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New petrographic and U–Pb geochronology data from the Mazagan Escarpment, offshore Morocco: Support for an African origin

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A B S T R A C T

Two samples of a granodiorite and a hypersthene granodiorite provided a unique opportunity to investigate the nature of the basement of the Mazagan Escarpment, the northwestern margin of continental Africa (Morocco) on a steep part of the lower continental slope in offshore Morocco. We conducted U–Pb LA-ICPMS geochronology on zircon from the granodiorite, which was acquired from a deep sea drilling program core DSDP544, and on zircon and monazite from a hypersthene granodiorite collected previously during the Cyamaz submersible campaign, to determine the ages of the rocks of the Mazagan Escarpment and interpret their origins. Zircon from the granodiorite yielded a 556 ± 10 Ma crystallization age, abundant inherited zircon cores up to 620 Ma and three ~2.68, ~1.76 and ~1.20 Ga cores. The hypersthene granodiorite yielded ~1950–1750 Ma zircon and ~1820–1640 Ma monazite ages. Some rocks of the closest onshore continental platform have recently been interpreted as belonging to an exotic Avalonian terrane, and correlated with the Mazagan Escarpment. Our data do not provide evidence that the Mazagan Escarpment is part of an exotic terrane. It is more likely that the hypersthene granodiorite formed in an extensional setting after the 2.25–2.07 Ga Eburnean orogeny, at a time of otherwise predominantly mafic magmatism that may have caused magmatic underplating and heating from below. The granodiorite formed during the late Ediacaran, which is characterized by widespread magmatism in Northwest Africa. Therefore, it is likely that the rocks of the Mazagan Escarpment have a Northwest African origin, which implies that the Pangean suture zone lies west of it.

1. Introduction

It is generally thought that the Atlantic Ocean opened along the same line as where the Rheic Ocean had closed in the late Paleozoic to form supercontinent Pangea (Wilson, 1966). At the time of Pangea, continental rocks of the northeastern USA and southeastern Canada were joined with those of Morocco (Wegener, 1912; Choubert, 1935; Wilson, 1966; Bullard et al., 1965; Lefort, 1983, 1988; Letsch, 2017). Recently, Kuiper et al. (2017) analyzed detrital zircon in metasedimentary rocks from the bottom of the COST No. G-1 core in the Georges Bank (Fig. 1), in order to test whether these rocks were part of Meguma or Avalonia (two Gondwanan-derived terranes in the northern Appalachians), or any other crustal material. This is the only well in offshore Massachusetts that was drilled deep enough to penetrate basement below the overlying Jurassic and younger rocks. The detrital zircon signature, characterized by ~3.05–1.90 Ga populations with a 2.2–2.0 Ga peak, is not consistent with those of Meguma or Avalonia, but with Paleoproterozoic platform, predominately clastic rocks that exist on top of the Arche- an–Paleoproterozoic West African Craton. These are exposed in the Anti-Atlas domain of Morocco (Taghdout Group; e.g., Abati et al., 2010; Soulaimani et al., 2019; Ait Lahna et al., 2020) and, therefore, the Georges Bank basement is a piece of West African crust. It is interpreted as having been transferred from Northwest Africa to North America during the Carboniferous to Early Permian formation of Pangea (Alleghanian/Variscan orogeny; Nance et al., 2008; van Staal et al., 2009; Hatcher, 2010) and its subsequent breakup. If correct, the Pangean

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Fig. 1. Simplified geologic map at the time of Pangea (~200 Ma). Geology of North America modified after Hibbard et al. (2006). Geology of Morocco modified after Michard et al. (2010a,b). Pangean breakup line after Labails et al. (2010). Fault and shear zones: EMSZ – East Meseta Shear Zone, RTFZ – Rabat-Tiflet Fault Zone, SAFZ – South Atlas Fault Zone, SMFZ – South Meseta Fault Zone, WMSZ – West Meseta Shear Zone. States/provinces: CT – Connecticut, MA – Massachusetts, ME – Maine, NB – New Brunswick, NH – New Hampshire, NL – Newfoundland, NS – Nova Scotia, QC – Quebec, RI – Rhode Island., VT – Vermont. Other locations: GM – Grand Manan, I – Islesboro.

suture zone must lie northwest of the COST No. G-1 well, on the continental shelf or on land.

Similar to the transfer of a West African fragment to offshore New England, a North American fragment (e.g., Avalonian) may have been transferred to the African continent, either on land or in offshore Morocco. While parts of northwest Morocco (e.g., Sehoul Block and Eastern Meseta; Fig. 1, see below) experienced mid-Paleozoic Caledonian/Acadian deformation and/or plutonism that is associated with the accretion of Avalonia (Simancas et al., 2005; Tahiri et al., 2010), detrital zircon data suggest Northwest African origins for these domains (e.g., Pérez-Cáceres et al., 2017; Letsch et al., 2018; Accotto et al., 2020). The only possible exotic part of northwest Morocco may be basement rocks of the Mazagan Escarpment (Figs. 1 and 2; Ruellan, 1985; Ruellan and Auzende, 1985), a steep part of the lower continental slope off Morocco, formed by normal faulting during the opening of the Atlantic Ocean (Favre et al., 1991). An exotic, Avalonian origin has been suggested for the Mazagan Escarpment (El Haibi et al., 2020) based on the ~1000 Ma K/Ar date previously obtained by one of us (Ruellan, 1985). In order to test this hypothesis, we conducted U–Pb LA-ICPMS geochronology on two available samples from the escarpment. Zircon was analyzed from a granodiorite from a deep sea drilling program core DSDP544 (Hinz et al., 1984), and zircon and monazite from a hypersthene granodiorite

Fig. 2. Bathymetric map of the Mazagan Plateau and Escarpment (traced from Auzende et al., 1983) with locations of drill core DSDP544 and sample CZ-91-5 indicated (Vema cores V30–225 and V30-227 are no longer preserved).

(sample CZ-91-5) collected during the Cyamaz submersible campaign (Ruellan, 1985). The data are presented and discussed in the context of the amalgamation and breakup of supercontinent Pangea as well as earlier possible terrane configurations.

2. Geological background

The northwestern part of Morocco that was adjacent to the northeastern USA and southeastern Canada in the Pangean configuration can be divided into the Anti-Atlas domain to the south and the Atlas-Meseta (in short: Meseta) domain to the north (Fig. 1). These domains are separated by the South Meseta Fault Zone, a crustal scale dextral strike-slip fault zone that was active during the Variscan/Alleghanian orogeny as a result of the formation of Pangea (e.g., Michard et al., 2010b). The South Atlas Fault overprinted it during the Mesozoic-Cenozoic Atlas orogeny (Fig. 1; Michard et al., 2010a). The Meseta domain can be divided into an Eastern and Western Meseta domain, and the Western Meseta domain can be separated in the Central Meseta Block to the east, the Sehoul Block to the north, and the Coastal Block to the west (Fig. 1; Hoepffner et al., 2006; Michard et al., 2010b; Accotto et al., 2019, 2020). Each of these domains is fault bounded (e.g., Michard et al., 2010b).

Regionally, the oldest rocks occur in the WAC, exposed in the Reguibat Shield ~300 km south of the Anti-Atlas domain (Fig. 1). The WAC basement consists of Archean and Paleoproterozoic crust with ~3.6–3.5 Ga, ~3.24–2.92 Ga, ~2.91–2.70 Ga, ~2.46 Ga, ~2.2–2.1 Ga, ~2.14–2.02 Ga and ~1.85 Ga ages (e.g., Barth et al., 2002; Thiéblemont et al., 2004; Schofield et al., 2006; Montero et al., 2014, 2016). Paleoproterozoic rocks are also locally exposed in the Coastal Block (Pereira et al., 2015).

Neoproterozoic orogenic events resulted in ~760–700 Ma,

Fig. 3. Photographs of granodiorite from deep sea drilling program core DSDP544 (33° 46.0′ N, 09° 24.3′ W; Hinz et al., 1984) with samples indicated: three pieces from core section 24.1 at 20–30 cm depth and two from section 28.1 at 30–38 cm depth.

Table 1
X-ray fluorescence analysis for DSDP granodiorite core sample 544A (from Kreuzer et al., 1984).

