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User's guide to the interpretation of sandstones using whole-rock chemical data, exemplified by sandstones from Triassic to Miocene passive and active margin settings from the Southern Neotethys in Cyprus

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Title: User's guide to the interpretation of sandstones using whole-rock chemical data, exemplified by sandstones from Triassic to Miocene passive and active margin settings from the Southern Neotethys in Cyprus

Article Type: Research Paper

Keywords: user's guide; sandstone geochemistry; Cyprus; weathering and recycling; provenance; Southern Neotethys

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Abstract: Sandstone geochemistry provides useful insights into source-rock weathering, erosion, sedimentary transport, deposition, diagenesis and provenance. We identify and discuss useful geochemical methods and plots for the description and interpretation of whole-rock chemical data for a wide range of sandstone compositions, which we present as a user's guide. As a test, we apply this to late Triassic-late Miocene sandstones from two contrasting depositional-tectonic settings in Cyprus that are already extensively documented and interpreted. The chemical approach adds useful information/interpretation and deserves to be used more widely.

Late Triassic-early Cretaceous sandstones in southwest and southern Cyprus (Mamonia Complex and Moni Melange) were ultimately derived from felsic-dominated source rocks (e.g., granodiorite) that became more weathered through time, as conditions became more humid; sorting and recycling effects increased over the same time interval. The sandstones were mainly recycled from Paleozoic siliciclastic shelf deposits in southernmost Turkey (Taurides) during the rift/passive margin development of the Southern Neotethys. For the late Cretaceous-late Miocene sandstones in northern Cyprus (Kyrenia Range), the chemical signals are more complex related to a more variable provenance. Paleocurrent and other geological evidence support initial supply during the late Eocene-Oligocene from a mostly felsic continental source to the north in southern Turkey, with accumulation in a trench-type setting in north Cyprus, related to northward subduction. Paleocurrent data for during and after early-middle Miocene indicate sediment westward supply, including mafic/ultramafic material from ophiolite-related rocks, related to suturing of the Southern Neotethys in southeast Turkey. Overall, sandstone composition in Cyprus was strongly influenced by the regional Cadomian basement that was amalgamated during the late Precambrian-Cambrian Pan-African orogeny.

Research Data Related to this Submission

There are no linked research data sets for this submission. The following reason is given:
Data will be made available on request

Dear Prof. Knight,

Thank you very much for reviewing our manuscript. We also greatly appreciate the reviewers for their constructive comments and suggestions. We believe that we have acted on the review comments effectively and have produced a substantially improved paper.

We attach a track changes version showing changes made (the final editing was carried out on a clean copy as the file became sluggish and unwieldy).

A detailed comment-by-comment response to each of the Reviewers' concerns follows. Our replies are indicated clearly. We hope that you will now find our paper suitable for publication and look forward to hearing from you.

Thanks for your help.

Yours sincerely,

Guohui Chen and Alastair Robertson

Revision notes:

COMMENTS FROM EDITOR AND REVIEWERS

Editor:

Thanks for sending the above paper to Sedimentary Geology. I now have two reviews on the above paper, which are below and in the files which you should download. I have also read and made comments on the paper, which you should download. Both reviewers see merit in the paper but ask that revisions are made before it may be acceptable for the journal. Please note that you need to add much more information to the methods section, including a greater discussion of the analytical methods. This is because the focus of the paper should be the utility of integrating different analysis methods/approaches, as exemplified by your flow diagram fig 3. This is the most interesting and important bit about this paper. Therefore please expand on this. This also needs to be discussed in more detail in the Discussion and Conclusions sections. Please do this. I do not just want to see a paper on regional geology.

Dear Prof. Knight,

Thanks for returning our paper with two helpful reviews and your suggestions for improvements. We have acted on all of these as follows:

- (1) We now put more stress on the user's guide as you suggested, which is now upfront (see new Section 2, Line 93-278). We have systematised this to make it more user friendly and to incorporate more information on the methods of chemical interpretation, as well as the background science. The user's guide flow diagram was modified (new Fig. 1) so that the user can proceed through a series of logical steps without much prior knowledge. We also make integration with other forms of field and lab data an additional step 7 in Fig. 1 (Line 251-278). After doing this we treat the Cyprus whole-rock sandstone chemical data as a case history that effectively tests and applies the method, following the same logical order of steps for both the (differing) S and N Cyprus sandstones (see new Section 4.1 and 4.2, separately).*
- (2) We mention different diagrams/methods that could be used for differing sandstone compositions (e.g., volcanoclastic sandstones) to increase the applicability (Line 292-297).*
- (3) Please note that we do not think that it is necessary to explain the actual lab methods that may be used to obtain the initial chemical data. Users may obtain such data by several different methods and then apply our user's guide (new Fig. 1). For our study we refer to the well-known, published methods used for the Edinburgh XRF/ACME ICP-MS analysis (available on line). There seems no value in repeating this information again here. Also, our focus is on whole-rock analysis of sandstones. We now mention complementary methods (step 7, Line 257-276) but we do not wish to go into these in detail as this would dilute our message (and take a lot of space). The overall interpretation is based largely on information published in two (longish) papers in*

Sedimentary Geology, and we do not wish to try to repeat this here. Our main point is that the sandstone chemistry provides 'added value' and it is this aspect that we focus on, via the user's guide.

Additional notes of in the attached pdf are replied as follows:

- 'chemical' should be all changed to 'geochemical'.

We partly accepted the suggestion and changed it accordingly. However, we keep 'chemical' as original in some areas (more appropriate) because we consider the chemical changes or processes etc. as well;

- Line 66: 'the domain of specialist' is not clear;

The text is explained in the new Line 56-57;

- Line 142: 'you mean methods, not diagrams';

We meant both methods and diagrams. Explained in the new Line 292-297;

- Line 145-147: 'This needs to be expanded';

Yes, additional lines were added for explanation, see new Line 257-276;

- Line 149: 'need to state that you provide a different analytical methods etc.';

Yes. Revised as the new Section 3, Line 280-286;

- Line 190-191: 'dating indicate provenance?';

It is explained in more detailed, see Line 383-391;

- Line 237: 'This is completely missing, you do not describe any field or lab methods in this paragraph';

Sorry, we meant to describe the sample sources and well-known, published methods for whole-rock chemical data acquisition. Section title revised to be "Sampling and data analysis", Line 338.

- Line 259-260: 'more needed on methods to describe what you did with the data';

Yes. Methods are combined and upfront as the expanded user's guide, see New Section 2 and Fig. 1, for example, the seven-step methods illustrated in the text.

- PCA, UCC, REE etc. should be in full;

Thanks. They are in full when first used now.

- Line 394: 'the weathering indices must be described in the methods';

Yes, they are combined in the new Section 2.3, Line 156-166.

- Line 399: 'the observed bimodal grain-size' is not describe;

It is the petrographic observation (Torley and Robertson, 2018). Explained now, see Line 487-488.

- Line 594: evidence for 'tectonic re-activation'?

Yes. They are represented by the “localised alkaline magmatism in the Mamonia Complex (Chan et al., 2008) and renewed rifting in the Levant (Homberg and Bachmann, 2010; Robertson et al., 2012a)”, see new Line 806-808.

- Age “Early, Late” should be modified to be “early, late”;

Accepted, revised as suggested.

- References style and errors are corrected as indicated.

Reviewer #1:

The authors aim to provide sandstone geochemistry as a tool to interpret the source area, depositional environment and tectonic setting. For this they claim that they have identified the most useful geochemical plots and methods, which they present as a “users guide”. As a case to examine their guide they have chosen the Late Triassic-Late Miocene sandstones in two terranes in Cyprus where different petrological aspects are well-documented and the geological evolution is relatively well-understood. By this, the ms is an interesting contribution to sedimentary petrology and hence welcome for SEDGEO.

