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Sedimentary Processes, Environments and Basins: a Tribute to Peter Friend

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Provenance of Quaternary sands in the Algarve (Portugal) revealed by U–Pb ages of detrital zircon

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ABSTRACT

The application of U–Pb dating by laser ablation–inductively coupled plasma–mass spectrometry (LA–ICP–MS) to determine the sources of detrital zircon in Neogene and Quaternary sands of the Algarve (southern Portugal) revealed the presence of three age groups: Palaeozoic to Neoproterozoic (200–800 Ma), Palaeoproterozoic (ca. 1700–2100 Ma) and Neo- to Meso-Archaean (2600–3200 Ma). The results suggest that at least some of the detrital grains were derived from pre-existing formations from the Southern Portuguese Zone of the Variscan orogen (namely Palaeozoic metasediments) and Mesozoic sedimentary rocks. The older sources from which zircons probably derived originally seem to be metamorphic rocks cropping out northeast of the Southern Portuguese Zone. Previous work shows that these older rocks from the Variscan Ossa–Morena and Central Iberian Zones contain inherited zircons with the same ages as those obtained in the present study from sediments. In parallel, the results also show a consistency in the source ages of the detrital zircons from Lower Pliocene to Holocene sediments, thus contributing to the discussion of known changes to the river drainage network in the Algarve region during the Pliocene based on published field observations.

Keywords Detrital zircons, Neogene, Quaternary, U–Pb ages, river drainage network, tectonics.

INTRODUCTION

Present-day river drainage networks are strongly influenced by climatic factors and changes in climate through the Holocene. However, in the Algarve region (southern Portugal), the present drainage network characteristics have been defined by the geomorphological and tectonic settings established during Pliocene–Pleistocene time. Drainage networks are modified, therefore, by changes in two main factors: climate and tectonics. In the Algarve region, a relatively important change in the river drainage network occurred between Early and Late Pleistocene time, as recorded by the change in the fluvial system from deeply incised channels to braided rivers migrating laterally on top of older formations (Cabral, 1993; Moura & Boski, 1994, 1997). However, the most recent tectonic event in the Algarve, which corresponds to the uplift of the northern part of the region and was due to the NW–SE compression linked to the convergence of tectonic plates, seems to have occurred between the Early and Late Pliocene (Cabral, 1993; Moura & Boski, 1999).

The cause and timing of the observed reorganization of the drainage network in the Algarve region are still under discussion. The above interpretations are based on field observations and stratigraphic evidence, lacking absolute dating to constrain timing. The present work aims, therefore, to highlight and quantify the contribution of geomorphological changes to drainage network modifications through numerical dating of detrital minerals, which allows the characterization and identification of sediment sources since the Pliocene. Accordingly, the present study focuses on zircons from the heavy mineral assemblages in Pliocene and Pleistocene sandstone formations, as well as in sands from modern beaches.

The mineralogical composition of beach and fluvial sands results from several factors, the most important of which are the composition of the source rocks and mixing by hydrodynamic processes. Since the pioneering work of Trask (1952), who used the mineral augite as a tracer, the study of the heavy mineral assemblages of beach sands has been used to determine sediment sources and to characterize sediment transport and mixing. This is important not only in order to reconstruct the evolution of river drainage networks but also to understand ongoing and evolving coastal processes. However, specific mineral tracers are seldom found in most beach sediments and physicochemical characteristics of heavy mineral assemblages are often difficult to relate to specific sources. In contrast, the crystallization age of single zircon grains, a common constituent of heavy mineral assemblages, is a direct indication of the age of the source rock.

Although traditionally used for precise dating of geological events such as magmatism and metamorphism (e.g. Krogh, 1993), U–Pb dating of zircon has been shown to be a valuable tool in studies of sediment provenance (Machado & Gauthier, 1996; Machado *et al.*, 1996; Fernandéz-Suárez *et al.*, 1999, 2002; Sircombe, 1999). Zircon dating has not been used often in sedimentary studies, in part because the method most commonly used, isotope dilution–thermal ionization–mass spectrometry, although more precise, is expensive and time consuming. However, it is likely that the recent development of affordable and relatively fast U–Pb dating methods based on laser ablation (e.g. Horn *et al.*, 2000; Machado & Simonetti, 2001) will widen their application in unravelling sedimentary processes. The results reported here represent the first attempt at using U–Pb ages of zircon from Pliocene–Pleistocene formations and Holocene beach sands from the central Algarve in order to determine their provenance.

GEOLOGICAL SETTING

Located in the western part of the Iberian Peninsula, Portugal is bordered to the west and south by the Atlantic Ocean and to the north and east by Spain. The western part of the Iberian Peninsula is mostly represented by the Iberian Massif, also known as the Hesperic Massif, which forms the most continuous portion of the European Variscan orogen (Fig. 1). The Iberian Variscan belt is divided into five structural zones (Fig. 1), the: (i) Cantabrian Zone (CZ); (ii) West Asturian-Leonese Zone (WALZ); (iii) Central Iberian Zone (CIZ); (iv) Ossa–Morena Zone (OMZ); and (v) South Portuguese Zone (SPZ). Isolated during the Pangean fragmentation, the Iberian block also shows some remnant ophiolitic units identified as oceanic exotic terranes (Terrinha, 1998; Fig. 1).

The Algarve, 5019 km^2 in area, is Portugal's southernmost region and is underlain by Variscan basement rocks of the South Portuguese Zone (Fig. 1). This zone is overthrust by the Ossa–Morena Zone (Fig. 1), in which Lower Palaeozoic and Upper Proterozoic formations are widespread (Terrinha, 1998), in contrast to the South Portuguese Zone (SPZ) where the oldest rocks consist essentially of Upper Devonian shales and greywackes. Acidic and mafic volcanic rocks of Mississipian (Tournaisian and Early Visean) age are also present in the southeastern sector of the SPZ. These rocks are of economic interest due to their high content of pyrite and other sulphides, which makes this region one of the most important in the world for massive sulphide ore deposits. The South Portuguese Zone is also characterized by low-grade regional metamorphism decreasing from northeast to southwest and containing diverse mineral assemblages (Oliveira, 1990).