	Rock	Feldspar-Quartz
SiO2	73.18	73.2
TiO2	0.1	0.02
Al2O3	14.82	14.02
Fe2O3	1.1	0.27
MnO	0.03	0.01
MgO	0.26	0.09
CaO	1.63	2.69
Na2O	3.99	4.52
K2O	3.4	2.93
P2O5	0.03	0.02
LOI	0.63	1.5
Total	99.17	99.27
Quartz	31.47	29.45
Orthoclase	14.92	17.51
Albite	36.52	41.52
Anorthite	8.46	0.71
Muscovite	5.93	
Biotite	2.2	0.33
Epidote		10.4
Apatite	0.06	0.14
Ilmenite	0.14	0.03
Magnetite	0.28	
Zircon	0.01	0.01

~680–640 Ma and ~620–555 Ma igneous rocks northwest of the Reguibat Shield, including structural inliers of the Anti-Atlas domain and rare exposures in the Meseta domain (Soulaimani and Burkhard, 2008; Michard et al., 2010b; Ikenne et al., 2017; Ouabid et al., 2017, 2020; El Houicha et al., 2018; Accotto et al., 2019). Cambrian to Devonian sedimentary rocks and minor volcanic rocks overlie the Paleoproterozoic and Neoproterozoic basement and are exposed in the Anti-Atlas and Meseta domains (Thomas et al., 2002, 2004; Walsh et al., 2002, 2012; Soulaimani and Burkhard, 2008; Michard et al., 2010b; El Houicha et al., 2018; Letsch et al., 2018; Accotto et al., 2019). The rocks were variably metamorphosed, up to amphibolite facies, in the Carboniferous (e.g., Michard et al., 2010b; Chopin et al., 2014) and intruded by Late Devonian to Early Permian felsic and mafic rocks (e.g., Tahiri et al., 2010; Michard et al., 2010b; Ikenne et al., 2017).

The Sehoul Block experienced deformation prior to intrusion of the ~367 Ma Rabat granitoid (Tahiri et al., 2010), suggesting some pre- or Eo-Variscan (late Caledonian/Acadian?) tectonism. However, rock types and detrital zircon signatures suggest that the (meta)sedimentary rocks in all Meseta domains have Northwest African origins (Pérez-Cáceres et al., 2017; Letsch et al., 2018; Accotto et al., 2019). The Meseta domain (except the Sehoul Block?) can be interpreted as part of Cadomia (cf. Armorican Terrane Assemblage; Franke et al., 2021, and references therein) that rifted from Gondwana before it accreted back on to it during the ~620-555 Ma Cadomian orogeny (Hefferan et al., 2014; Michard et al., 2017; Pérez-Cáceres et al., 2017). The only part of northwest Morocco that might be exotic is the Mazagan Plateau with its large steep drop-off, the Mazagan Escarpment, along the continental slope in offshore Morocco (Figs. 1 and 2). Basement rocks of the Mazagan Escarpment consist of granodiorite and hypersthene granodiorite (Kreuzer et al., 1984; Ruellan, 1985). Rocks of El Jadida on the northwest coast of the Coastal Block (Fig. 1) have been tentatively correlated with the Mazagan Escarpment (El Haibi et al., 2020).

3. Basement rocks of the Mazagan Escarpment; methods and results

3.1. Samples

Two samples were available from the base of the Mazagan Escarpment, a steep part of the continental slope along the northwestern edge of the Mazagan plateau in offshore Morocco (Fig. 2). Deep sea drilling program core DSDP544 (33°46.0′N, 09°24.3′W; Hinz et al., 1984) was one of a few cores drilled deep enough to penetrate basement rocks and the only one still preserved. It was drilled into a lower steep part of the continental shelf, at 3607 m depth (Fig. 2). A granodiorite was available from the IODP core repository in Bremen and three pieces from core section 24.1 at 20–30 cm depth and two from section 28.1 at 30–38 cm depth were analyzed in this study (Fig. 3). Two Vema expedition cores containing basement rocks, V30–225 and V30-227 (Kreuzer et al., 1984, Fig. 2) were last seen at the Lamont-Doherty core repository but are no longer there and therefore not analyzed. The granodiorite of DSDP544 is coarse grained and foliated, and contains quartz, K-feldspar, plagioclase, muscovite and biotite and minor epidote, magnetite, ilmenite, apatite and zircon (Table 1). It is described in detail in Kreuzer et al. (1984). It yielded K/Ar dates (Kreuzer et al., 1984) of ~516 and ~459 Ma (muscovite), ~369 and ~335 (biotite), and ~314 Ma (feldspar). Zircon LA-ICPMS analysis was carried out on a zircon separate from the five pieces of granodiorite from drill core DSDP544 in order to constrain its age, and inherited zircon populations.

A hypersthene granodiorite (sample CZ-91-5, 33°28.3′N, 09°33.1′W) was taken during the Cyamaz submersible campaign from an outcrop on the Mazagan Escarpment at 2650 m depth (described as charnockite by Ruellan, 1985; see Table 2 for composition). The continental basement of the margin is interpreted as having been exhumed from beneath the sedimentary cover through a set of major normal faults that formed the escarpment at the Atlantic Ocean/continent transition (Ruellan, 1985). One whole-rock sample and one separate of 'white minerals' (quartz and feldspar) previously yielded K/Ar dates of ~1.0–0.9 Ga (Ruellan, 1985).

Table 2
Average microprobe mineral compositions for sample CZ-91-5 (from Ruellan, 1985).

	Plagioclase		K-Feldspar		Orthopyroxene		Ilmenite	
SiO2	59.2		63.96		51.96		0.03	
TiO2	0.02		0.03		0.02		47.58	
Al2O3	26.35		18.82		1.74		0.02	
Fe2O3							10.7	
Cr2O3	0.04		0.01		0		0.05	
FeO	0.04		0.01		26.28		40.86	
MnO	0.02		0.03		0.8		0.32	
MgO	0.01		0.03		19.77		0.92	
CaO	7.74		0.02		0.37		0.02	
Na2O	7.04		0.89		0.15		0.03	
K2O	0.28		15.9		0.04		0	
Total	100.74%		99.70%		101.13%		100.53%	
	Orthoclase	1.6	Orthoclase	92.07	Wollastonite	0.75	Hematite	10.11
	Albite	61.21	Albite	7.83	Hypersthene	56.11		
	Anorthite	37.19	Anorthite	0.1	Ferrosilite	43.14		

Table 3
LA-ICPMS isotopic U–Pb data for zircon in sample DSDP 544.