The validity of the authors claim for their “users guide” can only be checked by understanding how well it fits to the specific case they examined. However, this is not possible for the readers not specifically informed on the geology of the Cyprus area and surroundings. I therefore suggest a brief introduction on the geological evolution of the case-area. Another weakness is why the zircon data published recently by the authors has not been considered for the interpretation of the provenance. Considering the recent papers of the authors and the evolutionary model (Fig 17) they provided in this ms, the N terrane (Kyrenia Range+Alanya) was separated from the Taurides by a narrow oceanic basin since ?Late Permian-Mid Triassic. The presence of this basin has not been considered at all. I wonder how the Pan African/Cadomian detritus of the Taurides were transported during the Late Triassic across this basin and deposited in the Kyrenian Basin. Moreover, the closest oceanic

basin to provide ophiolite-related chemistry to the Late Cretaceous and younger sandstones in the Kyrenian Basin is also this narrow? basin (Antalya Ocean the W and Berit-Bitlis Ocean in the E) but not the ophiolitic nappes from the Northern Neotethys as shown in Fig 17c.

Due to these discrepancies and other issues marked on the annotated text (and figures) I suggest moderate to major revision.

Comment 1: The validity of the authors claim for their “users guide” can only be checked by understanding how well it fits to the specific case they examined. However, this is not possible for the readers not specifically informed on the geology of the Cyprus area and surroundings. I therefore suggest a brief introduction on the geological evolution of the case-area.

Reply: Agreed; we added brief synopsis of Cyprus geology for the unfamiliar reader, see new Section 3.1, Line 305-337.

Comment 2: Another weakness is why the zircon data published recently by the authors has not been considered for the interpretation of the provenance.

Reply: We now integrate the U-Pb dating results more, see Line 528-537, 552-556, 697-699, 731-742. However, only a pilot study is published for the N Cyprus sandstones.

Comment 3: Considering the recent papers of the authors and the evolutionary model (Fig 17) they provided in this ms, the N terrane (Kyrenia Range+Alanya) was separated from the Taurides by a narrow oceanic basin since Late Permian-Mid Triassic. The presence of this basin has not been considered at all. I wonder how the Pan African/Cadomian detritus of the Taurides were transported during the Late Triassic across this basin and deposited in the Kyrenian Basin.

Reply: *This is a fair point. So as to avoid getting bogged down in all the complex geology of the Taurides before we slightly generalised the inferred northerly origin. The exact restoration of the Mamonia Complex is debatable. Torley and Robertson (2018) discuss alternatives. Our chemical data do not allow us to identify any specific source area. However, the likely source was recycling from Palaeozoic successions as exposed in one or more southerly microcontinental units, namely the Alanya Massif or the Kemer zone. These would have been to the south of the inferred southerly small ocean separation (basin) and so could supply the Mamonia Complex. We now explain this briefly, see Line 769-777.*

Comment 4: Moreover, the closest oceanic basin to provide ophiolite-related chemistry to the Late Cretaceous and younger sandstones in the Kyrenian Basin is also this narrow basin (Antalya Ocean the W and Berit-Bitlis Ocean in the E) but not the ophiolitic nappes from the Northern Neotethys as shown in Fig 17c.

Reply: *The sandstone chemistry does not allow any particular ophiolite to be identified as the source. Even U-Pb detrital data have limitations because ophiolites in several zones have similar ages. Potential sources in the Oligocene-early Miocene N Cyprus sandstones included ophiolitic rocks, potentially from the inferred small ocean basin in the south (which, however, does not include exposed ophiolites), or from the Mersin ophiolite (and equivalents) that was thrust from the 'northern Neotethys' in the latest Cretaceous. Any of these sources could supply detritus to a trench setting, see Line 870-882. In the Mid-Late Miocene, provenance was mainly from the east, from thrust sheets including ophiolites in SE Turkey (so no problem here).*

To make the regional setting clearer we added extra places/units to the tectonic framework map (Fig. 2) and the plate tectonic sketch map (Fig. 17).

Additional notes of in the attached pdf are replied as follows:

- Abstract 'Late' should be used all along the text;
Ages with 'middle/late' are used according to the author's guide of SG.
- Line 151: 'references needed';
Yes. Text revised and references added in new Line 306-309.
- Line 152: 'Brief mention the tectonic framework';
Yes. Brief tectonic framework is now given, see new Section '3.1 Cyprus geology in a nutshell'.
- Line 159: 'Better mention in previous paragraph the characteristics and the tectonic setting of the Moni Unit';
Yes, a general description of the Moni Melange is now given in Line 361-372;
- Line 349: 'role of volcanic inputs';
Probably yes.
- Line 379: 'no information on this unit'
It was mentioned in the text, see lines related to Pareklisia Member. It is now detailed and indicated in brackets, e.g., Lines 423, 455.
- Key for Figures, 'Ardana' should be 'Adana';
No. It is 'Ardana', as given by previous studies e.g., Robertson and Woodcock (1986), Robertson et al. (2014). Adana is a city in S Turkey.

Reviewer 2:

Dear corresponding author, this ms is nice good one, well written focussing on extremely interesting discussion of provenance signatures of sandstones by using correctly geochemical dataset. It is concise and direct to the focus, I just outlined directly in the attached file very few things that you are free to accept. This contribution deserves to be published, and certainly it is pertinent to the aims of Sedimentary Geology journal, and I suggest to accept it with very few minor revisions.

Reply: We thank Prof. Salvatore Critelli for his positive comments. Additional references are added as suggested.

In summary, we hope that you will agree that we have made every effort to improve our paper which we now think will attract a wide readership.

Yours sincerely,
Guohui Chen and Alastair Robertson

1 User's guide to the ~~Interpretation~~-interpretation of sandstones using ~~major and trace~~
2 ~~element~~whole-rock chemical data, exemplified by sandstones from Triassic to
3 ~~-Miocene sandstones from Cyprus~~passive and active margin settings from the
4 Southern Neotethys in Cyprus

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5
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12 China

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14 Abstract

15 Sandstone geochemistry provides useful insights into source-rock weathering,
16 erosion, sedimentary transport, deposition, diagenesis and provenance. We identify
17 and discuss useful geochemical methods and plots for the description and
18 interpretation of whole-rock chemical data for a wide range of sandstone
19 compositions, which ~~After evaluating numerous published chemical plots and~~
20 ~~methods, we identify widely useful ones and~~ present ~~these~~ as a user's guide. As a
21 ~~testn example~~, we apply this to use chemical data for late Triassic-late Miocene
22 sandstones from two contrasting depositional-tectonic settings in Cyprus that are
23 already extensively documented and interpreted. The chemical approach adds useful
24 information/interpretation and deserves to be used more widely.

25 ~~both the south (Mamonia Complex and Moni Melange) and the north (Kyrenia~~
26 ~~Range) of Cyprus, where facies, optical petrography, X-ray mineralogy and other~~
27 ~~aspects are all well documented.~~ Late Triassic-early Cretaceous sandstones in
28 southwest and southern Cyprus (Mamonia Complex and Moni Melange) were
29 ultimately derived from felsic-dominated source rocks (e.g., granodiorite) that became
30 more weathered through time, as conditions became more humid; sorting and
31 recycling effects ~~also~~ increased over the same time interval. The sandstones were
32 mainly recycled from Paleozoic siliciclastic shelf deposits in southern~~most~~ Turkey
33 (Taurides) during the rift/passive margin development of the Southern Neotethys. For
34 the late Cretaceous-late Miocene sandstones in northern Cyprus (Kyrenia Range),
35 the chemical signals are more complex ~~and varied related to a more variable~~