Sedimentary basins located at the periphery of the Iberian Massif (Fig. 1) contain Mesozoic successions first represented by Triassic sandstones, which overlie Palaeozoic metasediments. The genesis of the Algarve Basin is attributed to the opening of Tethys and the Atlantic Ocean (Terrinha & Ribeiro, 1995; Andeweg, 2002). Carbonate sediments deposited during the Jurassic Period now form an extensive E–W orientated zone, locally called the Barrocal (Fig. 2), that comprises limestones and dolomites. During the Cretaceous, sedimentation alternated between carbonate and terrigenous depending on sea-level fluctuations (Terrinha & Ribeiro, 1995; Andeweg, 2002). The Late Cretaceous was marked by the intrusion of a nephelinic syenite subvolcanic massif, the Monchique Massif

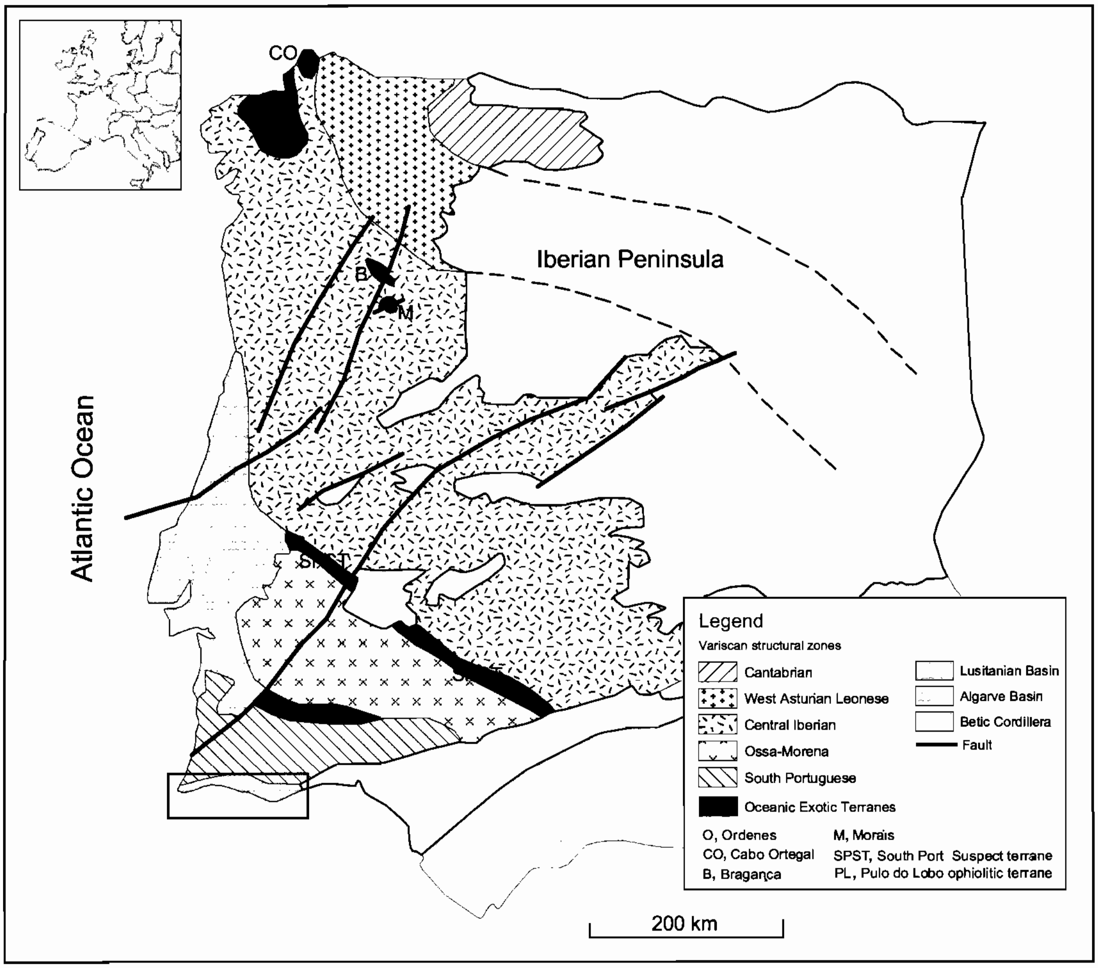

Fig. 1 Variscan structural zones of the Iberian Massif, as well as exotic terranes and main tectonic structures of the Iberian Peninsula. The South Portuguese Zone includes several domains such as the Baixo Alentejo Flysch group (Upper Visean to Namurian), the Pyritic belt (Upper Famennian to Mid-Visean), the Southwest Portuguese Flysch Group (Famennian to Lower Tournaisian) and the Pulo do Lobo terrane (PL; Tournaisian to Lower Devonian). The rectangle represents the area of Fig. 2.

(Rock, 1983). During the Cenozoic, sedimentation in the Algarve was first carbonate-dominated, represented by the Upper Miocene *Olhos de Água* calcarenites (unit F) and *Cacela* (unit E) Formation (Figs 2 & 3). Subsequently, during Early and Late Pliocene times, fluvio-marine and shallow continental shelf sedimentation took place, as recorded by the *Falésia* (unit D) and *Quarteira* (unit C) sandstones (Figs 2 & 3). Finally, the sedimentation became fluvial (units B and A) during the Pleistocene (Figs 2 & 3; Moura & Boski, 1999). The oldest formations are typically located in the north of the region and the youngest in the south.

Both Neogene and Quaternary formations show maximum lateral extent along the present-day coastline, and they dip and thicken to the south-southeast (Figs 1, 2 & 4).

METHODS

In general, the Plio-Pleistocene outcrops are neither continuous nor easy to reach (Figs 2 & 4). Accordingly, whenever possible, several samples of the same sedimentary units (Table 1) were taken from locations where outcrops had previously been