					Corrected isotope ratios[a]							Dates (Ma)[a,c]						
Analysis[b]	Grain label	U ppm	Pb* ppm	Th/U	207 Pb*/235U*	±2σ (%)	206 Pb*/238U	±2σ (%)	error corr.	207 Pb*/206 Pb*	±2σ (%)	207 Pb*/206 Pb*	±2σ (Ma)	207 Pb*/235U*	±2σ (Ma)	206 Pb*/238U	±2σ (Ma)	% disc.
IODP-24 L 132	A	115.2	12.38	0.31	0.7677	5.40	0.0936	3.57	0.66	0.0595	4.05	584	88	578	24	577	20	1
IODP-24 L 133	A	129.5	13.75	0.36	0.7312	6.89	0.0912	3.48	0.50	0.0581	5.95	535	130	557	30	563	19	5
IODP-24 L 134	A	106.3	11.04	0.30	0.7346	6.06	0.0917	3.67	0.60	0.0581	4.83	533	106	559	26	566	20	6
														MSWD¼0.6		**568**	**12**	**N¼3**
IODP-24 L 135	B	123.5	13.84	0.23	0.8233	5.18	0.0997	2.49	0.47	0.0599	4.54	598	98	610	24	613	15	2
IODP-24 L 136	B	136.7	15.00	0.20	0.8022	6.41	0.0991	4.58	0.71	0.0587	4.49	557	98	598	29	609	27	9
														MSWD¼0.1		**612**	**13**	**N¼2**
IODP-24 L 137	C	147.3	17.49	0.43	0.8328	5.24	0.0986	3.87	0.73	0.0613	3.53	648	76	615	24	**606**	**22**	6
IODP-24 L 140	D	110.6	13.72	0.47	0.8752	9.29	0.1022	3.44	0.37	0.0621	8.62	678	184	638	44	627	21	8
IODP-24 L 141	D	147.8	18.39	0.64	0.8339	7.33	0.0976	5.34	0.73	0.0619	5.02	672	107	616	34	601	31	11
														MSWD¼2.1		**619**	**13**	**N¼2**
IODP-24 M 142	E	294.4	34.03	0.44	0.8121	4.60	0.0959	3.67	0.79	0.0614	2.78	654	60	604	21	**590**	**21**	10
IODP-24 M 143	F	407.6	41.99	0.05	0.7983	4.33	0.0945	3.31	0.75	0.0613	2.80	650	60	596	20	**582**	**18**	10
IODP-24 M 147	G	474.8	51.97	0.40	0.7417	4.08	0.0911	3.12	0.75	0.0590	2.64	569	57	563	18	562	17	1
IODP-24 M 148	G	571.8	60.29	0.36	0.7186	4.02	0.0887	3.30	0.81	0.0588	2.31	558	50	550	17	548	17	2
														MSWD¼1.4		**555**	**13**	N=2
IODP-24 M 150	H	410.9	91.89	0.27	2.0471	3.56	0.1857	3.10	0.86	0.0800	1.76	1196	35	1131	24	1098	31	8
IODP-24 M 151	H	699.9	162.63	0.25	2.0452	4.27	0.1853	4.09	0.95	0.0801	1.25	1198	25	1131	29	1096	41	9
												1197	**22**	**MSWD¼0.01**				**N¼2**
IODP-24 M 153	I	313.4	34.28	0.31	0.7903	4.62	0.0944	3.20	0.68	0.0607	3.33	630	72	591	21	**581**	**18**	8
IODP-24 M 155	J	125.8	13.46	0.40	0.6993	6.71	0.0920	4.26	0.63	0.0551	5.18	416	116	538	28	**568**	**23**	36
IODP-24 S 158	K	148.9	56.79	0.48	4.4860	10.26	0.3001	8.24	0.80	0.1084	6.11	**1773**	**112**	1728	85	1692	123	5
IODP-24 S 161	L	211.2	24.01	0.60	0.7873	5.15	0.0951	3.87	0.75	0.0601	3.39	606	73	590	23	**585**	**22**	3
IODP-24 S 165	M	747.7	75.73	0.14	0.7339	3.01	0.0899	2.44	0.79	0.0592	1.77	576	38	559	13	555	13	4
IODP-24 S 166	M	904.6	92.93	0.15	0.7371	3.70	0.0904	3.17	0.84	0.0591	1.91	571	42	561	16	558	17	2
														MSWD¼0.1		**556**	**11**	**N¼2**
IODP-28 L 177	N	56.3	6.33	0.23	0.8473	9.63	0.0987	3.88	0.40	0.0623	8.81	684	188	623	45	**606**	**22**	11
IODP-28 L 178	O	113.9	13.28	0.47	0.8111	6.83	0.0966	4.24	0.62	0.0609	5.36	635	115	603	31	595	24	6
IODP-28 L 179	O	164.3	19.60	0.47	0.8175	5.91	0.0973	3.57	0.60	0.0609	4.71	636	101	607	27	599	20	6
IODP-28 L 180	O	202.4	24.39	0.66	0.7556	4.91	0.0929	3.96	0.80	0.0590	2.90	567	63	571	21	573	22	1
														MSWD¼1.7		**589**	**14**	**N¼3**
IODP-28 L 182	P	431.8	46.25	0.23	0.7791	4.00	0.0934	3.20	0.79	0.0605	2.40	622	52	585	18	575	18	7
IODP-28 L 183	P	682.4	73.82	0.09	0.8475	7.47	0.0954	5.41	0.72	0.0644	5.16	756	109	623	35	587	30	22
														MSWD¼0.45		**579**	**16**	**N¼2**
IODP-28 L 184	Q	428.4	45.64	0.02	0.8152	3.97	0.0985	3.28	0.82	0.0600	2.24	604	48	605	18	**606**	**19**	0
IODP-28 L 187	R	89.0	10.24	0.41	0.7893	6.77	0.0972	3.97	0.58	0.0589	5.49	564	120	591	30	**598**	**23**	6
IODP-28 M 189	S	970.1	104.96	0.24	0.7898	5.04	0.0900	3.22	0.63	0.0637	3.87	730	82	591	23	**555**	**17**	24
IODP-28 M 192	T	193.3	21.19	0.42	0.8227	4.76	0.0915	2.97	0.61	0.0652	3.72	780	78	610	22	**565**	**16**	28
IODP-28 M 193	U	170.3	19.26	0.48	0.9003	6.12	0.0915	3.56	0.57	0.0713	4.99	967	102	652	29	565	19	42
IODP-28 M 194	U	163.6	16.65	0.37	0.7577	4.28	0.0878	2.88	0.66	0.0626	3.16	694	67	573	19	542	15	22
IODP-28 M 195	U	226.1	24.05	0.40	0.7368	5.70	0.0902	2.96	0.51	0.0593	4.88	577	106	561	25	556	16	4
														MSWD¼1.8		**553**	**11**	**N¼3**
IODP-28 S 199	V	137.9	15.59	0.72	0.7669	5.66	0.0914	2.48	0.43	0.0609	5.09	635	109	578	25	**564**	**13**	11
IODP-28 S 200	W	179.4	21.68	0.97	0.7546	4.72	0.0931	2.84	0.59	0.0588	3.77	560	82	571	21	574	16	2
IODP-28 S 201	W	279.0	31.45	0.88	0.7254	4.03	0.0878	3.25	0.80	0.0599	2.38	600	52	554	17	**543**	**17**	10
IODP-28 S 202	X	166.8	21.41	0.86	0.9049	7.11	0.0978	4.24	0.59	0.0671	5.71	842	119	654	34	601	24	29

(*continued on next page*)

Table 3 (*continued*)

Analysis[b]	Dates (Ma)[a,c] 207 Pb*/206 Pb*	Grain label	±2σ (Ma)	U ppm	207 Pb*/235U*	Pb* ppm	±2σ (Ma) / Th/U	Corrected isotope ratios[a] 206 Pb*/238U* / 207 Pb*/235U*	±2σ (Ma) / ±2σ (%)	% disc.	206 Pb*/238U	±2σ (%)
IO4D4P-28 S 8935		X	92	471.36	6	65.87	261.65	**565** 0.8703	**17** 5.41	37	0.0916	3.09
IO2D3P-28 S **1758**		Y	**23**	290.814		95.34	290.37	1508.8995	46 3.62	14	0.2630	3.41
IO7DP-28 S 2986		Z	149	159.79		19.20	400.62	591 0.9522	18 7.99	40	0.0959	3.23
IO9D4P-28 S 7209		AA	84	305.44		33.75	260.42	577 0.8131	23 5.74	19	0.0936	4.17
IO3D6P-28 S 6083		AA	72	293.2 594		31.53	200.34	575 0.7947	16 4.44	14	0.0933	2.89
				MSWD¼0.02				**576**	**14**	**N¼2**		
IO3D6P-28 S 5309		AB	74	349.2 543		36.33	170.44	546 0.7071	12 4.12	3	0.0884	2.38
IO0D7P-28 S 7265		AB	65	409.4 586		44.74	210.65	540 0.7802	18 4.63	29	0.0874	3.47
				MSWD¼0.3				**544**	**11**	**N¼2**		
IO3D0P-28 S 7015		AC	70	295.89		34.20	230.84	**559** 0.7854	**21** 5.09	21	0.0906	3.88
IO8D6P-28 S 2663		AD	31	97.2451		57.89	301.03	2204 0.1745	48 3.20	17	0.4075	2.59
IO6D5P-28 S 2648		AD	27	78.2518		47.76	560.95	2313 0.9402	112 6.02	14	0.4315	5.79
	2677		**22**	**MSWD¼1.5**						**N¼2**		
IO8D7P-24 S 5163		AE	129	194.69		23.97	310.99	**583** 0.7519	**23** 7.20	13	0.0946	4.16

[a] Isotope ratio and date errors do not include systematic calibration errors of 0.50% (207Pb/206Pb) and

[b] Ablation used a laser spot size of 25 μm and a laser firing repetition rate of 5 Hz.