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provenance. ~~but can be interpreted in the context of facies, optical petrography and~~
~~XRD data.~~ Paleocurrent and other geological evidence support ~~initial dominant~~ supply
~~during the late Eocene-Oligocene~~ from a mostly felsic continental source to the north
~~in (southern Turkey) during the late Eocene-Oligocene,~~ with accumulation in a
~~trench-type setting in north Cyprus, n active margin setting~~ related to northward
subduction. Paleocurrent data ~~for during and after early-middle Miocene then~~ indicate
~~sediment~~ westward supply, including mafic/ultramafic material from ophiolite-related
rocks, ~~related to during and after early-middle Miocene~~ suturing of ~~the the~~ Southern
Neotethys in southeast Turkey. Overall, ~~sandstone chemical~~ composition ~~in Cyprus~~
was strongly influenced by ~~the regional Cadomian basement that was amalgamated~~
~~inherited tectonic setting, especially during the~~ late Precambrian-Cambrian
Pan-African orogeny ~~and subsequent Paleozoic continental shelf deposition.~~
~~Chemical methods, therefore, add much information/interpretation and deserve to be~~
~~used more widely.~~

Keywords: user's guide; sandstone geochemistry; Cyprus; weathering and recycling;
provenance; ~~tectonic setting~~Southern Neotethys

1. Introduction

Clastic sediments, as the products of mechanical and chemical processes, provide
important clues concerning many aspects of sedimentary geology (e.g., Dickinson,

1970; McLennan et al., 1993; Weltje and von Eynatten, 2004; Basu et al., 2016). Petrographic analysis of major framework constituents and petrofacies using the optical microscope is critical to the successful study of physical erosion, provenance (source units), paleogeography and tectonic setting (e.g., Dickinson and Suczek, 1979; Marsaglia and Ingersoll, 1992; Critelli et al., 1997, 2003; Marsaglia et al., 2016; Critelli, 2018; Garzanti, 2019).

It is widely accepted that a combination of field and laboratory techniques enhances the understanding of sedimentary geology (e.g., Dickinson and Suczek, 1979; McLennan et al., 1993; Critelli, 2018; Garzanti, 2019). However, literature survey suggests that one of these techniques, whole-rock chemical analysis, is not nowadays routinely applied to the study of sandstones but mainly undertaken by specialists in sedimentary geochemistry. Possible reasons for this may include the extra time and expense involved in chemical analysis and interpretation, a belief that the results might not add much to the overall interpretation, and the plethora of existing chemical plots and diagrams with different objectives that can be off-putting.

Here, we present a user's guide that can help the non-specialist to enhance the interpretation of sandstones using chemical evidence. For igneous rocks, users' guides have long been available that allow earth scientists to obtain useful information, for example on eruptive tectonic setting, by making use of chemical discriminant diagrams and plots, especially when combined with optical microscopy and other techniques (e.g., Pearce and Cann, 1973; Pearce and Norry, 1979; Pearce, 1996). Although many aspects of sandstones can be interpreted using other methods (e.g.,

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79 sedimentary structures and optical petrography), our present study, confirms that the
80 whole-rock chemical analysis of sandstones does indeed provide useful additional
81 information, especially concerning climate, diagenesis and provenance. We
82 recommend the routine chemical analysis of sandstones using a combination of major
83 and trace elements, including rare earth elements (REEs).

84 Here, we take a whole-rock chemical dataset for the Triassic to Miocene
85 sandstones of Cyprus as a case history. This, together with relevant sedimentological,
86 petrographic and geochronological data (e.g., Robertson, 1977; McCay and
87 Robertson, 2012; Trolley and Robertson, 2018; Chen et al., 2019), illustrates the value
88 of whole-rock sandstone geochemistry in understanding the geological development
89 of the Southern Neotethys and its margins.

90 The cChemical analysis of sandstones particularly helps with ~~the~~ an
91 understanding of chemical weathering (climate-related), diagenesis, provenance,
92 paleogeography and tectonic setting (Roser and Korsch, 1985, 1986, 1988;
93 McLennan et al., 1993; Garver et al., 1996; Cullers, 2000). CChemical composition
94 can change in identifiable ways during sand generation, transportation, deposition
95 and recycling (Singh and Rajamani, 2001; Ryan and Williams, 2007; Caracciolo et al.,
96 2012; von Eynatten and Dunkl, 2012; Verma and Armstrong-Altrin, 2013, 2016; ~~Basu~~
97 ~~et al., 2016~~). The iInterpretation of chemical data is most effective when the
98 stratigraphy, age and structure of a study area are well known, and where
99 petrographic, X-ray diffraction (XRD) and geochemical analysis techniques are used
100 together (Weltje and von Eynatten, 2004; Critelli et al., 2008; Basu et al., 2016;

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~~Marsaglia et al., 2016;~~ Chen and Robertson, 2019). For fine-grained clastic sediments (mudrocks), identification of constituents can best be achieved using both XRD and chemical composition (e.g., Palamakumbura and Robertson, 2019).

~~For igneous rocks, user's guides have long been available that allow earth scientists to obtain useful information, for example on eruptive tectonic setting, by means of chemical discriminant diagrams and plots, especially when combined with optical microscopy (e.g., Pearce and Cann, 1973; Pearce and Norry, 1979; Pearce, 1996). In contrast, literature survey suggests that whole-rock chemical analysis is not routinely applied to the study of sandstones but is largely the domain of specialists. Possible reasons for this may include the extra time and expense involved in chemical analysis and interpretation, a perception that the results might not add much to the overall interpretation, and the plethora of existing chemical plots and diagrams which could be off-putting for the non-specialist.~~

~~During our study of sedimentary geology, we were intrigued to find out whether the chemical analysis of sandstones is really worth the time and effort involved given that, unlike fine-grained sediments, most of the main components can clearly be identified using the optical microscope.~~

~~To test the value of sandstone chemical analysis we take the example of a classic geological region, the Mesozoic-Cenozoic of the easternmost Mediterranean, on the island of Cyprus, where compositionally different sandstones of a large age range exist. This is a region where the paleogeography and tectonic setting are already well known, and where the sandstones have already been studied in some detail~~

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sedimentologically and petrographically. Our main general conclusion will be that, although many aspects of the sandstones can be interpreted using other methods (e.g., sedimentary structures and optical petrography), sandstone chemical analysis does indeed provide useful additional information, especially concerning climate, diagenesis and provenance. We recommend the routine chemical analysis of sandstones using a combination of major and trace elements, including rare earth elements (REE). Following evaluation of numerous chemical plots in the literature (Chen, 2018), we have selected a small number of diagrams and methods that aid description and interpretation of sandstones of widely differing compositions and present these as a user's guide.

2. User's guide to interpreting sandstone chemical compositionBackground and chemical methods

Below, we suggest We begin with some basic considerations relevant to the chemical interpretation of sandstonesa series of steps for the interpretation of sandstones in which different diagrams provide complementary information and interpretation (Fig. 1).÷

2.1. Step 1: screening (grain-size and composition)Grain-size and chemical classification–

The first step is to select samples for appropriate grain-size and compositions of interest. Samples with inappropriate grain-size and, or unusual or irrelevant

compositions can then be excluded from further study.

Grain-size can significantly influence the chemical composition of terrigenous sediments. ~~However, t~~The selection of equivalent grain-sizes (i.e., fine to medium-grained sandstone; 63-250 μm) and the use of element ratios minimises the effects of grain size and mineral fractionation (Wronkiewicz and Condie, 1987; Cullers, 1995, 2000; Weltje and von Eynatten, 2004). In our study, we collected medium-grained sandstones and make extensive use of element ratios.