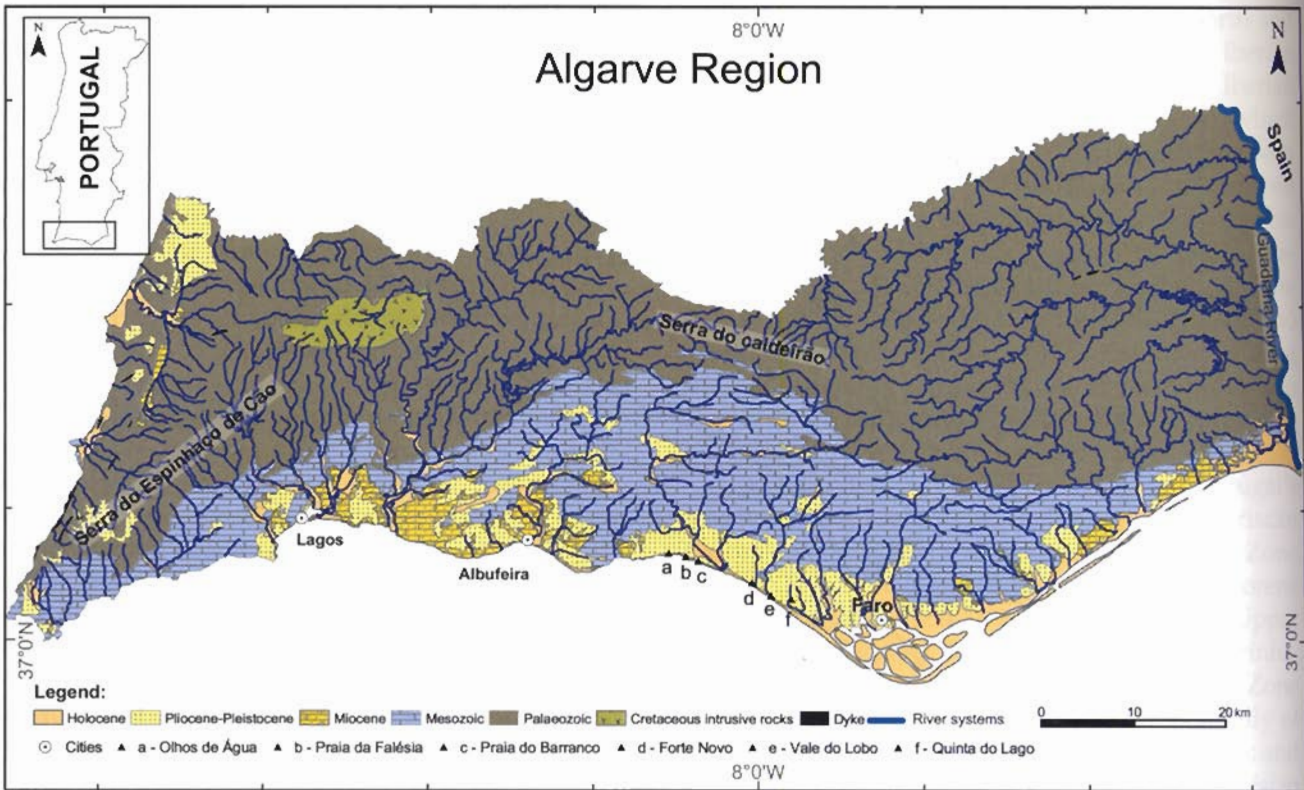

Fig. 2 Simplified geological map of the Algarve with the present-day river drainage network and the sampling sites (a–f).

identified (Moura & Boski, 1994, 1999). Samples consisted of poorly consolidated sandstones, which allowed them to be treated as if they were loose sediments. Heavy minerals were separated using a Wilfley table, heavy liquids and a Frantz isodynamic magnetic separator. Zircon was the only mineral found that is appropriate for U–Pb dating. Only zircon grains devoid of fractures, inclusions, alteration and other imperfections were selected for analysis. The grains analysed were representative of the chromatic and morphological types present in each sample. The zircons were analysed by laser ablation–multicollector–inductively coupled plasma–mass spectrometry (LA–MC–ICP–MS) at the GEOTOP-UQAM-McGILL Research Centre, Montreal (Canada).

Selected grains were mounted in epoxy known to be devoid of lead and uranium from previous analyses (Machado & Simonetti, 2001). Fragments of an in-house reference sample zircon (UQ-Z8) were also added at this stage to the sample mount. Samples were manually polished and cleaned with distilled water in an ultrasonic bath, sub-boiling 6.2 mol L^{-1} HCl and sub-boiling H_2O, and left to dry under a class 100 clean hood. The results were obtained with an excimer laser coupled to a multicollector mass spectrometer (Micromass Isoprobe) with an ICP source and a hexapole collision cell. Data were acquired in static, multicollection mode using six Faraday collectors, in the only possible configuration that allowed the large mass spread between ^{204}Pb and ^{238}U to be encompassed.

After determining the frequency and energy of the laser, as well as the beam diameter (Machado & Simonetti, 2001), the UQ-Z8 reference sample was ablated and the argon nebulizer gas flow rate adjusted to obtain a mean $^{206}Pb/^{238}U$ as close as possible to that of the reference sample (Machado & Gauthier, 1996). The 2σ precisions obtained for

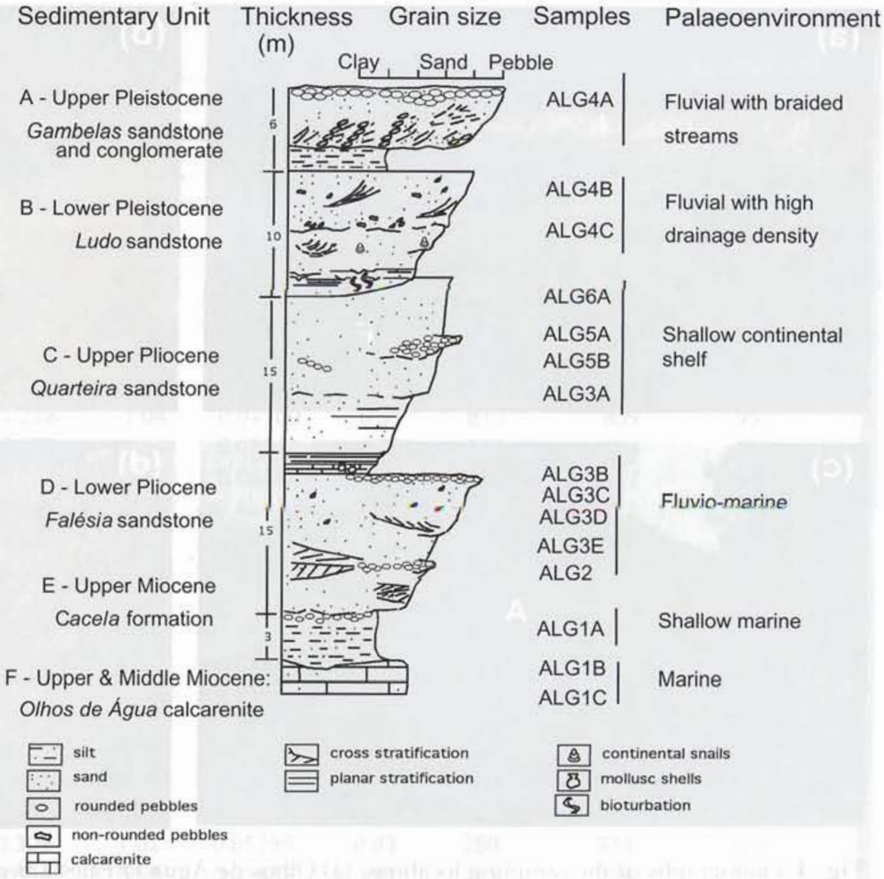

Fig. 3 Lithostratigraphic column from Miocene to Pleistocene. Sedimentary units are referred to by capital letters (A–F). (Adapted from Moura, 1998.)

$^{207}Pb/^{206}Pb$ and $^{238}U/^{206}Pb$ varied between 0.1 and 1.3%, respectively. All analyses were corrected for U fractionation relative to a $^{238}U/^{235}U$ ratio of 137.88. Age calculations were performed using Isoplot/Ex Version 2 (Ludwig, 2000).