[c] Crystallization ages from best date, or weighted mean of dates (MSWD indicated; error includes standar

Fig. 4. U–Pb laser ablation inductively coupled mass spectrometry (LA-ICPMS) data for zircon in granodiorite in drill core DSDP544 (see Fig. 3). (a) Wetherill Concordia diagram with 2σ error ellipses. Analytical spot sizes indicated in white on zircon cathodoluminescence images are 25 μm. (b) Probability density diagram of $^{206}Pb/^{238}U$ ages (<1000 Ma) and $^{207}Pb/^{206}Pb$ ages (>1000 Ma). Ages are averages per grain where more than one spot analysis per grain.

The only sample preserved is a small piece with a volume of about 6 cm^3. To preserve most of the sample, U–Pb LA-ICPMS zircon and monazite geochronology was carried out in situ in thin section.

3.2. Methods

Zircon grains of the granodiorite of DSDP544 were separated from rocks at Boise State University using standard techniques, annealed at 900 °C for 60 h in a muffle furnace, and mounted in epoxy and polished until their centers were exposed. Cathodoluminescence (CL) images were obtained with a JEOL JSM-300 scanning electron microscope and Gatan MiniCL (Supplementary Fig. 1). Zircon was analyzed by LA-ICPMS using a ThermoElectron X-Series II quadrupole ICPMS and New Wave Research UP-213 Nd:YAG UV (213 nm) laser ablation system. Detailed methods are outlined in the Appendix.

Prior to zircon and monazite U–Pb LA-ICPMS analysis in a thin section of the hypersthene granodiorite sample CZ-91-5, an automated mineralogy (AM) – bright phase search was conducted, which helped to locate zircon and monazite, and other phases that are bright (high Z-

Table 4
Chemical data for best date or weighted mean data of Table 1.

Grain label	Date (Ma)	n =	Ti-in-zircon Ti(ppm)	T(°C)	Eu/Eu*	$\sum$REE	(Gd/Yb)cn	Nb/Ta	U(ppm)	Th/U
AD	2677	2	6.69	729	0.29	382	0.08	1.79	88	0.99
K	1773	1	5.90	718	0.08	758	0.04	1.12	149	0.48
Y	1758	1	5.94	719	0.31	1151	0.08	1.91	291	0.37
H	1197	2	6.75	730	0.02	810	0.04	1.40	555	0.26
D	619	2	9.45	760	0.24	445	0.07	0.83	129	0.56
B	612	1	3.42	672	0.42	476	0.02	3.27	130	0.21
N	606	1	4.74	699	0.38	520	0.02	3.58	56	0.23
C	606	3	10.79	775	0.24	396	0.05	2.19	147	0.43
Q	606	1	5.84	717	0.07	152	0.44	0.31	428	0.02
R	598	1	4.58	696	0.37	556	0.03	3.31	89	0.41
E	590	1	3.99	685	0.49	534	0.03	1.92	294	0.44
O	589	3	9.91	766	0.30	475	0.05	1.38	160	0.53
L	585	1	8.60	753	0.24	439	0.05	1.50	211	0.60
AE	583	1	7.25	737	0.57	1894	0.05	6.34	195	0.99
F	582	1	3.73	679	0.25	408	0.04	1.43	408	0.05
I	581	1	5.68	715	0.17	403	0.04	1.52	313	0.31
P	579	2	3.96	686	0.06	2129	0.02	2.82	432	0.23
AA	576	2	2.98	660	0.23	946	0.05	1.87	299	0.38
A	568	3	3.22	667	0.39	810	0.03	3.52	117	0.33
J	568	1	3.48	673	0.41	860	0.03	4.30	126	0.40
X	565	1	11.04	777	0.30	1419	0.07	6.78	472	1.65
T	565	1	5.58	713	0.57	1012	0.02	3.17	193	0.42
V	564	1	4.26	690	0.37	1532	0.05	3.22	138	0.72
AC	559	1	5.74	716	0.62	603	0.04	1.98	295	0.84
M	556	2	1.71	619	0.47	1188	0.02	2.22	826	0.14
S	555	1	1.97	629	0.57	528	0.06	3.59	970	0.24
G	555	2	2.74	654	0.45	1520	0.03	3.94	523	0.38
U	553	3	5.14	705	0.47	1315	0.04	3.57	187	0.42
AB	544	2	6.61	728	0.22	1476	0.03	5.94	379	0.55
W	543	1	12.00	785	0.40	2037	0.05	5.40	279	0.88

Activity of TiO_2 for Ti-in-Zircon temperature calculation is 0.8.
Weighted mean dates are shown for grains with multiple analyses.
Errors on weighted mean dates include systematic calibration errors.
Chemical compositions are averages for grains with multiple analyses.

number) in backscattered electron (BSE) images (Supplementary Fig. 2). Identified zircon and monazite grains were then imaged using BSE analysis on a MIRA3 field emission scanning electron microscope. Detailed full AM analysis was carried out on part of the thin section to determine mineral phase and composition of the hypersthene granodiorite. AM and BSE imaging was conducted at the Colorado School of Mines, and details are provided in the Appendix. Zircon and were ablated and analyzed at the U.S. Geological Survey G3 Plasma Lab (Denver, CO USA) using a Photon Machines Excite™ 193 nm ArF excimer laser that was coupled to a Nu Instruments AttoM high-resolution magnetic-sector inductively coupled plasma mass spectrometer. See Appendix for detailed methods.

3.3. Results

The analyzed samples from drill core DSDP544 are shown in Fig. 3. Forty-five LA-ICPMS analyses were placed in 30 zircon grains with 1–3 analyses per grain (Table 3, Fig. 4). CL images show complex zoning, most commonly with CL-bright and CL-dark cores and CL-dark rims (Fig. 4a; Supplementary Fig. 1). A few grains are entirely CL-bright or CL-dark. Three analyses of CL-dark domains in grains M and S (Tables 3 and 4) are U-rich (750–970 ppm), have low Th/U ratios (0.14–0.24), have low Ti-in-zircon temperatures (618–629 °C; cf. Watson et al., 2006), and yielded dates with a weighted mean of 556 ± 10 Ma (MSWD = 0.05). Sixteen dates from CL-bright cores with modest U concentrations (100–500 ppm), modest Th/U ratios (generally 0.3–0.9), and 650–780 °C Ti-in-zircon temperatures overlap with the 556 ± 10 Ma weighted mean from the CL-dark rims. Their characteristics are typical of zircon formed during crystallization of arc magmas. They either formed during protolith crystallization or were inherited in the protolith magma.

Many grains up to ~620 Ma (Table 3, Fig. 4) are interpreted has being inherited in the protolith magma based on chemical composition or age. Two of those grains have compositions typical of metamorphic zircon (Tables 3 and 4). Grain Q with a date of 606 ± 19 Ma has low total REE concentrations (152 ppm), a low Th/U ratio (0.02), and a shallow slope of MREE to HREE ((Gd/Yb)cn = 0.44), which suggests zircon grew before or during crystallization of the granodiorite. Grain F with a date of 582 ± 18 Ma has a low Th/U ratio (0.05). Four inherited grains yielded much older dates (Fig. 4, Tables 3 and 4). Grain H has two dates with a weighted mean of 1197 ± 22 Ma (MSWD = 0.01) and 8–9% discordance. Grain K has a date of 1773 ± 112 Ma with 5% discordance. Grain Y has a date of 1758 ± 23 Ma with 14% discordance. Grain AD has two dates with a weighted mean of 2677 ± 22 Ma (MSWD = 1.5, probability of fit = 0.22) and 14–17% discordance.