~~2.2. Chemical classification~~

~~Chemical composition can be used to classify~~The sandstones can then be classified using two schemes in conjunction; i.e., binary plots of log ratios of $\text{Na}_2\text{O}/\text{K}_2\text{O}$ vs. $\text{SiO}_2/\text{Al}_2\text{O}_3$ (Pettijohn scheme; Pettijohn et al., 1972) and $\text{Fe}_2\text{O}_3/\text{K}_2\text{O}$ vs. $\text{SiO}_2/\text{Al}_2\text{O}_3$ (Herron scheme; Herron, 1988). ~~(e.g., Pettijohn et al., 1972; Herron, 1988).~~ Key element ratios include: (1) $\text{SiO}_2/\text{Al}_2\text{O}_3$, which reflects mineralogical maturity in clastic sediments (Pettijohn et al., 1972). This ratio increases as quartz is progressively concentrated at the expense of less resistant phases during weathering, transport or recycling (Maynard et al., 1982; Roser and Korsch, 1999); (2) $\text{Na}_2\text{O}/\text{K}_2\text{O}$ characterizes the relative abundance of feldspars (e.g., plagioclase vs. K-feldspar); and (3) $\text{Fe}_2\text{O}_3/\text{K}_2\text{O}$ indicates mineralogical stability (lithic vs. feldspathic fragments) (Herron, 1988). ~~For log-ratios, where the data set contains zeros; i.e., below detection limits of X-ray fluorescence (XRF) spectrometry, or inductively coupled plasma mass spectrometry (ICP-MS), an arbitrary value of 0.65 times the detection limit can be set~~

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165 (Martín-Fernández et al., 2003).

166 2.2. Step 2: Whole-rock chemical composition

167 The next step is to gain an understanding of the bulk chemical composition. A useful
168 first step is to plot binary variation, for example of key major elements (e.g., Al_2O_3 ,
169 SiO_2 , Fe_2O_3 , MgO) against other components, equivalent to the widely used Harker
170 diagrams for igneous rocks (Harker, 1909). This can be supplemented using specific
171 bivariate plots, for example of major and trace elements ($\text{Na}_2\text{O}+\text{K}_2\text{O}$ vs. SiO_2 of Le
172 Bas et al., 1986) (e.g., Chen and Robertson, 2019). It is useful then to plot the
173 sandstone composition against that of average chondrite and also of upper
174 continental crust (UCC) for selected major elements (e.g., K and P) and trace
175 elements (e.g., REEs) (Taylor and McLennan, 1985; Rudnick and Gao, 2003). As for
176 igneous rocks, certain trace elements; i.e., high field strength elements (HFSEs), e.g.,
177 Ti, Zr, Y and heavy rare earth elements (HREEs), are particularly useful as they are
178 relatively immobile and little affected by diagenesis or low-grade metamorphism, as is
179 well understood in the study of igneous rocks (Cann, 1970; Pearce and Cann, 1971,
180 1973).

181 Chemical correlations can also be identified using principal component analysis
182 (PCA) of the major and trace element data (Aitchison, 2003). This can be carried out
183 by means of a centred log-ratio (clr) transformation. Multivariate observations (points)
184 and variables (rays) are displayed as a compositional plot (Gabriel, 1971). The length
185 of each ray is proportional to the variance of the corresponding element in the dataset.

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The angle between the two rays of c. 0°, 90°, and 180° and shows whether the relevant elements are directly correlated, uncorrelated or inversely correlated. This approach can be refined by plotting a second PCA that excludes highly mobile elements; e.g., K, Rb, Ba, Sr, Mn and Na. Where carbonate cement is present, Ca should be excluded; also Mg if a high-magnesium cement is present.–

2.3. Step 3: Role of weathering and alteration~~Weathering, sorting and recycling~~

The next step is to assess the importance of weathering and alteration that could have taken place in the source area and, or during sediment transport. Chemical alteration can also take place during burial diagenesis (e.g., Tucker, 2001).

Variable degrees of chemical weathering in the source area strongly affect the major-element composition and the mineralogy of siliciclastic sediments (e.g., Nesbitt and Young, 1982; Taylor and McLennan, 1985; McLennan, 1993; Fedo et al., 1995).

The intensity of chemical weathering affecting a source rock is mainly controlled by the– source-rock composition, climatic conditions, duration of weathering, and rate of uplift/exhumation (e.g., Wronkiewicz and Condie, 1987; Scarciglia et al., 2007, 2016).

Chemical indices have been introduced to evaluate weathering effects quantitatively (e.g., Nesbitt and Young, 1982; Harnois, 1988; Fedo et al., 1995; Garzanti et al., 2013a, b, 2014a, b).

The mobility of elements during chemical weathering and post-depositional chemical diagenesis of source materials can be evaluated using the $\text{Al}_2\text{O}_3\text{-(CaO}^*\text{+Na}_2\text{O)-K}_2\text{O}$ molecular proportion diagram and the Chemical Index of

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207 Alteration (CIA of Nesbitt and Young, 1982). Chemical indices can customised to
208 circumvent problems associated with anomalous enrichment in potassium, such as
209 the Chemical Index of Weathering (CIW of Harnois, 1988), the Plagioclase Index of
210 Alteration (PIA of Fedo et al., 1995), the modified Chemical Index of Alteration (CIX of
211 Garzanti et al., 2014a, b), the Weathering Index (WIP of Parker, 1970), and the α^{Al}
212 values (Garzanti et al., 2013a, b). These indices can utilised individually, or preferably
213 together, to infer weathering effects. The formulae used to calculate the weathering
214 indices are given in Table 1.

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215 Oxidation, one of the major reactions in chemical weathering, influences the
216 oxidation state of some elements (e.g., U^{4+} to U^{6+}) (Taylor and McLennan, 1985).
217 Oxidising conditions can be inferred using proxies; e.g., elevated Th/U (>3.8; Taylor
218 and McLennan, 1985), but lower V/Cr (<2; Jones and Manning, 1994) and V/Sc (<9;
219 Kimura and Watanabe, 2001). The Th/U vs. Th diagram that can be used to help
220 evaluate successive cycles of weathering and redeposition (McLennan et al., 1993)
221 works in the same way mathematically.

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222 2.4. Step 4: Role of sedimentary sorting and recycling

223 ~~In contrast, s~~Sorting/recycling processes strongly fractionate mineralogical
224 components (e.g., clays, zircon) and therefore significantly influence bulk sediment
225 composition (Garcia et al., 1991; McLennan et al., 1993). Sedimentary sorting and
226 recycling processes affect the energy, rate, and/or duration of deposition, as well as
227 transport processes (e.g., debris-flow, aeolian). Such processes can also fractionate

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chemical components within sediments; e.g., clay minerals (Al_2O_3), Ti-oxides (TiO_2), zircon (Zr) and quartz (SiO_2) (Garcia et al., 1991). The related Al_2O_3 -Zr- TiO_2 plot eliminates weathering effects and can, therefore, highlight sorting-related fractionation (Garcia et al., 1991). By comparison, Zr/Sc usefully indicates petrogenetic evolution and sedimentary zircon concentration (McLennan et al., 1993). A combination of Th/Sc ratio (as in the Th/Sc vs. Zr/Sc plot), together with comparisons with the igneous differentiation trend and the model source evolution trend (e.g., Roser and Korsch, 1999; Roser et al., 2002) can, therefore, help to indicate sorting and recycling effects.

2.45. Step 5: Provenance indicators and tectonic setting

The chemical compositions of ~~detrital sediments and~~ sedimentary rocks can help indicate their provenance ~~and tectonic setting~~ (Dickinson and Suczek, 1979; ~~Bhatia, 1983~~ Roser and Korsch, 1988; von Eynatten et al., 2012). Major and trace element compositions, including SiO_2 , Al_2O_3 , $\text{Fe}_2\text{O}_3 + \text{MgO}$, K_2O , Na_2O , TiO_2 , Th, Sc, Zr, Cr, Ni, Co, V, Y, La, and Eu ~~anomaly~~anomalies, have been used to infer sediment provenance (~~Bhatia, 1983~~; Roser and Korsch, ~~1986~~1988; McLennan and Taylor, 1991).

Major-element compositions can be significantly affected during alteration and diagenesis (see above) and, therefore, are not ideal provenance indicators, although some ratios ($\text{SiO}_2/\text{Al}_2\text{O}_3$, $\text{K}_2\text{O}/\text{Na}_2\text{O}$, $\text{Al}_2\text{O}_3/\text{TiO}_2$) have been widely used for this purpose (Pettijohn et al., 1972; Roser and Korsch, 1988; Fyffe and Pickerill, 1993).