RESULTS

All samples contained similar heavy mineral suites, dominated by staurolite, andalusite and sillimanite, typical of intermediate- to high-temperature metamorphism. Other minerals present in minor amounts were zircon, epidote and rutile. The majority of zircon grains were colourless and a minor proportion was light brown to pink. Two distinct types of zircon were present in all samples: a predominant group of rounded grains; and a lesser number of euhedral ones. The latter included both perfect crystals and crystals with percussion marks and slightly abraded edges. The lack of intermediate types is noteworthy.

The sample numbers and their stratigraphic position are indicated in Table 1 and the isotopic data in Table 2 and Figs 5–7. The $^{207}Pb/^{206}Pb$ ages of 103 zircon grains range between 199 Ma and 3.18 Ga, and can be classified into three groups: Neoproterozoic–Palaeozoic, Palaeoproterozoic and Archaean. Zircons with ages younger than 800 Ma were the most abundant, followed by those with ages around 2 Ga (Fig. 6) and finally by those in the 2.6–2.9 Ga range. The younger group could be subdivided, but it is possible that the observed gaps (Fig. 6) are due to sampling bias. Excepting the fact that the Archaean zircons are rounded, no correlation was found between zircon types and ages or between ages and stratigraphic position. This suggests that the same source or sources with identical ages have been available since the Pliocene.

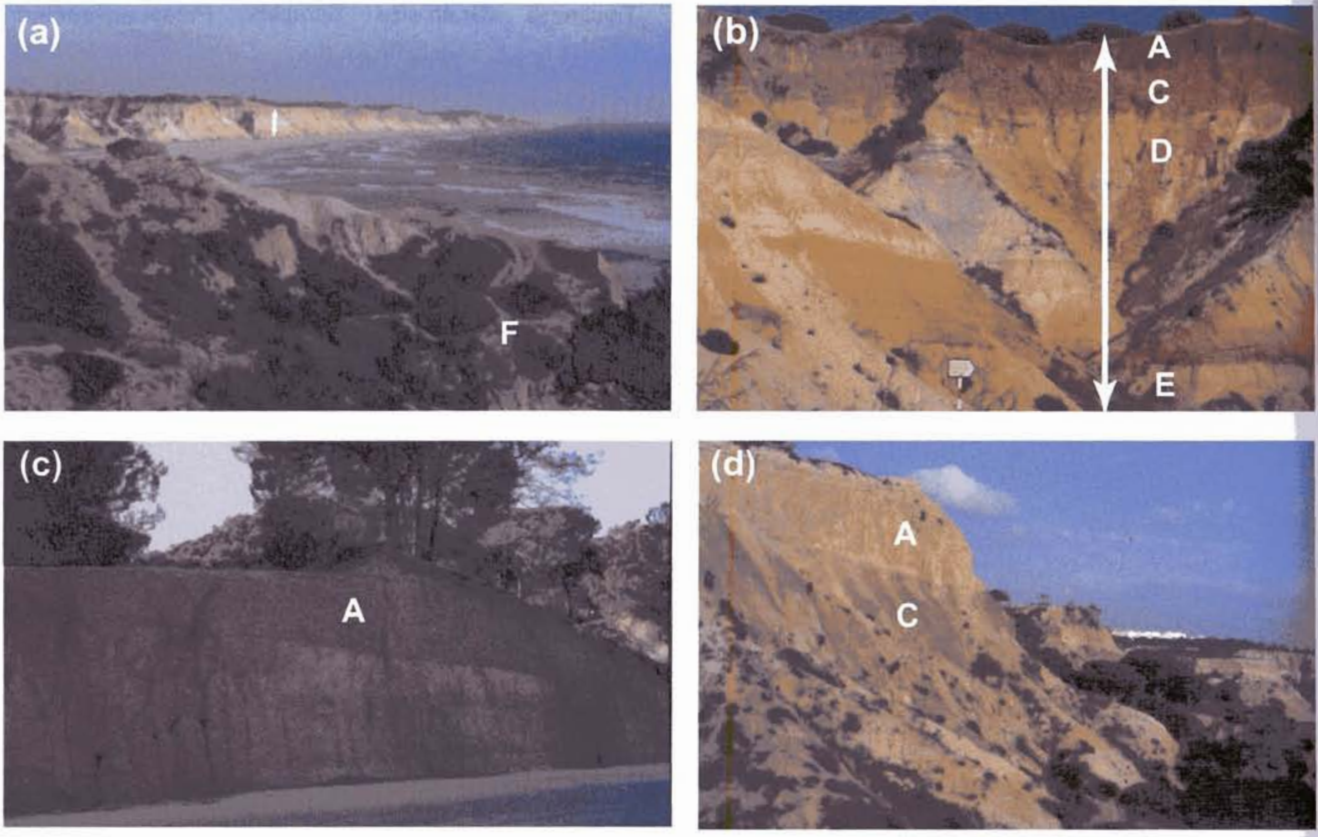

Fig. 4 Photographs of the sampling locations. (a) Olhos de Água to Falésia Beach; the double arrow shows the specific location of Falésia sampling. (b) Falésia sampling location. (c) Quinta do Lago sampling outcrop. (d) Vale do Lobo sampling location. Capital letters refer to the sedimentary units in Fig. 3.

Table 1 Sample location and identification

Site	Location	Holocene beach (n = 54)	Pleistocene		Pliocene		Miocene (n = 1)
			Upper (n = 4)	Lower (n = 0)	Upper (n = 27)	Lower (n = 17)	
1	Olhos de Água						ALG1A*, ALG1B, ALG1C
2	Falésia					ALG2*	
3	Barranco	ALG3F*			ALG3A	ALG3B*, ALG3C*, ALG3D, ALG3E	
4	Quinta do Lago		ALG4A*	ALG4B, ALG4C			
5	Vale do Lobo	ALG5C*			ALG5A*, ALG5B*		
6	Forte Novo	ALG6B*			ALG6A		

n, total number of dated zircons.
* Samples analysed.

