example, by the Middle Eocene extensional dynamic of the foreland system, which was coeval with existence of the active intra-oceanic subduction, preserved as magmatic arcs within the overriding plate, i.e. the Walash arc in the Paleocene-Eocene (Aswad et al. 2011; Aziz et al. 2011b) and Bulfat arc magmatism in the Middle Eocene (Aswad et al., 2016). The short-lived subduction would likely prompt a change in tectonic strain due to subducted slab-pull force. The DZ data suggest the age peaks observed from Gercus molasse is similar to that of Tanjero flysch indicating that the detritus was mainly derived from the Campanian-accreted terranes (Sadiq, 2020). The lack of detritus with Paleogene zircons in the Gercus molasse suggests that the orogenic wedge forms a topographic barrier that prevented the arrival of detritus from the Paleogene intraoceanic arc volcanicity of Walash reaching the flexural foreland basin (e.g. Fig. 10). Combined with other research (Kamen-Kaye, 1971; Sengor and Yilmaz, 1981), It is considered that the Gercus Formation as an integral part of flysch-molasse sequence of the flexural foreland basin, which is developed in the periphery of the advancing orogenic wedges.

Fig.9.Summary of detrital zircon age spectra of the sandstones of the Gercus Formation versus the main tectono-magmatic events of Arabian Plate

Fig. 10. Generalized paleogeography of Eocene (~40Ma) (Hussain and Aghwan 2015) (modified after Saura et al. 2011; Aswad et al. 2014)

The Late Eocene marks the end of the Maastrichtian-Middle Eocene foreland cycle, during which the area was subjected to pre-collision marine transgression (Foreland shallowing upward with the development of the subduction movement). This promoted deposition of the Pila Spi shallow-water carbonates along the entire flexural foreland basin, marking the end of the extension processes contemporaneous with the initiation of orogenic processes. The latter is marked by a Late Eocene subsidence which was induced by ongoing mantle drag forces. Middle Eocene extension is thought to have been triggered by short-lived slab-pulls geodynamic (Fig. 11). Pre-collision Late Eocene marine transgression indicates that the geodynamic process of Zagros Fold-Fault belt is nonlinear and episodic.

Fig. 11. Tectonic evolution of the Iraqi segment of the North Zagros Thrust Zones during Middle Eocene shows that the extensional dynamic of the foreland system which was coeval with existence of the active intra-oceanic subduction which is preserved as magmatic arcs within the overriding plate (i.e., the Walash arc in the Paleocene–Eocene)

6. Conclusions

It is believed that the DZ grains acquired from the Gercus Formation are not directly fed from a primary, cratonic source but are rather recycled from a proximal sediment source in high-relief

accretionary complex terrane (ACT), which acted as a likely origin of a major input of DZ. The accreted terranes (i.e. Qulqula Radiolarite and serpentinites–matrix mélangé) are composed of blocks of different ages and lithologies (post-Cenomanian age of mantle exhumation, Palaeoproterozoic exotic blocks (1,523-1,968 Ma) and Late Triassic age (e.g. 221 Ma)). During pre-accretion, however, the radiolarite basin, located along the Arabian passive margin, certainly acted as an intermediate sediment repository of mostly Neoproterozoic DZ (401-982 Ma). The U-Pb data point to the Arabian passive margin (e.g. the craton or recycled from its sedimentary cover) as one of the main sources of detrital materials for the Qulqula radiolarite sequences. In addition, the upper part of the sequences, characterised by high yields of DZ, was likely transported from the contemporaneously active magmatic arc of Albian-Cenomanian (i.e. 106-92 Ma). The U-Pb ages from DZ in Gercus molasse can provide key information on the deposition age of the Qulqula radiolarite sequences. The zircon U-Pb ages of 221 ± 5 Ma (Norian) (e.g. Fig. 8) may represent the initial stage of oceanic crust formation in a continental rift environment (i.e. between the Arabian and the Avroman-Bisotoun block). The oceanisation process was followed by the formation of a deep (oceanic) basin during the Pliensbachian Stage, dominated by radiolarian cherts (i.e. Qulqula Radiolarite). The age of the youngest DZ population indicates sedimentation occurred during the Cenomanian-Turonian event (97.4 ± 3.4 Ma; $n=10$) at the top of the Qulqula radiolarite sequences.

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