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Trace elements, which are relatively immobile during sedimentary processes (see above) are generally considered to be useful for provenance determination (e.g., Taylor and McLennan, 1985; Floyd and Leveridge, 1987; Wronkiewicz and Condie, 1987; McLennan et al., 1993; Cullers, 1995). Zr, Th, Hf and REEs are mainly derived from felsic rocks, as they are highly incompatible during most igneous melting and fractionation processes (McLennan, 1989; Cullers, 1995; Varga et al., 2007). However, sediments derived from mafic or ultramafic sources have relative enrichments in Sc, Co, Cr and Ni, representing their more compatible behaviour (Garver and Scott, 1995; Zimmermann and Bahlburg, 2003). Therefore, key trace-element ratios (e.g., La/Co, Th/Co, Th/Cr, La/Sc and Th/Sc) help to distinguish compositional differences (e.g., Taylor and McLennan, 1985; Cullers, 1995, 2000). Combinations of the above ratios are commonly used for provenance analysis, for example, the La-Th-Sc diagram and its variants (Taylor and McLennan, 1985; Jahn and Condie, 1995).

The progressive dissection of a magmatic arc and erosion of its basement increases the Hf content via release of zircon (Floyd and Leveridge, 1987). Therefore, La/Th vs. Hf can discriminate between different arc compositions and sources (and can also be related to framework modal analysis) (Floyd and Leveridge, 1987).

Chromium and Ni are widely used to indicate ultramafic components in clastic sediments. Enrichments of Cr (>150 ppm), Ni (>100 ppm), Cr/Ni (1.3-1.5) (Garver and Scott, 1995; Garver et al., 1996), together with elevated Cr/V (McLennan et al., 1993) suggest an ultramafic rock provenance (i.e., ophiolite-related sources). The addition of Th (e.g., V-Ni-Th and Th/Sc vs. Cr/Th diagrams; Bracciali et al., 2007; Taylor and

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271 McLennan, 1985) can help to indicate contributions from ultramafic, mafic or felsic
272 rocks.

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273 2.6. Step 6: Tectonic setting of deposition

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274 Although ~~s~~Some widely used chemical plots have shortcomings ~~when used by~~
275 ~~themselves~~ for tectonic discrimination (e.g., Ryan and Williams, 2007; von Eynatten
276 and Dunkl, 2012; Verma and Armstrong-Altrin, 2013, 2016; Basu et al., 2016; Chen,
277 2018). Major element-related diagrams can help indicate tectonic setting (Bhatia,
278 1983) and tectonic discrimination based on trace elements (e.g., La-Th-Sc, Th-Co-Zr)
279 (Bhatia and Crook, 1986). However, the database used to construct the original
280 template diagrams has limitations. The comparative tectonic settings used,
281 represented by the Paleozoic of Eastern Australia (an ancient orogen), are inevitably
282 interpretative; the database is restricted (<100 samples), and the presence of either
283 authigenic or allochthonous carbonate required recalculation prior to plotting of the
284 diagrams, which is potentially problematic.

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285 More recently, new diagrams have been developed using a more consistent
286 statistical treatment of the compositional data, a larger number of analyses and a
287 greater variety of comparative source lithologies (e.g., Armstrong-Altrin and Verma,
288 2005; Ryan and Williams, 2007; von Eynatten and Dunkl, 2012; Verma and
289 Armstrong-Altrin, 2013, 2016). The recently proposed diagrams of Verma and
290 Armstrong-Altrin (2013, 2016), based on multicomponent algorithms (i.e., log_e-ratio
291 transformation of 10 major elements with SiO₂ or isometric log-ratio transformation of

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10 major elements and 6 trace elements) are effective where sandstones have a wide range of compositions and are likely to encompass several different settings. Diagrams using a selected (customised) combination of relatively immobile major and trace elements can best determine provenance effectively (e.g., LaMaskin et al., 2008). Experience suggests that interpretations are most effective when a wide suite of geochemical plots are used in conjunction, especially in cases where the field sedimentological context is well understood tectonic setting (e.g., Robertson and Palamakumbura, 2019).

It should be noted that any discriminated tectonic setting refers to the source area and not necessarily the depositional setting (e.g., Verma and Armstrong-Altrin, 2013, 2016). In some cases, for example, long-lived subduction zone both source and sink may have similar sources (e.g., volcanic arc). In other settings, the depositional setting may postdate and be entirely different from the source area setting (e.g., sandstones above an unconformity).

2.7. Step 7: Synthesis including additional evidence

In practice, the above six steps provide complementary information requiring them to be evaluated together. Interpretations are most effective when a wide suite of chemical plots are used in conjunction, especially in cases in which the field sedimentological context is well understood and in which detailed optical petrography has been carried out (e.g., statistically valid point-counting) (e.g., Caracciolo et al., 2012; Scarciglia et al., 2016; Chen and Robertson, 2019).

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The interpretation is greatly enhanced when other methods and resulting data are used in conjunction. Some examples are as follows: (1) The chemical analyses of heavy minerals (e.g., zircon, rutile, pyroxene) can help to identify specific provenances (Morton and Hallsworth, 1994; Bahlburg and Floyd, 1999; Tucker, 2001; von Eynatten and Dunkl, 2012); (2) Microprobe and, or ion probe analysis of selected grains. For example, the composition of clinopyroxene, plagioclase or volcanic glass can help indicate magma type and thus provenance (e.g., Nisbet and Pearce, 1977; Bryant et al., 2003; Deer et al., 2013; Chen and Robertson, 2019). Also, the Cr composition of chrome spinel can be used to help constrain the original tectonic setting of an ultramafic rock (Poher and Faupl, 1988; Mange and Morton, 2007; von Eynatten and Dunkl, 2012); (3) The U-Pb age spectra of detrital zircon and/or rutile help to identify sandstone provenance and how it may have evolved through time (e.g., Gehrels et al., 1995; Fedo et al., 2003; Meinhold, 2010; von Eynatten and Dunkl, 2012); (4) Lu-Hf isotopic data (combined with U-Pb data) can provide additional clues to crustal origin, growth and recycling (Knudsen et al., 2001; Meinhold, 2010; Ustaömer et al., 2019); and (5) Apatite/zircon fission track ages can help identify the provenance terranes via the timing of uplift (Wagner, 1968).

In addition, the source area of metamorphic rocks can be further elucidated using methods such as tourmaline/garnet major element composition and rutile geochemistry/geochronology (Meinhold, 2010; von Eynatten and Dunkl, 2012).

However, further consideration of such methods is beyond our present scope which focusses on bulk chemical composition.

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~~In summary, we suggest that the plots/methods indicated above and in the Supplementary material, effectively a user's guide, are followed successively to achieve a comprehensive interpretation. However, sandstones with unusual compositions or limited compositional variation may need a different selection of diagrams. For example, some tectonic discrimination diagrams may be of little use if all of the samples come from one tectonic setting (e.g., subduction trench) or if there is little compositional variation (e.g., some volcanoclastic sandstones). Clearly, interpretation is enhanced where other methods are used in conjunction, for example, U-Pb and Lu-Hf isotopic analysis (e.g., Ustaömer et al., 2019) or pyroxene composition discrimination (Chen and Robertson, 2019).~~

3. Selected case history: Mesozoic-Cenozoic sandstones related to South Neotethys

Example of the Triassic-Miocene sandstones of Cyprus

To test the application and effectiveness of our user's guide to sandstone whole-rock chemical analysis, as explained above, we now take the example of a classic geological region, the island of Cyprus, in the easternmost Mediterranean. Compositionally variable sandstones of a large age range are exposed in Cyprus, related to the Mesozoic-Cenozoic geological development of the Southern Neotethys, the most southerly strand of the Tethys in the Eastern Mediterranean region (e.g., Robertson, 1998; Stampfli and Borel, 2002; Barrier et al., 2018). In this region, the paleogeography and tectonic setting are relatively well known and where the

sandstones have already been studied in some detail, both sedimentologically (e.g., facies analysis, paleocurrent evidence) and petrographically (e.g., optical petrography and point-counting) (Robertson, 1977; McCay and Robertson, 2012; Torley and Robertson, 2018). Some U-Pb dating of detrital zircons is also available (Chen et al., 2019). Here, we focus on terrigenous sandstones. Sandstones with different compositions, such as ophiolite-derived sandstones, volcanoclastic sandstones and mixed carbonates-siliciclastics ideally require a different selection of diagrams/methods (e.g., Caracciolo et al., 2011; Perri et al., 2012). For this reason, we exclude late Cretaceous volcanoclastic sandstones in west Cyprus (Robertson, 1977) for which whole-rock chemical data are also available (Chen and Robertson, 2019).