Table 2 Isotopic ratios and U–Pb ages

Sample-grain number	Isotopic ratios						Ages (Ma)		
	$^{206}Pb/^{238}U$	±1σ%	$^{207}Pb/^{235}U$	±1σ%	$^{207}Pb/^{206}Pb$	±1σ%	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
2A-1	0.4147	1.09	6.743	1.16	0.12608	0.10	2236	2078	2044
2A-2	0.4122	0.83	6.835	0.98	0.12226	0.05	2225	2090	1990
2A-3	0.3867	0.92	6.582	1.33	0.12908	0.38	2107	2057	2085
2A-4	0.0994	1.93	0.855	2.86	0.07417	3.58	611	628	1046
2A-5	0.1081	0.88	0.926	1.47	0.06310	0.58	662	665	712
2A-6	0.0984	0.65	0.854	0.71	0.06358	0.34	605	627	728
2A-7	0.1338	0.95	1.218	1.04	0.07100	0.35	810	809	957
2A-8	0.0604	0.69	0.473	1.64	0.05813	1.70	378	394	535
2A-9	0.1032	0.69	0.872	0.47	0.06127	0.32	633	637	649
2A-10	0.0969	0.44	0.844	0.75	0.06419	0.29	596	621	748
2A-22	0.0644	0.31	0.823	3.11	0.08061	3.62	402	610	1212
3B-2	0.0912	0.67	0.752	1.59	0.05982	0.94	563	569	597
3B-5	0.0770	0.38	0.593	0.98	0.05956	0.80	478	473	588
3B-6	0.0424	0.35	0.356	0.85	0.06153	1.07	268	310	658
3B-7	0.0452	0.57	0.328	1.08	0.05266	0.91	285	288	314
3B-8	0.0453	0.93	0.333	1.61	0.05298	1.73	286	292	328
3C-2	0.3205	0.91	4.915	2.35	0.12614	0.49	1792	1805	2045
3C-3	0.1004	0.35	0.747	4.69	0.06035	2.95	616	566	616
3C-4	0.1143	0.85	1.066	1.14	0.06840	0.27	698	737	881
3C-5	0.0852	0.58	0.702	0.74	0.06282	0.52	527	540	702
3C-6	0.0444	0.60	0.309	1.02	0.05299	0.83	280	273	328
3C-7	0.0452	0.64	0.336	0.98	0.05455	0.92	285	294	394
3C-8	0.3284	0.65	5.532	2.30	0.12165	0.44	1831	1906	1981
3C-9	0.0504	0.67	0.368	0.94	0.05299	0.71	317	318	328
3C-10	0.0933	0.71	0.788	0.71	0.06117	0.51	575	590	645
3C-11	0.0518	0.64	0.420	1.49	0.05893	1.35	326	356	565
3F-1	0.1000	0.72	0.869	0.79	0.06302	0.27	614	635	709
3F-3	0.1355	0.25	1.449	1.81	0.08048	1.28	819	909	1209
3F-4	0.0971	0.75	0.805	0.62	0.06052	0.25	597	599	622
3F-5	0.1010	0.76	0.853	0.79	0.06155	0.14	620	626	658
3F-6	0.1127	0.67	1.000	0.77	0.06421	0.20	688	704	749
3F-7	0.0549	0.56	0.395	1.23	0.05345	1.12	344	338	348
3F-8	0.0567	0.38	0.446	0.76	0.05748	0.64	355	375	510
3F-9	0.0555	0.36	0.416	1.44	0.05427	1.35	348	353	382
3F-10	0.0564	0.30	0.476	0.76	0.06292	0.77	353	395	706
3F-11	0.0535	0.20	0.453	0.74	0.06259	0.75	336	379	694
3F-12	0.3708	0.71	6.581	0.87	0.13007	0.05	2033	2057	2099
4A-1	0.0540	0.63	0.403	0.54	0.05472	0.37	339	344	401
4A-2	0.0892	0.57	0.805	2.83	0.06560	2.15	551	600	794
4A-4	0.3379	0.38	5.610	0.47	0.12306	0.08	1877	1918	2001
4A-5	0.0922	0.85	0.780	1.44	0.06196	1.14	569	585	673
5A-1	0.3578	0.55	6.597	1.12	0.12578	0.12	1972	2059	2040
5A-2	0.0525	0.71	0.395	1.07	0.05580	0.76	330	338	445
5A-3	0.0520	0.84	0.385	0.84	0.05412	0.54	327	331	376
5A-4	0.0482	0.59	0.384	0.74	0.05801	0.95	304	330	530
5A-5	0.0484	0.63	0.339	0.92	0.05257	1.02	305	296	310
5A-6	0.3693	0.80	6.339	1.10	0.13026	0.15	2026	2024	2101
5A-7	0.0926	0.72	0.735	1.48	0.05909	1.03	571	560	570
5A-8	0.1045	0.82	0.876	0.93	0.06128	0.31	641	639	649

Table 2 *(cont'd)*

Sample-grain number	Isotopic ratios						Ages (Ma)		
	$^{206}Pb/^{238}U$	±1σ%	$^{207}Pb/^{235}U$	±1σ%	$^{207}Pb/^{206}Pb$	±1σ%	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
5A-9	0.4776	1.25	13.101	1.51	0.20103	0.20	2517	2687	2835
5A-10	0.0682	0.32	0.858	1.90	0.10002	1.47	425	629	1625
5B-1	0.0849	0.62	0.695	1.39	0.06286	1.10	525	536	703
5B-2	0.0605	0.79	0.478	8.74	0.06450	7.23	379	397	758
5B-3	0.0468	0.69	0.354	0.96	0.05474	0.73	295	307	402
5B-4	0.1045	0.46	0.915	0.44	0.06554	0.42	641	660	792
5B-5	0.0485	0.50	0.357	1.04	0.05491	0.80	305	310	408
5B-6	0.0819	0.81	0.678	0.82	0.05994	0.25	507	526	601
5C-1	0.0453	0.87	0.344	1.64	0.05483	1.02	286	300	405
5C-2	0.0103	0.68	0.071	2.07	0.05009	1.78	66	70	199
5C-3	0.0506	0.67	0.399	1.27	0.05590	1.21	318	341	449
5C-4	0.0481	0.52	0.383	1.33	0.05881	1.16	303	329	560
5C-5	0.0499	0.54	0.432	2.02	0.06248	1.88	314	365	690
5C-6	0.0455	0.61	0.355	1.90	0.05771	2.00	287	309	519
5C-9	0.3425	0.65	5.709	1.11	0.12760	0.12	1899	1933	2065
6B-1	0.0588	0.75	0.500	1.29	0.06316	1.24	368	412	714
6B-2	0.0467	0.85	0.351	0.85	0.05464	0.66	294	305	397
6B-3	0.0496	0.72	0.373	1.31	0.05508	1.44	312	322	416
6B-4	0.0488	0.71	0.347	1.60	0.05194	1.25	307	302	283
6B-5	0.0454	0.62	0.341	1.32	0.05510	1.09	286	298	416
6B-6	0.0467	0.74	0.354	1.05	0.05473	0.49	294	308	401
6B-7	0.0940	0.74	0.806	0.99	0.06320	0.47	579	600	715
6B-8	0.0454	0.45	0.350	0.74	0.05563	0.51	286	305	438
6B-9	0.0506	0.23	0.469	1.34	0.06762	1.17	318	391	857
6B-10	0.0502	0.41	0.417	1.86	0.06060	2.11	316	354	625
6B-11	0.0480	0.50	0.364	0.67	0.05443	0.37	302	315	389
6B-12	0.0450	0.40	0.332	1.63	0.05500	1.41	284	291	412
6B-13	0.0466	0.23	0.340	2.15	0.05360	1.75	294	297	354
6B-14	0.0734	0.73	0.586	0.67	0.05952	0.35	457	468	586
6B-15	0.0456	0.28	0.337	1.56	0.05506	1.64	287	295	414
6B-16	0.0843	0.70	0.651	1.18	0.05758	1.08	522	509	514
6B-17	0.0960	0.59	0.829	0.59	0.06293	0.20	591	613	706
6B-18	0.0735	0.63	0.601	0.59	0.05933	0.21	457	478	579
6B-19	0.0795	0.66	0.616	0.76	0.05790	0.60	493	487	526
6B-20	0.0495	0.66	0.374	1.33	0.05533	1.32	312	322	425
6B-21	0.0852	0.73	0.741	3.59	0.06497	2.97	527	563	773
6B-22	0.0946	0.46	0.737	2.93	0.06075	2.21	583	561	630
6B-23	0.0897	0.57	0.721	3.59	0.06072	2.75	554	551	629
6B-24	0.0949	0.75	0.788	0.76	0.06097	0.44	584	590	638
6B-25	0.3416	0.92	5.966	1.21	0.12868	0.07	1894	1971	2080
6B-26	0.3254	0.67	5.525	0.69	0.12355	0.05	1816	1904	2008
6B-27	0.3442	0.92	6.112	1.26	0.13197	0.23	1907	1992	2124
6B-28	0.3295	0.61	5.613	0.96	0.12581	0.18	1836	1918	2040
6B-29	0.5065	0.76	14.166	1.44	0.20365	0.09	2642	2761	2856
6B-30	0.4637	0.62	11.470	2.07	0.18424	0.20	2456	2562	2691
6B-31	0.5306	0.54	15.515	0.98	0.21546	0.04	2744	2847	2947
6B-32	0.3454	0.58	6.169	0.56	0.12843	0.15	1913	2000	2077
6B-33	0.0120	0.39	0.100	4.25	0.06007	4.26	77	97	606
6B-34	0.0106	0.72	0.089	3.00	0.06103	3.12	68	86	640