Sample location images for hypersthene granodiorite sample CZ-91-5 are shown in Fig. 5 a and b. Minerals as determined using optical microscopy and AM analysis (Fig. 5c) are plagioclase, K-feldspar, quartz, hypersthene, and minor pyrite, biotite, chlorite, ilmenite, magnetite, rutile, apatite, zircon and monazite. The hypersthene granodiorite has a granoblastic texture and feldspar is partly perthitic (cf. Ruellan, 1985). On a quartz-alkali feldspar-plagioclase feldspar (QAP) ternary diagram (Fig. 5d), the hypersthene granodiorite composition (Ruellan, 1985, Table 2) plots in the 'opdalite' or orthopyroxene-bearing granodiorite field along the border with the 'charnockite' or orthopyroxene-bearing granite fields of Le Maitre (1989) and Frost and Frost (2008). The A (Al_2O_3), F (FeO), and M (MgO), iron–magnesium variation, modified alkali lime index (MALI) and alumina saturation index (ASI) diagrams show a magnesian, calk-alkaline and metaluminous composition (Fig. 5e–h; Frost and Frost, 2008).

Zircon in the hypersthene granodiorite all display zoned cores with unzoned overgrowths (Fig. 6a; Supplementary Fig. 2). U–Pb data are

Fig. 5. (a) Location of sample CZ-91-5. The outcrop consists of massive platform limestone that is difficult to distinguish from the basement rocks. Viewing direction is 129°. (b) Sample CZ-91-5 in the clamp of the submersible. The viewing direction is 097°. (c) Automated mineralogy analysis image of a thin section of sample CZ-91-5. (d) QAP diagram showing the names of rocks in the charnockite series of igneous rocks, including the now abandoned charnockite subdivisions of 'charnockite' (orthopyroxene-bearing granite), 'opdalite' (orthopyroxene-bearing granodiorite) and 'enderbite' (orthopyroxene-bearing tonalite) of Le Maitre (1989) for completeness. (e) AFM diagram. (f) Iron–magnesium variation diagram. (g) Modified alkali lime index (MALI) diagram. (h) Alumina saturation index (ASI) diagram. Data from Ruellan (1985) and diagrams after Frost and Frost (2008, 2019).

presented in Table 5. Cores and rims yielded similar ages (Fig. 6b and c). These ages can be interpreted as one age population or three. They may represent continuous growth between ~1950 Ma and ~1750 Ma or variable amounts of Pb loss in rims and cores until ~1750 Ma. Monazite is apparently unzoned and ages are ~1820–1640 Ma, reflecting either continuous growth or Pb loss until 1640 Ma (Table 5, Fig. 6d and e).

4. Discussion

The granodiorite of DSDP544 yielded a 556 ± 10 Ma U–Pb LA-ICPMS zircon crystallization age with significant Neoproterozoic inheritance. These results are consistent with most African or Amazonian late Ediacaran plutonic rocks, and therefore provide limited information about the origin of the basement below the granodiorite. Four older inherited zircon cores yielded ~2.68 Ga, ~1.76 Ga and ~1.20 Ga ages.

Analyzed zircon from Neoproterozoic igneous rocks in the Anti-Atlas show only rare ~2.2–1.2 Ga ages of inherited zircon (Thomas et al., 2002; Gasquet et al., 2005; Bouougri et al., 2020), and only one Neoproterozoic sedimentary rock from the Anti-Atlas yielded ~2.2–1.0 Ga detrital zircon ages (Bouougri et al., 2020). The Meseta domain shows rare but increasing evidence for Mesoproterozoic and Paleoproterozoic zircon sources. A ~2.05 Ga rhyolitic porphyry as a result of the 'Eburnean' magmatic event and orogeny is exposed along the eastern border of the Coastal Block (Pereira et al., 2015). Reported Mesoproterozoic and older inherited zircon ages are from three ~1.8, ~1.5 and ~1.2 Ga grains in a Carboniferous granite in the Eastern Meseta (Oukemeni et al., 1995), ~1.2–1.0 Ga grains in Cambrian–Ordovician intrusive rocks in the Central Meseta (Ouabid et al., 2020), four ~1.1 Ga grains in an Ediacaran granitoid from the Sehoul Block (Tahiri et al., 2010), and ~2.5–2.0 Ga and ~1.2 Ga grains in Neoproterozoic rhyolite in the El Jadida horst of the western Coastal Block (El Haibi et al., 2020). Elsewhere in the Anti-Atlas or Meseta domains no Mesoproterozoic or older inherited zircon is reported (e.g., Thomas et al., 2002; Inglis et al., 2004, 2005; Gasquet et al., 2005; D'Lemos et al., 2006; Walsh et al., 2002,

Fig. 6. (a) Backscattered electron images of typical zircon from hypersthene granodiorite sample CZ-91-5. (b–e) In situ LA-ICP-MS data for zircon (b,c) and monazite (d,e) on Wetherill Concordia (b,d) and float bar charts of $^{207}Pb/^{206}Pb$ ages with weighted averages indicated (c,e). Uncertainties on ellipses and bars are 2σ.

2012; Toummite et al., 2013; Ouabid et al., 2017; Letsch et al., 2018). Thus, the three ~2.68 Ga, ~1.76 Ga and ~1.20 Ga inherited core ages in the granodiorite do not necessarily suggest an exotic origin and late Ediacaran crystallization age and abundant inherited zircon cores up to ~620 Ma may simply suggest an affiliation with the Meseta basement. Previously obtained ~516–314 Ma K/Ar dates (Kreuzer et al., 1984) are younger than the crystallization age obtained here and may represent Ar loss, e.g. during the Variscan orogeny.

The hypersthene granodiorite yielded ~1950–1750 Ma zircon and ~1820–1640 Ma monazite U–Pb dates, acquired by in situ LA-ICPMS methods, suggesting Paleoproterozoic crystallization and metamorphism. Ruellan (1985) suggested that the hypersthene granodiorite (CZ-91-5) has a Grenville (Laurentian) origin, based on its apparent ~1.0–0.9 Ga K/Ar ages. However, the K/Ar ages may represent Ar loss and they are geologically meaningless. The magnesian, calk-alkaline and metaluminous composition of the hypersthene granodiorite (Fig. 5e–h) is consistent with an arc or convergent setting (Frost and Frost, 2008). Thus, this rock is expected to have formed in one of the Paleoproterozoic orogens linked to the mainly 2.1–1.8 Ga global-scale collisional events that resulted in supercontinent Columbia (Zhao et al., 2004; Meert and Santosh, 2017).

There are two possible interpretations for the new Paleoproterozoic ages reported here from the hypersthene granodiorite of the Mazagan Escarpment. First, the hypersthene granodiorite and probably all basement rocks from the escarpment may represent a fragment of any of the Gondwanan terranes exposed in the northeastern USA and southeastern Canada. These are Avalonia, Ganderia and Meguma (Fig. 1). However, Meguma does not contain Precambrian rocks or basement (e.g., Waldron et al., 2009, 2011; White and Barr, 2010, 2012; Pothier et al., 2015) and the hypersthene granodiorite is unlikely to represent part of it. Based on detrital zircon signatures of metasedimentary rocks, inherited zircon in plutonic and volcanic rocks, and Sm/Nd model ages, Avalonia is interpreted as having predominately 1.3–1.0 Ga and Ganderia a 1.8–1.2 Ga basement (e.g., Nance and Murphy, 1996; Murphy et al., 2000, 2004; 2013; Keppie et al., 2003; Samson et al., 2000, 2003; 2005; Schofield and D'Lemos, 2000; Rogers et al., 2006; Hibbard et al., 2007; Thompson et al., 2010, 2012; Pollock et al., 2012; Dorais et al., 2012; Henderson et al., 2016; Kay et al., 2017). While it is possible that the hypersthene granodiorite represents basement of Ganderia, it is unlikely to be basement of Avalonia.

If this part of the Mazagan escarpment has Ganderian origin, it was most likely amalgamated with the Meseta domain (which may be interpreted as the Moroccan segment of Cadomia; see above) during the amalgamation of Pangea (Alleghanian-Variscan orogeny; Torsvik and

Table 5
LA-ICPMS isotopic U–Pb for zircon in sample CZ-91-5.