The main objectives of our chemical study of the Cyprus sandstones, as presented below are as follows: (1) To determine the nature and extent of weathering of possible source rocks; (2) To evaluate the influence of sedimentary processes on sediment chemical composition; (3) To shed light on the provenance and paleogeography; and (4) To evaluate alternative possible controls of chemical composition in relation to the tectonic development of Cyprus and the Southern Neotethys in the eastern Mediterranean region.

3.1. Cyprus geology in a nutshell

The outline below is based on several overview contributions (e.g., Robinson and Malpas, 1990; Robertson and Xenophontos, 1993; Robertson, 1998; Göncüoğlu and

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Kozlu, 2000; Pearce and Robinson, 2010; Cyprus Geological Survey Department, 2020). Cyprus comprises three litho-tectonic assemblages ('terranes'), the Troodos Massif (central), the Mamonia Complex (in the west), and the Kyrenia Range (in the north) (Fig. 2). During the late Precambrian, the area that is now Cyprus formed part of the Cadomian orogen along the northern margin of the Pan-African continent. During most of the Paleozoic, the area formed part of a wide continental shelf bordering Gondwana with oceans (Rheic and Paleotethys) to the north. During the Permian-Triassic, the continental borderland rifted to form the Southern Neotethys. In conjunction, several continental fragments rifted and drifted northwards. As a result, these continental units, including crust that is now in Cyprus, became isolated from direct input of clastic sediment from the Pan-African basement to the south, whereas compositionally similar metamorphic and igneous material became available from the north. Several interconnected rift and small ocean basins existed during the Mesozoic. Clastic sediment supply was probably derived mainly from the most southerly of the rifted continental fragments, such as the Alanya Massif and/or the Antalya Complex (e.g., Tahtahlı Dağ) (Fig. 2) and accumulated in Cyprus within the Mamonia Complex and the Moni Melange in the west and south of the island. During the Jurassic and/or early Cretaceous, the Southern Neotethys reached its widest extent. Incipient closure during the late Cretaceous (c. 90 Ma) triggered subduction and the genesis of ophiolites, including the Troodos Massif in Cyprus above a subduction zone. The Southern Neotethys subducted northwards during late Cretaceous to Miocene resulting in voluminous clastic sediment accumulation, as studied here, in a trench

399 setting, now exposed in the Kyrenia Range, northern Cyprus. Further crustal
400 shortening was accommodated along a subduction zone south of Cyprus. Today, the
401 island is in an incipient collisional setting between the Eurasian and African plates.

402 The Mesozoic sandstones discussed here, accumulated during the passive
403 margin stage of opening of the Southern Neotethys (Mamonia Complex and Moni
404 Melange), whereas the late Mesozoic-Cenozoic sandstones (Kyrenia Range)
405 accumulated in trench-type setting related to subduction, making an interesting
406 comparison.

407 3.2. Sampling and data analysis

408 In total, 68 samples of sandstone were selected for major and trace element analysis,
409 made up of 31 samples from the Mamonia Complex (southwest Cyprus), one from the
410 Moni Melange (southern Cyprus) and 36 from the Kyrenia Range (northern Cyprus).
411 We used a combination of previously collected samples, together with some
412 additional samples to give a more complete coverage. The samples mainly come from
413 logged successions that cover the range of compositions and ages. Medium-grained
414 sandstones were analysed preferentially to minimise grain-size and mineral
415 fractionation effects (e.g., Wronkiewicz and Condie, 1987; Cullers, 1995, 2000). Major
416 and trace elements were analysed by XRF spectrometry at the School of
417 GeoSciences, University of Edinburgh, using the methods explained by Fitton et al.
418 (1998) and Fitton and Godard (2004). Accuracy and precision are typically c. 5%.

419 In addition, five samples of sandstone from the Mamonia Complex, one from the

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Moni Melange and 19 samples from the Kyrenia Range were analysed for selected trace elements and a full set of REEs by ICP-MS at the ACME Analytical Laboratories, Vancouver. A larger number of samples was utilised for the Kyrenia range sandstones than the Mamonia Complex/Moni Melange sandstones because of their greater compositional range based on petrographic study (McCay and Robertson, 2012). For detailed information on the procedures, geostandards and precision for the elements analysed, see <http://acmelab.com>. All of the analytical data for the major, trace and REEs are listed in the Supplementary material.

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~~comprised of three tectonic terranes (Troodos Massif, Mamonia Complex and Kyrenia Range) (Fig. 1), includes a variety of sandstones of different composition that range in age mainly from late Triassic to late Miocene (Fig. 2). The sandstones and other associated sedimentary rocks contribute to an understanding of the geological development of the Tethyan ocean and its margins (e.g., Robertson and Woodcock, 1979, 1986; Robertson et al., 2012a, b, 2014).~~

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3.43. Sandstones of the Mamonia Complex, SW Cyprus and the Moni Melange, ~~southern S~~ Cyprus

The Mamonia Complex in southwest Cyprus and Moni Melange in southern Cyprus represent remnants of rifted passive margins of the Southern Neotethys (Robertson, 1977; Robertson and Woodcock, 1979). ~~The~~ Triassic-Cretaceous sandstones occur in the Mamonia Complex, southwest Cyprus (Ealey and Knox, 1975; Lapierre, 1975; Ealey and Knox, 1975; Robertson and Woodcock, 1979; Torley and Robertson, 2018),

with equivalents in the Moni Melange, southern Cyprus (Robertson, 1977) (Fig. 23).

The Moni Melange is a collection of blocks of sedimentary and igneous rocks including some serpentinite, in a matrix of late Cretaceous deep-water argillaceous sediments. Some of the sandstones are similar in age and petrography to those in the Mamonia Complex. The Moni Melange is basically a more deformed and disaggregated equivalent of the Mamonia Complex and restores as a part of the same Mesozoic passive margin (Robertson, 1977).

Data available for the sandstones of the Mamonia Complex mainly concern lithostratigraphy (Robertson and Woodcock, 1979), depositional processes, paleoenvironments and diagenesis (Torley and Robertson, 2018). The age of deposition is mainly inferred from macro- and micro-paleontological studies of interbedded deep-sea sediments (e.g., radiolarites) (Ealey and Knox, 1975; Lapierre, 1975; Robertson and Woodcock, 1979; Bragin and Kyrlov, 1996; Bragin, 2007). ~~Some~~ Data are also available for the chemical composition of interbedded mudrocks and metalliferous sediments (Robertson and Boyle, 1983; Torley and Robertson, 2018). For the sandstones of the Moni Melange, southern Cyprus, facies and petrographic data are likewise published, coupled with a tentative age assignment using sporomorphs from interbedded mudrocks (Robertson, 1977). In addition, recent U-Pb dating of detrital zircons in the late Triassic and ~~the~~ late Jurassic-early Cretaceous sandstones of the Mamonia Complex and also the early Cretaceous sandstones from the Moni Melange indicates an ultimate source from the northeast African/Arabian-Nubian Shield area (Chen et al., 2019), today to the southeast of

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Cyprus. However, following rifting of the Southern Neotethys, the probable source was in one or more of the microcontinental fragments that were located to the north in Anatolia (Turkey). The clastic sediment probably reached Cyprus via reworking of Paleozoic successions exposed in the Taurides (Chen et al., 2019; Ustaömer et al., 2019) shed light on the provenance and regional tectonic setting of these sediments (Chen et al., 2019).