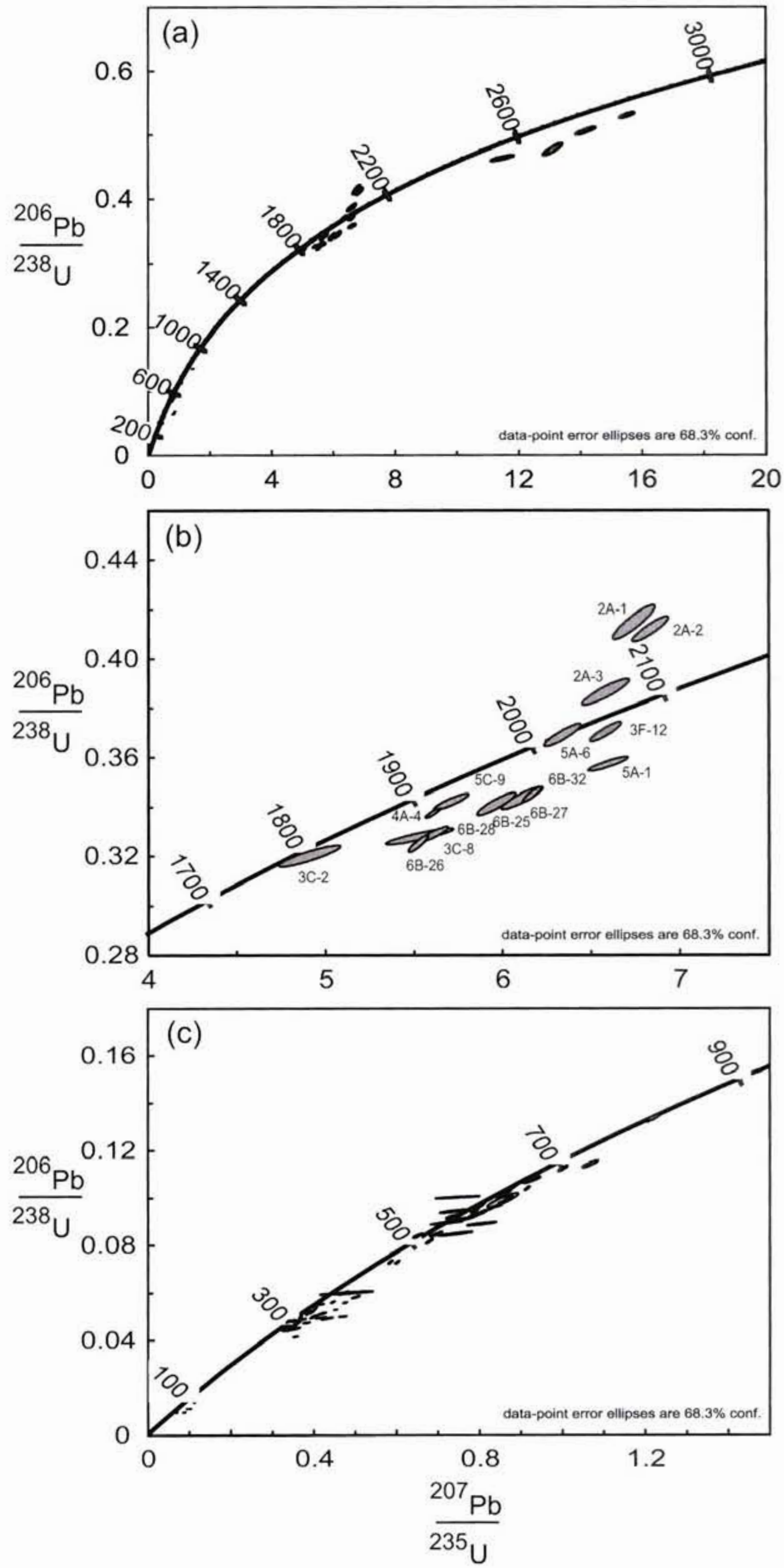

Fig. 5 Concordia diagrams for the detrital zircons analysed. (a) All grains. (b) Grains of Palaeoproterozoic age. The grain numbers are keyed to those in Table 2. (c) Neoproterozoic and younger zircons.

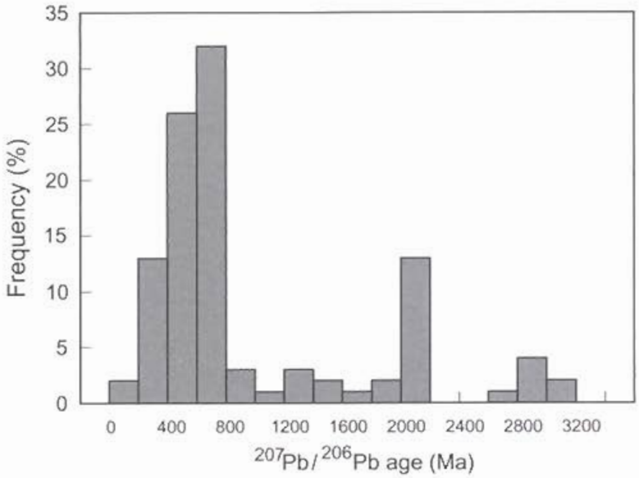

Fig. 6 Histogram illustrating the general age pattern of the detrital zircons.