					Isotope ratios							Dates (Ma)							
Analysis	Spot	U ppm	Pb ppm	Th/U	207 Pb/235U	±2σ	206 Pb/238U	±2σ	error corr.	207 Pb/206 Pb	±2σ	207 Pb/206 Pb	±2σ (Ma)	207 Pb/235U	±2σ (Ma)	206 Pb/238U	±2σ (Ma)	% disc.	core/rim
Zircon																			
CZ95d1_01	CZ95-1-1R	699	71	1.7	5.66	0.17	0.344	0.016	0.83241	0.1188	0.0035	1935	52	1923	27	1902	75	2	rim (mix)
CZ95d1_02	CZ95-1-1c	1144	58	3.3	5.53	0.12	0.342	0.010	0.64787	0.1169	0.0026	1908	43	1905	19	1898	49	1	core
CZ95d1_03	CZ95-1-2R	99	25	0.6	5.03	0.16	0.325	0.013	0.75687	0.1117	0.0031	1825	50	1823	26	1811	61	1	rim
CZ95d1_04	CZ95-1-2C	878	92	1.5	4.92	0.16	0.322	0.011	0.90760	0.1103	0.0024	1804	39	1805	28	1800	52	0	core
CZ95d1_05	CZ95-1-3R	169	13	2.0	4.98	0.18	0.313	0.013	0.75280	0.1150	0.0032	1878	51	1813	30	1753	61	7	rim
CZ95d1_06	CZ95-1-3C	749	86	1.5	5.65	0.13	0.356	0.010	0.65631	0.1155	0.0026	1887	42	1923	19	1962	49	4	core
CZ95d1_07	CZ95-1-4R	1131	31	6.1	5.57	0.16	0.346	0.013	0.71369	0.1160	0.0027	1894	43	1910	24	1912	62	1	rim (mix)
CZ95d1_08	CZ95-1-4C	3950	297	2.3	5.93	0.16	0.375	0.014	0.90306	0.1160	0.0027	1895	43	1964	23	2053	66	8	core
CZ95d1_09	CZ95-1-5A	1929	132	2.5	5.60	0.13	0.359	0.011	0.84127	0.1126	0.0024	1845	39	1916	20	1978	54	7	core (mix)
CZ95d1_10	CZ95-1-5B	1680	276	1.1	5.68	0.17	0.361	0.012	0.88480	0.1139	0.0025	1863	41	1927	26	1985	57	7	core
CZ95d1_11	CZ95-1-6R	46	8	0.9	4.71	0.23	0.317	0.012	0.00100	0.1099	0.0059	1783	100	1775	38	1773	57	1	rim
CZ95d1_12	CZ95-1-6C	1153	103	1.7	4.96	0.10	0.328	0.009	0.77471	0.1096	0.0023	1792	39	1812	17	1831	45	2	core
CZ95d1_13	CZ95-1-7A	621	66	1.4	4.86	0.10	0.323	0.009	0.71214	0.1097	0.0024	1794	41	1794	18	1804	44	1	core
CZ95d1_14	CZ95-1-7B	608	65	1.3	4.80	0.11	0.317	0.011	0.70363	0.1104	0.0029	1804	48	1784	19	1774	53	2	core
CZ95d1_15	CZ95-1-8R	238	41	1.0	5.09	0.23	0.351	0.019	0.79135	0.1057	0.0033	1723	58	1840	36	1937	91	12	rim (mix)
CZ95d1_16	CZ95-1-8C	1170	44	5.6	5.10	0.17	0.334	0.016	0.70446	0.1124	0.0037	1834	60	1834	29	1868	70	2	core
CZ95d1_17	CZ95-1-9A	2390	86	4.7	5.45	0.15	0.353	0.012	0.91905	0.1129	0.0025	1846	42	1892	24	1947	56	5	core
CZ95d1_18	CZ95-1-9B	1689	49	6.2	5.46	0.13	0.350	0.011	0.84460	0.1127	0.0026	1842	43	1894	21	1935	51	5	core (mix)
CZ95d1_19	CZ95-1-10	3950	151	4.7	5.75	0.23	0.371	0.016	0.94333	0.1112	0.0025	1823	39	1943	32	2032	74	11	core
CZ95d1_20	CZ95-1-11A	1218	116	1.8	5.51	0.17	0.348	0.011	0.82043	0.1146	0.0028	1872	45	1901	27	1924	55	3	core
CZ95d1_21	CZ95-1-11B	1242	96	2.3	5.31	0.12	0.341	0.010	0.49571	0.1128	0.0029	1851	45	1871	19	1891	49	2	core
CZ95d1_22	CZ95-1-12A	1143	96	2.0	5.59	0.14	0.348	0.012	0.80697	0.1159	0.0028	1899	40	1914	21	1922	58	1	core
CZ95d1_23	CZ95-1-12B	1750	64	4.8	5.64	0.14	0.351	0.013	0.82413	0.1160	0.0030	1902	45	1921	21	1939	61	2	core
CZ95d1_24	CZ95-1-13	3610	98	6.2	5.39	0.13	0.347	0.011	0.90928	0.1130	0.0024	1848	40	1882	20	1918	50	4	core
CZ95d1_25	CZ95-1-14A	937	65	2.5	5.35	0.15	0.326	0.011	0.75057	0.1198	0.0030	1951	47	1877	24	1819	54	7	core (mix)
CZ95d1_26	CZ95-1-14B	759	106	1.2	5.48	0.12	0.340	0.011	0.68625	0.1171	0.0027	1912	42	1897	20	1885	51	1	core (mix)
CZ95d1_27	CZ95-1-15A	1454	261	1.0	5.75	0.14	0.361	0.011	0.79600	0.1160	0.0028	1900	47	1938	22	1988	54	5	core
CZ95d1_28	CZ95-1-15B	2688	438	1.1	5.76	0.15	0.363	0.012	0.72363	0.1154	0.0029	1884	46	1939	22	1994	55	6	core
CZ95d1_29	CZ95-1-16	738	79	1.5	5.16	0.14	0.340	0.009	0.81123	0.1100	0.0025	1798	42	1845	24	1888	45	5	core
CZ95d1_30	CZ95-1-17	421	36	1.9	5.72	0.15	0.357	0.011	0.69869	0.1172	0.0030	1912	45	1937	24	1966	51	3	core
CZ95d1_31	CZ95-1-18A	1388	87	2.3	5.12	0.11	0.339	0.010	0.67769	0.1102	0.0026	1802	44	1842	19	1882	48	4	core (mix)
CZ95d1_32	CZ95-1-18B	5840	656	1.4	5.97	0.17	0.381	0.014	0.90014	0.1129	0.0025	1846	41	1970	25	2079	66	13	core
CZ95d1_33	CZ95-1-19	1710	84	3.4	5.70	0.16	0.359	0.011	0.66004	0.1173	0.0032	1914	49	1930	24	1977	52	3	core (mix)
CZ95d1_34	CZ95-1-20	422	45	1.4	4.73	0.12	0.317	0.010	0.59101	0.1086	0.0032	1791	50	1771	22	1777	47	1	core
Monazite																			
CZ95d1_01	CZ95-1Mz-1.1	459	6030		4.78	0.30	0.307	0.019	0.63451	0.1107	0.0045	1819	69	1779	51	1723	95	5	
CZ95d1_02	CZ95-1Mz-1.2	417	5850		4.86	0.28	0.315	0.022	0.61465	0.1106	0.0042	1802	68	1793	48	1764	110	2	
CZ95d1_03	CZ95-1Mz-1.3	391	5230		4.72	0.29	0.308	0.019	0.66748	0.1093	0.0031	1798	46	1768	51	1728	92	4	
CZ95d1_04	CZ95-1Mz-1.4	423	5770		4.76	0.30	0.319	0.019	0.60137	0.1100	0.0040	1792	68	1775	53	1782	96	1	
CZ95d1_05	CZ95-1Mz-1.5	426	5490		4.36	0.24	0.298	0.018	0.56716	0.1096	0.0040	1785	66	1705	45	1681	91	6	
CZ95d1_06	CZ95-1Mz-1.6	409	6550		4.60	0.29	0.308	0.018	0.00100	0.1096	0.0044	1807	83	1755	48	1727	87	4	
CZ95d1_07	CZ95-1Mz-2.1	711	787		4.20	0.21	0.288	0.015	0.40817	0.1065	0.0018	1739	31	1677	46	1632	74	6	
CZ95d1_08	CZ95-1Mz-2.2	721	715		4.20	0.23	0.286	0.015	0.69588	0.1068	0.0020	1743	35	1673	45	1628	79	7	
CZ95d1_09	CZ95-1Mz-2.3	742	595		4.29	0.22	0.291	0.015	0.11071	0.1072	0.0019	1751	32	1691	43	1647	76	6	
CZ95d1_10	CZ95-1Mz-3	652	9210		4.47	0.24	0.300	0.017	0.41414	0.1077	0.0030	1757	51	1725	43	1690	84	4	
CZ95d1_11	CZ95-1Mz-4.1	844	534		4.13	0.21	0.282	0.014	0.72955	0.1058	0.0015	1727	26	1659	42	1602	72	7	
CZ95d1_12	CZ95-1Mz-4.2	791	583		3.85	0.21	0.273	0.014	0.49972	0.1041	0.0024	1695	43	1603	43	1555	70	8	
CZ95d1_13	CZ95-1Mz-5	532	47.7		3.90	0.20	0.282	0.015	0.42764	0.1010	0.0027	1639	50	1612	43	1600	75	2	
CZ95d1_14	CZ95-1Mz-6	845	1015		4.25	0.22	0.286	0.015	0.67104	0.1071	0.0019	1749	33	1684	43	1623	77	7	
CZ95d1_15	CZ95-1Mz-7	134	12.9		5.26	0.42	0.299	0.021	0.55604	0.1228	0.0062	1984	89	1855	68	1684	100	15	
CZ95d1_16	CZ95-1Mz-8	586	22440		4.61	0.24	0.300	0.015	0.55654	0.1108	0.0019	1811	31	1758	44	1689	76	7	