3.24. Sandstones of the Kyrenia Range, northern N Cyprus

The Kyrenia Range, northern Cyprus, represents part of the northerly active continental margin of the Southern Neotethys (Robertson and Woodcock, 1986; Robertson et al., 2012a, 2014; Chen et al., 2019). Sandstones are well exposed along the northern and southern flanks of the Kyrenia Range, mainly ranging in age – mainly from latest Cretaceous (Maastrichtian) to late Miocene (Tortonian), – are well exposed along the northern and southern flanks of the Kyrenia Range (Fig. 23). Basic information was provided by from –geological mapping and lithostratigraphy (Ducloz, 1972; Baroz, 1979; Robertson and Woodcock, 1986; Hakyemez et al., 2000) is supplemented by recent studies of. In addition, depositional facies and petrography is evidence have been published for sandstones of latest Cretaceous (Robertson et al., 2012b), early-middle Eocene (Robertson et al., 2014) and late Eocene-late Miocene age (McCay and Robertson, 2012). These sandstones are mainly dated using microfossils in interbedded mudrocks and pelagic/hemipelagic sediments (Baroz, 1979; McCay et al., 2013), coupled with strontium isotopes dating – (McCay et al.,

2013). XRD data are available for interbedded mudrocks ~~throughout much of the~~
~~succession~~ (McCay and Robertson, 2012). Microfossil, XRD and ~~geo~~chemical data
have also been published for mudrocks and manganese deposits of specifically early
Messinian age (Robertson et al., 2019a). In addition, preliminary U-Pb dating has
been carried out on detrital zircons of sandstones of latest Cretaceous, Eocene and
middle Miocene age ~~(Chen et al., 2019). Paleocurrent data and lithological~~
~~comparisons suggest that the source areas were located in the Taurides of southern~~
~~Turkey, both to the north and northeast (McCay and Robertson, 2012; Chen et al.,~~
~~2019), giving useful pointers to provenance (Chen et al., 2019).~~

~~In summary, the new chemical data set out below can be interpreted in the light of~~
~~an extensive body of prior information.~~

~~4. Specific objectives of chemical analysis~~Application of the user's guide to the Cyprus sandstones

~~Our study of the Cyprus sandstones, as presented below, has the following main~~
~~objectives:~~

- ~~(i) To determine the nature and extent of weathering of possible source rocks;~~
- ~~(ii) To evaluate the influence of sedimentary processes on sediment chemical~~
~~composition;~~
- ~~(iii) To shed light on the provenance and paleogeography;~~
- ~~(iv) To evaluate alternative possible control of sand and sandstone chemical~~

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composition in relation to the regional tectonic development of Cyprus and Tethys in the eastern Mediterranean region.

To achieve the above objectives, we applied our user's guide (Fig. 3), utilising particular plots and methods as appropriate to our sandstones' compositions. We used several plots (e.g., Na₂O/K₂O vs. SiO₂/Al₂O₃ and Fe₂O₃/K₂O vs. SiO₂/Al₂O₃) to classify the sandstones initially in terms of rock type (Pettijohn et al., 1972; Herron, 1988). The whole-rock composition is illustrated using compositional biplots or simple binary plots. The compositions are also indicated using upper continental crust (UCC)/chondrite-normalised spider plots of major, and trace elements, including rare earth elements (relatively unaffected by alteration or low-grade metamorphism). We assessed weathering (alteration) that may relate to climatic or diagenetic conditions, utilising the Al₂O₃-(CaO*+Na₂O)-K₂O molecular proportion diagram (Nesbitt and Young, 1982), together with several chemical indices (e.g., Harnois, 1988; Fedo et al., 1995; Parker, 1970; Garzanti et al., 2013a, b). Recycling and sorting effects were assessed using the plots of Th/Sc vs. Zr/Sc (McLennan et al., 1993), Al₂O₃-Ti-TiO₂ (Garcia et al., 1991) and LaN/YN vs. SiO₂/Al₂O₃ (Rosier and Korsch, 1999). Provenance and source mixing are indicated using the La-Th-Sc plot (McLennan and Taylor, 1984), or variants. An ultramafic rock source is revealed by combinations of the Cr vs. Ni and the Cr/V vs. Y/Ni plots (Garver and Scott, 1995; McLennan et al., 1993). In contrast, ultramafic-felsic sources are indicated using the V-Ni-Th plot (Bracciali et al., 2007), and felsic-mafic ones using the Th/Sc vs. Cr/Th plot (Taylor and McLennan, 1985). The final objective was to shed light the possible tectonic

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527 ~~settings of deposition, for which several ternary plots (e.g., La-Th-Sr; Bhatia, 1983;~~
528 ~~Roser and Korsch, 1986) and normalised data plots (e.g., UCC; Floyd et al., 1991)~~
529 ~~were used. While these can give useful indications, recently introduced~~
530 ~~multicomponent algorithms may be more reliable (Verma and Armstrong-Altrin, 2013;~~
531 ~~2016), although requiring more computation. All such tectonic discrimination diagrams~~
532 ~~(similar to point-count data obtained under the optical microscope) typically indicate~~
533 ~~the setting of initial sediment accumulation and not necessarily the tectonic setting of~~
534 ~~final deposition. For example, if a sandstone accumulated in a passive margin setting~~
535 ~~and was later redeposited in a trench or foreland setting it might retain its original~~
536 ~~passive margin chemical signature. Any such ambiguities can be cleared up in cases~~
537 ~~in which the tectonic setting at the time of deposition is well understood, as in Cyprus.~~

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539 5. Field and Laboratory methods Having obtained the chemical data, we carried out
540 the seven-step evaluation and interpretation, as explained in the user's guide (see
541 Section 2) (Fig. 1). The samples discussed below passed the initial screening step;
542 i.e., are of suitable grain size and composition to proceed usefully.

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544 A combination of new and previously collected samples were used during this study,
545 as detailed in the Supplementary material. Sampling sites were chosen to take
546 advantage of previous stratigraphic, sedimentological and petrographic research in
547 different areas (Robertson, 1977; Torley and Robertson, 2018; McCay and Robertson,
548 2012). Medium grained sandstones were analysed preferentially to minimise

~~grain size and mineral fractionation effects (e.g., Wronkiewicz and Condio, 1987; Cullers, 1995, 2000).~~

~~5.1. Data base of Cyprus sandstones~~

~~In total, sixty-eight samples of sandstone were selected for major and trace element analysis, made up of 31 samples from the Mamonia Complex (southwest Cyprus), one from the Moni Melange (southern Cyprus) and 36 from the Kyrenia Range (northern Cyprus). Major and trace elements were analysed by X-ray fluorescence (XRF) spectrometry at the School of GeoSciences, University of Edinburgh, using the methods specified by Fitton et al. (1998) and Fitton and Godard (2004). Accuracy and precision estimates are typically c. 5%.~~

~~In addition, five samples of sandstone from the Mamonia Complex, one from the Moni Melange and 19 samples from the Kyrenia Range were analysed for selected trace elements and a full set of REEs by inductively coupled plasma-mass spectrometry (ICP-MS) at the ACME Analytical Laboratories, Vancouver. For detailed information on the procedures, geostandards and precision for the elements analysed, see <http://acmelab.com>. All of the analytical data for the major, trace and REEs are listed in the Supplementary material.~~

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~~6. Results of chemical analysis~~

~~6.1. Sandstones from south~~Southwest/southern Cyprus sandstones: Mamonia Complex and Moni Melange

4.1.1. Chemical classification

The late Triassic sandstones (Vlambouros Formation, ~~southwest Cyprus~~Mamonia Complex) show relatively consistent $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios, whereas the late Jurassic-early Cretaceous sandstones (i.e., Episkopi Formation including Akamas Member, ~~southwest Cyprus~~Mamonia Complex; Pareklisia Member, ~~southern Cyprus~~Moni Melange) have variable $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios and relative depletion in Na (Fig. 4a). As a result, the late Triassic sandstones are subarkoses and the late Jurassic-early Cretaceous sandstones are mainly quartz_arenites. In the Herron scheme (Fig. 4b), the late Triassic sandstones are litharenites or sublitharenites, whereas the late Jurassic-early Cretaceous sandstones (with variable $\text{Fe}_2\text{O}_3/\text{K}_2\text{O}$) are mainly Fe-sand and quartz_arenite.