DISCUSSION

The latest tectonic event in the South Iberian Peninsula occurred in the Late Pliocene due to tectonic plate movements that accompanied the formation of the Betics (Cabral, 1993). Along the southwestern Iberian margin, NW–SE compression and perpendicular NE–SW extension occurred, resulting in the uplift of the northern part of the Algarve region (Dias & Cabral, 1997; Andeweg, 2002). This tectonic event was probably responsible for changes in the drainage network, such as the change in the drainage path of the Guadiana River (Fig. 2), which started draining for the first time towards the south during Late Pliocene times (Martinez Del Olmo *et al.*, 1984; Cabral, 1993; Hurtado *et al.*, 1993; Vidal *et al.*, 1993;

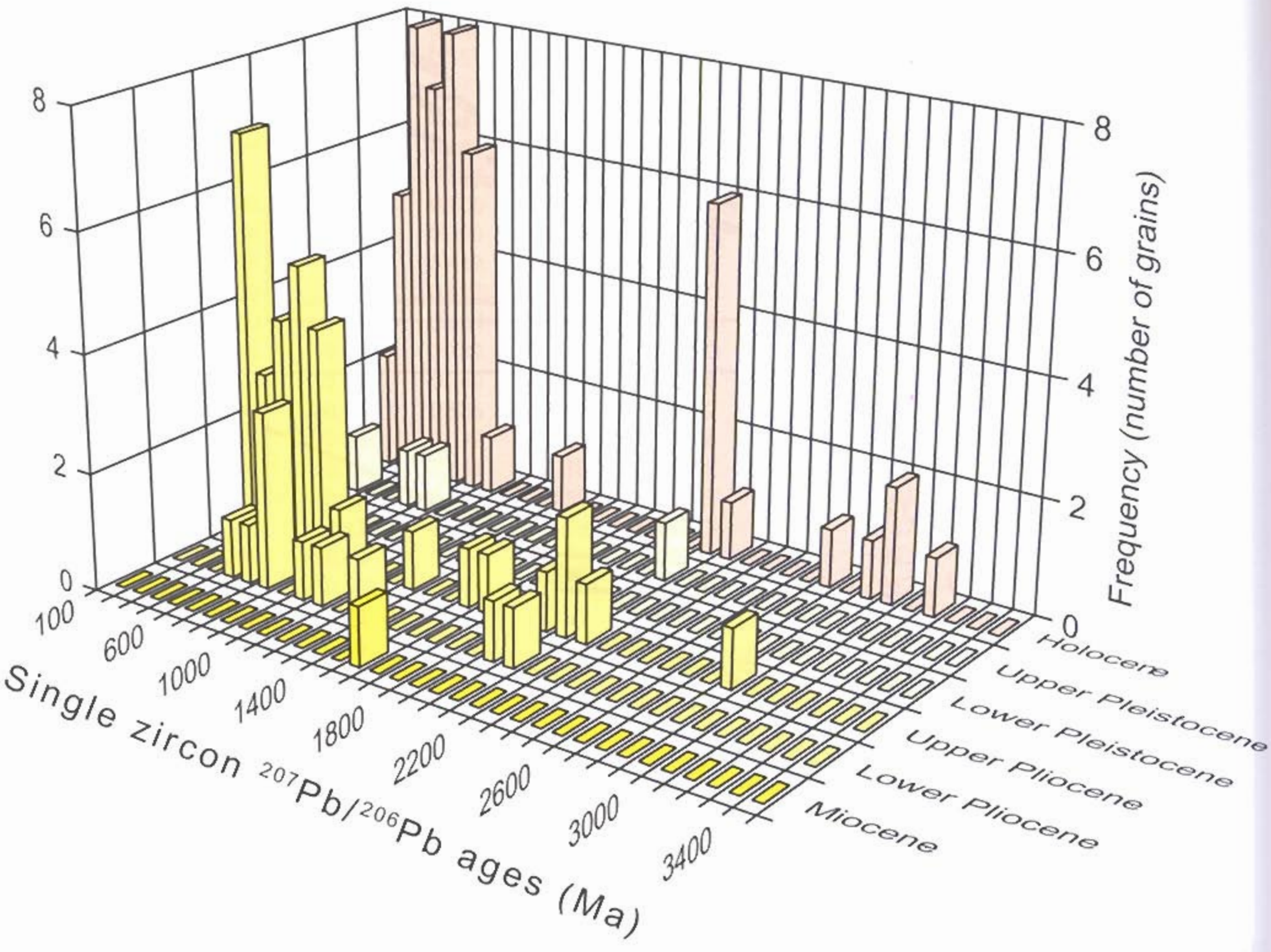

Fig. 7 Histogram of $^{207}Pb/^{206}Pb$ ages from single zircon grains plotted in relation to the age of the sample formation.

Hurtado & Vidal, 1994; Moura & Boski, 1997; Andeweg, 2002).

The Quaternary sandy fluvial facies, which cover Pliocene feldspathic sands, have a geometry and structure that point to very different fluvial regimes during the Early and Late Quaternary. The existence of euhedral and subrounded grains, evenly distributed in all samples, indicates at least two different sources. High grain-roundness can be due to either long transport distance, long residence time in shallow and/or high-energy marine waters, or to several cycles of transport and deposition. On the other hand, euhedral grains can be associated with short distance of transport if entrained as individual clasts and, hence, linked to a closer source, or they can lack abrasion marks due to their inclusion in other minerals, in which case, their sedimentary history can be difficult to reconstruct.

Nevertheless, detrital zircons from Late Pliocene formations to present-day beaches show the same three groups based on $^{207}Pb/^{206}Pb$ ages (Figs 5–7). The first and most abundant group is associated with Palaeozoic to Neoproterozoic ages (200–800 Ma); the second group is associated with Palaeoproterozoic ages (1700–2100 Ma); and the third and less common group with Archaean ages (> 2600 Ma). Zircons displaying Archaean to Lower Palaeozoic ages are superficially difficult to explain, since Archaean rocks are unknown in the entire Iberian Peninsula, and Neoproterozoic to Palaeozoic rocks are unknown in the South Portuguese Zone (Fig. 1). However, Archaean zircons are reported as being incorporated in Neoproterozoic and Palaeozoic rocks from Iberia, namely in the Ossa–Morena and Cantabrian Zones (Fig. 1; de la Rosa *et al.*, 2002; Fernández-Suárez *et al.*, 2000, 2002). These Archaean detrital zircons are probably derived from the West African craton and parts of the old craton remobilized by the Pan-African orogeny in northern Africa (Fernández-Suárez *et al.*, 2002; Zeck *et al.*, 2004). Nevertheless, to explain the wide range of ages obtained from detrital zircons in the present study, and their morphological and colour variations, three hypotheses can be formulated.