Cocks, 2004; Simancas et al., 2005; Linnemann et al., 2007, 2008; Stampfli et al., 2013; Domeier and Torsvik, 2014; Ouabid et al., 2020; Franke et al., 2021). If true, then the Pangean suture zone would lie southeast of the Mazagan Escarpment.

Alternatively, it is possible that the hypersthene granodiorite has a Northwest African origin, despite the fact that the ~1950–1750 Ma zircon and ~1820–1640 Ma monazite ages are too young for the 2.25–2.07 Ga Eburnean/Birimian orogeny (Abouchami et al., 1990; Peucat et al., 2005; O'Connor et al., 2010; Blein et al., 2014; Block et al., 2015; Pereira et al., 2015). It is possible that the ~1.95 Ga oldest zircon date represents its crystallization age at the end of the Eburnean orogeny, or the beginning of subsequent extension (Ait Lahna et al., 2020). All younger analyses may then be interpreted as a result of metamorphic zircon growth or Pb loss. This could be explained by the widespread mafic magmatism recorded by the dolerite sills and dykes that were emplaced in the Anti-Atlas between ~1.76 and ~1.64 Ga (Youbi et al., 2013; Ikenne et al., 2017; Ait Lahna et al., 2020). In that case the hypersthene granodiorite would have formed in an extensional setting through bimodal magmatism and continuous heating from below, due to magmatic underplating (cf. Frost and Frost, 2008, their Fig. 11a). While extensional hypersthene granodiorite is typically ferroan, alkali-calcic to alkalic and metaluminous in composition (Frost and Frost, 2008), it may be possible that they display an arc/convergent geochemical signature (see above), due to incorporation of crust that was previously thickened in a convergent setting. If correct, then the Pangean suture zone would have been northwest of the Mazagan Escarpment.

In a 605 ± 11 Ma rhyolite from onshore outcrops of the El Jadida horst, ~70 km southeast of the Mazagan Escarpment (Fig. 1), El Haibi et al. (2020) reported 1289.5 ± 10.4 Ma, 2068.7 ± 5.4 Ma, 2179.3 ± 4.8 Ma, and 2493.9 ± 6.2 Ma $^{207}Pb/^{206}Pb$ dates on <2% discordant inherited zircon data. Based on the Mesoproterozoic inheritance, they interpret the El Jadida area as an Avalonian terrane that they named 'Mazagonia', suggesting that the Mazagan Escarpment (with its previous 1.0–0.9 Ga K/Ar date on the hypersthene granodiorite) may be part of such an exotic terrane with Amazonian basement. However, with four inherited zircon cores only (three from this study and one from El Haibi et al., 2020), and the increasing evidence for Mesoproterozoic zircon occurrences in the Meseta domain, we believe it is more likely that the Mazagan escarpment and El Jadida horst are formed on Northwest African basement.

Based on the new zircon and monazite U–Pb ages and the arguments presented above, we believe that there is no compelling reason to interpret the Mazagan Escarpment as an exotic terrane. Instead, the Mazagan Escarpment can be simply regarded as the offshore edge of the Meseta Coastal Block continental crust. In the El Jadida horst, felsic lavas yielded crystallization ages of 605–580 Ma (El Haibi et al., 2020), which compares with the ~560 Ma age of the granodiorite in the Escarpment and with the 593 ± 8 Ma SHRIMP age of a meta-rhyolite of the easternmost Coastal Block (Baudin et al., 2003). The Paleoproterozoic basement that underlies the eastern Coastal Block (Pereira et al., 2015) may be comparable with the hypersthene granodiorite of the Escarpment, assuming the latter was submitted to extensional heating after the Eburnian collision (see above). While Mesoproterozoic inherited zircon (as in the granodiorite) is not typical for Northwest African igneous rocks, rare Mesoproterozoic detrital zircon exists in Cambrian sedimentary rocks of the Coastal and Sehoul blocks (Pérez-Cáceres et al., 2017; Letsch et al., 2018), which are rocks interpreted as having a Northwest African origin. Therefore, it is likely that the rocks of the Mazagan Escarpment also have a Northwest African origin.

5. Conclusions

U–Pb zircon LA-ICPMS data from granodiorite in drill core DSDP544 yielded a 556 ± 10 Ma crystallization age, abundant inherited zircon cores up to 620 Ma and three ~2.68, ~1.76 and ~1.20 Ga cores. Hypersthene granodiorite sample CZ-91-5 yielded ~1950–1750 Ma zircon and ~1820–1640 Ma monazite U–Pb ages. The granodiorite may have formed during widespread late Neoproterozoic magmatism in Northwest Africa. The hypersthene granodiorite may have formed in an extensional setting by the end of the Eburnean orogeny, at a time of extension and otherwise predominantly mafic magmatism. Rare inherited Mesoproterozoic zircon in the granodiorite and in Neoproterozoic rhyolite of El Jadida (El Haibi et al., 2020) do not provide sufficient evidence for an exotic origin. Based on the growing wealth of inherited/detrital zircon data for the Anti-Atlas and Meseta domains, and on our new data for the Mazagan Escarpment, the Pangean suture zone probably does not lie on the continental shelf in offshore or onshore Morocco, but west of the Escarpment.

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Intellectual property

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jafrearsci.2021.104249.

Appendix

DSDP544 – granodiorite – U–Pb LA-ICPMS analysis at Boise State University

Zircon grains of the granodiorite of DSDP544 were separated at Boise State University using standard techniques, annealed at 900 °C for 60 h in a muffle furnace, and mounted in epoxy and polished until their centers were exposed. Cathodoluminescence (CL) images were obtained with a JEOL JSM-300 scanning electron microscope and Gatan MiniCL.