First, detrital zircons in Plio-Pleistocene formations could come from the erosion of northern Algarve Palaeozoic schists and greywackes, considering that these formations already contain inherited zircons from older formations. In this case, the Serra do Caldeirão region (Fig. 2) would be a possible Palaeozoic source since it is included in the Baixo Alentejo Flysch Domain of the SPZ, which is formed of Carboniferous terrigenous sediments of syn-orogenic character derived from the OMZ and probably also from the CIZ (Fig. 1; Oliveira, 1990).

Second, if it is considered that zircons come directly from Precambrian and Palaeozoic formations, then the drainage network must have been oriented from northeast to southwest. Indeed, the domains where such older rocks exist are located northeast of the Algarve and correspond to the formations of the Ossa–Morena and Central Iberian Zones (Fig. 1). This hypothesis could corroborate the change in the river drainage network orientation from NE–SW to the present-day NW–SE, documented in the Algarve and Andalusia (Martinez del Olmo *et al.*, 1984; Hurtado & Vidal, 1994; Moura & Boski, 1997). Such a change could have been due to a late Alpine orogenic phase, which caused the general uplift of southwestern Iberia during the Late Pliocene (Cabral, 1993; Andeweg, 2002).

Third, the detrital zircons and the associated metamorphic minerals could have been derived from both previous sources. With the existing data and the actual knowledge of the South Portuguese Zone, more specifically the Baixo Alentejo Flysch Domain, it is difficult to preferentially support one or another hypothesis.

In any case, if the roundness and altered colour of some individual grains are taken into consideration, then the provenance for the Pliocene drainage network could have been pre-existing Cretaceous and Triassic clastic formations (Andeweg, 2002). Accordingly, zircons would have undergone several sedimentary cycles, the first of which must have had a source area northeast of the South Portuguese Zone. This would explain the observed sparse distribution and remains of Cretaceous clastic formations associated with the main E–W oriented Jurassic fold belt (Moura, 1998).

At the present day, the main rivers in the Algarve are oriented NW–SE or N–S (Fig. 2). Their drainage basin source areas are either Palaeozoic shales and greywackes or Mesozoic carbonate rocks (Fig. 2). Sedimentological evidence, such as palaeocurrent patterns and facies distributions, points to a drastic change of the drainage network in the south Iberian Peninsula after the Late Pliocene (Gouvêa, 1938; Feio, 1946; Vidal *et al.*, 1993; Moura & Boski, 1997). Assuming that the southeastwards-directed drainage pattern was initiated in Plio-Pleistocene times, detrital zircon should be derived from a unique source.

The oldest rocks cropping out in the southern Alentejo–northern Algarve region are Devonian flysch sequences of the South Portuguese Zone of the Iberian Massif, deformed and metamorphosed during the Variscan orogeny (Oliveira, 1990; Terrinha, 1998). However, the lithostratigraphy of southern Portugal reveals the absence of significant magmatic and metamorphic events that could produce zircon-bearing rocks. Rather, it shows that detrital zircon from the Palaeozoic flysch units could have been through sedimentary cycles during the Triassic, Cretaceous and Cenozoic, and underwent further recycling in the Holocene beaches. Apparently, most detrital zircons therefore could be derived from this Palaeozoic flysch, which can be found in the Serra do Caldeirão (Fig. 2).

However, a striking observation is that the most frequent heavy minerals found in both the Holocene beaches and the Plio-Pleistocene rocks are staurolite and andalusite typical of medium-grade schists. These minerals are absent in the Palaeozoic flysch sequences of southern Alentejo, which are characterized by low-grade metamorphism (Oliveira, 1990), implying that these sequences are themselves derived from older metamorphic rocks. The source(s) of the sediments typical of the South Portuguese Zone are still a long-standing problem, but their age characterization by the method reported here is underway.

It is also of interest to note that with the exception of Archaean zircons that are well rounded, the younger ones are either euhedral to little rounded or very well rounded. This bimodality suggests that zircon grains display two abrasion histories, whereby rounded grains probably underwent multiple sedimentary cycles, whereas the euhedral ones could have been liberated from the source rock in the Holocene. The processes leading to rounding of detrital grains are not well understood, but if the conclusion of Kuenen (1959) that grains are not significantly rounded during transport is accepted, it is appropriate to suggest that zircon underwent rounding in beach settings. This would imply the recycling of coastal sediments.

The current study did not directly assess evidence for multiple sedimentary cycles, but a project with such an objective has been initiated. It is possible, however, to identify three main orogenic episodes: at 300–450 Ma, 450–800 Ma and 1.8–2.2 Ga, corresponding to Variscan tectonometamorphic events in Europe, and to Pan-African and Eburnean events in Gondwana. The interval 2.6–3.18 Ga is too poorly defined to be ascribed to a specific event, but several events in this age range are known in Gondwana (e.g. Machado *et al.*, 1996). These Archaean ages obtained on several zircon grains open a vast new domain to study on sediment recycling and palaeogeographical reconstructions.

Nevertheless, reworking of previous clastic formations, probably of Cretaceous and Triassic age, seem to be responsible for the existing Pliocene and Pleistocene formations, just as at the present time, when Holocene beach and fluvial sediments are mainly the result of the erosion of Pliocene and Pleistocene formations. Moreover, even the difference in drainage network characteristics observed between the Lower and Upper Pleistocene (Fig. 3) cannot be explained by a change in the drainage orientation. Indeed, based on the obtained single detrital zircon ages, the detrital sources do not seem to differ from the Pliocene to the present.

CONCLUSIONS

This work illustrates the application of U–Pb dating of individual detrital zircon grains to investigate the sources of Plio-Pleistocene detrital formations and of Holocene sands of the Algarve region. The results suggest that these units comprise both newly liberated and recycled detritus derived mainly from the pre-existing clastic formations or extensive Palaeozoic flysch sequences present in the South Portuguese Zone. Besides indicating that most zircons crystallized during Variscan, Pan-African and Eburnean tectonometamorphic events, these results also corroborate the existence of several sedimentary cycles through the Iberian Massif. However, the expected quantitative support for the timing of the river drainage network reorganization, previously documented in the Southern Iberian Peninsula during the Late Pliocene and linked to a late Alpine orogenic phase, has not been achieved. This is because single zircon ages from Lower Pliocene through Holocene sediments reveal the same source ages, ranging from the Palaeozoic to Archaean.

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