Zircon was analyzed by LA-ICPMS using a ThermoElectron X-Series II quadrupole ICPMS and New Wave Research UP-213 Nd:YAG UV (213 nm) laser ablation system. In-house analytical protocols, standard materials, and data reduction software were used for acquisition and calibration of U–Pb dates and a suite of high field strength elements (HFSE) and rare earth elements (REE). Zircon was ablated with a laser spot of 25 μm wide using fluence and pulse rates of 5 J/cm^2 and 5 Hz, respectively, during a 45 s analysis (15 s gas blank, 30 s ablation) that excavated a pit ~25 μm deep. Ablated material was carried by a 1.2 L/min He gas stream to the nebulizer flow of the plasma. Dwell times were 5 ms for Si and Zr, 200 ms for ^{49}Ti and ^{207}Pb, 80 ms for ^{206}Pb, 40 ms for ^{202}Hg, ^{204}Pb, ^{208}Pb, ^{232}Th, and ^{238}U and 10 ms for all other HFSE and REE. Background count rates for each analyte were obtained prior to each spot analysis and subtracted from the raw count rate for each analyte. Ablations pits that appear to have intersected glass or mineral inclusions were identified based on Ti and P. U–Pb dates from these analyses are considered valid if the U–Pb ratios appear to have been unaffected by the inclusions. Analyses that appear contaminated by common Pb were rejected based on mass 204 being above baseline. For concentration calculations, background-subtracted count rates for each analyte were internally normalized to ^{29}Si and calibrated with respect to NIST SRM-610 and -612 glasses as the primary standards. Temperature was calculated from the Ti-in-zircon thermometer (Watson et al., 2006). Because there are no constraints on the activity of TiO_2, an average value in crustal rocks of 0.8 was used.

Data were collected in one experiment in November 2017. For U–Pb and ^{207}Pb/^{206}Pb dates, instrumental fractionation of the background-subtracted ratios was corrected and dates were calibrated with respect to interspersed measurements of zircon standards and reference materials. The primary standard Plešovice zircon (Sláma et al., 2008) was used to monitor time-dependent instrumental fractionation based on two analyses for every 10 analyses of unknown zircon. A secondary correction to the ^{206}Pb/^{238}U dates was made based on results from the zircon standards FC1 (1098 Ma, Paces and Miller, 1993) and Zirconia (327 Ma, Covey et al., 2012), which were treated as unknowns and measured once for every 10 analyses of unknown zircon. These results showed a linear age bias of several percent that is related to the ^{206}Pb count rate. The secondary correction is thought to mitigate matrix-dependent variations due to contrasting compositions and ablation characteristics between the Plešovice zircon and other standards (and unknowns).

Radiogenic isotope ratio and age error propagation for all analyses includes uncertainty contributions from counting statistics and background subtraction. For groups of analyses that are collectively interpreted from a weighted mean date (i.e., igneous zircon analyses), a weighted mean date is first calculated from equivalent dates (probability of fit >0.05) using Isoplot 4.15 (Ludwig, 2012) with errors on individual dates that do not include a standard calibration uncertainty. A standard calibration uncertainty is then propagated into the error on the date. This uncertainty is the local standard deviation of the polynomial fit to the interspersed primary standard measurements versus time for the time-dependent, relatively larger U/Pb fractionation factor, and the standard error of the mean of the consistently time-invariant and smaller ^{207}Pb/^{206}Pb fractionation factor. These uncertainties are 1.0% (2σ) for ^{206}Pb/^{238}U and 0.5% (2σ) for ^{207}Pb/^{206}Pb. Age interpretations are based on ^{207}Pb/^{206}Pb dates for analyses with ^{207}Pb/^{206}Pb and ^{206}Pb/^{238}U dates >1000 Ma. Otherwise, interpretations are based on ^{206}Pb/^{238}U dates. Analyses with ^{206}Pb/^{238}U dates >1000 Ma and >20% positive discordance or >10% negative discordance are not considered. Errors on the dates are at 2σ. Forty-five LA-ICPMS analyses were placed in 30 zircon grains with 1–3 analyses per grain (Tables 3 and 4). Thirty-eight other analyses were attempted, but are considered to be inaccurate, mostly due to high concentrations of common Pb, and thus were discarded.

CZ-91-5 – hypersthene granodiorite – Scanning Electron Microscopy (SEM)-based automated mineralogy (TIMA) and BSE imaging backscattered electron (BSE) imagings – Colorado School of Mines

Samples were analyzed using automated scanning electron microscopy (automated mineralogy) in the Mineral and Materials Characterization (MMC) Facility at the Colorado School of Mines. Samples were loaded into the TESCAN-VEGA-3 Model LMU VP-SEM platform and analysis was initiated using the control program TIMA3. Four energy dispersive X-ray (EDX) spectrometers acquired spectra from each point with a beam stepping interval (i.e., spacing between acquisition points) of 10:m for the false-color overview scan and 5:m for bright phase search scans (zircon and monazite), with an acceleration voltage of 25 keV and a beam intensity of 14. Using the bright phase search scanning method, only minerals and phases with a brightness of >35% for zircon and a brightness of >60% for monazite, respectively, were analyzed. Interactions between the beam and the sample were modeled through Monte Carlo simulation. The energy-dispersive X-ray (EDX) spectra were compared with spectra held in a look-up table, allowing a mineral or phase assignment to be made at each acquisition point. The assignment makes no distinction between mineral species and amorphous grains of similar composition and composition assignments are grouped appropriately. Results were output by the TIMA software as a spreadsheet giving the area percent of each composition in the look-up table. Following this procedure, a compositional map was generated and zircon and monazite were highlighted.

BSE images were acquired using a TESCAN MIRA3 LMH Schottky field emission-scanning electron microscope (FE-SEM) in the MMC Facility. The instrument provides topographical and elemental information at magnifications of 10 × to over 300,000 × at a spatial resolution down to the nanometer scale. The FE-SEM features a TESCAN motorized retractable annular, single-crystal YAG backscatter electron detector. Operating conditions used were 15 kV acceleration voltage and a beam intensity of 11.

CZ-91-5 – hypersthene granodiorite – U–Pb LA-ICPMS analysis at the U.S. Geological Survey – Denver

Zircon in thin section of hypersthene granodiorite sample CZ-91-5 was ablated at the U.S. Geological Survey G3 Plasma Lab (Denver, CO USA) using a Photon Machines Excite™ 193 nm ArF excimer laser that was coupled to a Nu Instruments AttoM high-resolution magnetic-sector inductively coupled plasma mass spectrometer in spot mode (150 total bursts for zircon) with a repetition rate of 5 Hz, laser energy of ~3 mJ, and an energy density of 4.11 J/cm2. Pit depths are typically ~7–9 μm. The rate of He carrier gas flow from the HelEx cell of the laser was ~0.6 L/min. Make-up Ar gas (~0.2 L/min) was added to the sample stream prior to its introduction into the plasma. Nitrogen with flow rate of 5.5 mL/min was added to the sample stream to allow for significant reduction in ThO^+/Th^+ (<0.5%) and improved the ionization of refractory Th (Hu et al., 2008). The laser spot sizes for zircon were ~25 μm. With the magnet parked at a constant mass, the flat tops of the isotope peaks of ^{202}Hg, ^{204}(Hg + Pb), ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{232}Th, ^{235}U, and ^{238}U were measured by rapidly deflecting the ion beam with a 30s on-peak background measured prior to each 30s analysis. Raw data were reduced off-line using the Iolite™ 2.5 program (Paton et al., 2011) to subtract on-peak background signals, correct for U–Pb downhole fractionation, and normalize the instrumental mass bias using external mineral reference materials, the ages of which had previously been determined by isotope dilution thermal ionization mass spectrometry. Ages were corrected by standard sample bracketing with the primary zircon reference material FC-1 (Paces and Miller, 1993) and/or secondary reference materials, Temora2 (417 Ma; Black et al., 2004) and Plešovice (337 Ma, Sláma et al., 2008). Reduced data were compiled into Wetherill concordia diagrams using Isoplot 4.15 (Ludwig, 2012). ^{207}Pb/^{206}Pb ages are used for all ages, as they are >1600 Ma, following the recommendations of Gehrels (2012). Monazite analyses were conducted similarly to zircon analyses, but with spot analyses of 10–15:m in diameter. Further, the ^{232}Th peak was excluded from this analytical sequence due to high Th concentration in monazite and high sensitivity of the instrument. All isotopic data were normalized to the monazite reference materials 3345 (Stern and Berman, 2001; ^{207}Pb/^{206}Pb thermal ionization mass spectrometry age = 1821.0 ± 0.6 Ma) and 44069 (Aleinikoff et al., 2006). The reference material was analyzed after every five spot analyses of monazite unknowns. Reduced data were compiled into Wetherill concordia diagrams/Tera-Wasserburg plots using Isoplot 4.15 (Ludwig, 2012). Data are also available as a U.S. Geological Survey data release (Holm-Denoma and Pianowski, 2021).

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