The above geochemical classification of the ~~late Jurassic-early Cretaceous~~ sandstones is generally consistent with their petrographic descriptions (Robertson, 1977; Robertson and Woodcock, 1979; Torley, 2015; Torley and Robertson, 2018). The relatively low $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios are likely to have resulted from high mobility of Na_2O during chemical weathering, diagenesis and/or secondary alteration (e.g., Gaillardet et al., 1999; Varga et al., 2007).

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4.1.2. Chemical composition and correlations

—The late Triassic sandstones have variable SiO₂ contents (18.9-85.9 wt%), low K₂O (<2.0 wt%), Na₂O (<0.7 wt%), TiO₂ (<0.8 wt%) and P₂O₅ (<0.1 wt%). Al₂O₃ values are variable (1.3-7.7 wt%). CaO is generally high (2.8-43.3 wt%), consistent with the petrographically observed abundances of fine-grained micritic lithics and carbonate fragments (both skeletal and non-skeletal) (Torley and Robertson, 2018). In contrast, the late Jurassic-early Cretaceous sandstones are characterised by extremely high and uniform SiO₂ (91.5-98.2 wt%), together with low CaO (<0.5 wt%), K₂O (<0.2 wt%) and Na₂O (<0.01 wt%).

~~The PCA biplot of major elements (Fig. 5a), reveals a clear separation between the late Triassic sandstones and the late Jurassic-early Cretaceous sandstones. Potassium, Na, Ca and LOI are relatively high in the late Triassic sandstones, whereas Si, Ti, Al and Fe relatively enriched in the late Jurassic-early Cretaceous ones. The three principal components of the PCA, excluding mobile elements and carbonates (Fig. 5b), together account for 86% of the total variability. Specifically, the late Triassic sandstones are enriched in Ni, Sc, V, Cr, Al and Fe but are depleted in Si, Zr and Nb compared to the late Jurassic-early Cretaceous sandstones.~~

When selected trace element concentrations for the sandstones are normalised to upper continental crust (UCC) (Fig. 6a5a-b), the late Triassic sandstones are seen to be characterised by relatively low and scattered elemental abundances (e.g., Ba, Th, U), together with small relative enrichments in Zr and Hf (0.2-2xUCC). The main

influence is likely to be detrital zircon ~~content~~, in line with petrographic observations (Torley and Robertson, 2018; [Chen et al., 2019](#)). The late Jurassic-early Cretaceous sandstones are poor in trace elements, with the exception of Zr, K and Sr (probably also P) and show pronounced negative anomalies, whereas Th and U are relatively enriched.

The chondrite-normalised REE patterns confirm the presence of [light rare earth elements \(LREEs\)](#) enrichment in the sandstones (Fig. ~~6e5c-d~~). ~~The~~ The late Triassic sandstones have higher concentrations of REEs in relation to UCC, and also moderate Eu depletion ($\text{Eu}/\text{Eu}^*=0.65$). The early Cretaceous sandstone (Pareklisia Member) has lower REE concentrations ($\Sigma\text{REE}=36.3$ ppm), together with significant Eu depletion ($\text{Eu}/\text{Eu}^*=0.5$).

The PCA biplot of major elements (Fig. 6a), reveals a clear separation between the late Triassic sandstones and the late Jurassic-early Cretaceous sandstones. Potassium, Na, Ca and loss on ignition (LOI) are relatively high in the late Triassic sandstones, whereas Si, Ti, Al and Fe relatively enriched in the late Jurassic-early Cretaceous ones. The three principal components of the PCA, excluding mobile elements and carbonates (Fig. 6b), together account for 86% of the total variability. Specifically, the late Triassic sandstones are enriched in Ni, Sc, V, Cr, Al and Fe but are depleted in Si, Zr and Nb compared to the late Jurassic-early Cretaceous sandstones.

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4.1.3. Weathering

Moderate weathering conditions are inferred for the late Triassic sandstones (Vlambouros Formation) with CIA and PIA values of 52-77 (Fig. 7a) and 52-89, respectively (see Supplementary material). CIX values of 65-80 are more restricted. The CIA values for most of the late Triassic sandstones (excepting a few outliers) lie along a different trend from that generally expected (Fig. 7a). This can be explained by potassium metasomatism, specifically the conversion of aluminous clay minerals to illite and the replacement of plagioclase by K-feldspar (McLennan et al., 1993; Fedo et al., 1995). Petrographic observations indicate the presence of a variable clay matrix and also of plagioclase alteration in the late Triassic sandstones (see Supplementary material in Torley and Robertson, 2018). Oxidising depositional conditions are inferred, as represented by the proxies of e.g., high CIA, coupled with elevated Th/U but lower V/Cr and V/Sc ratios (Nesbitt and Young, 1982; Taylor and McLennan, 1985; Jones and Manning, 1994).

In contrast, the late Jurassic-early Cretaceous sandstones (Episkopi Formation including Akamas Member) exhibit higher CIA (90-95) (Fig. 7a), PIA (98-99), CIW (98-99) and CIX (90-95) values (see Supplementary material). These higher values are attributed to CaO and Na₂O depletion, in response to intense or prolonged weathering of the source area (Nesbitt and Young, 1982). In addition, extreme textural maturity is indicated by the abundance of very well-rounded grains (Robertson, 1977; Torley and Robertson, 2018). The bimodal grain-size variation, as previously

described and illustrated, is also indicative of reworking (Robertson, 1977; Robertson and Woodcock, 1979; Torley and Robertson, 2018). The combined textual and chemical evidence point to prolonged weathering in a tropical environment, coupled with reworking (e.g., Weltje et al., 1998). The early Cretaceous sandstone of the Moni Melange (Pareklisia Member) is chemically similar but has a lower CIA value (76) (Fig. 7a). This sample has a relatively high K/Al ratio (possibly resulting from K-metasomatism), which shifts the point on the diagram towards illite (Fig. 7a). Although variable, the sandstones trend back to crustal source compositions (andesite and granodiorite), in line with the petrographic evidence, which is generally consistent with a felsic-dominated source (Robertson, 1977; Torley and Robertson, 2018).

Na is strongly depleted relative to the other mobile elements (e.g., K, Mg, Ca, Rb, Sr and Ba). $\alpha^{Al}Na$ ranges from 32-83 in the late Jurassic-early Cretaceous sandstones, c. 33 in the early Cretaceous sandstones, and from 1-7 in the late Triassic sandstones (Fig. 7b). Ca is more depleted relative to K and Rb (Fig. 7b). There is little relative depletion in Mg, Sr and Ba, with $\alpha^{Al}Mg$, $\alpha^{Al}Sr$ and $\alpha^{Al}Ba$ rarely >2 (Fig. 7b). The following bulk-sediment mobility sequence is inferred: $\alpha^{Al}Na \gg \alpha^{Al}Ca > \alpha^{Al}K \geq \alpha^{Al}Rb > \alpha^{Al}Ba \geq \alpha^{Al}Sr > \alpha^{Al}Mg$. The notably higher $\alpha^{Al}Na$ and $\alpha^{Al}Ca$ (preferentially removed during weathering), together with the low values of $\alpha^{Al}Mg$ (fixed in secondary clay minerals) and $\alpha^{Al}Ba$ (absorbed onto clays), demonstrates that the sandstone composition is strongly influenced by weathering processes (e.g., Nesbitt et al., 1980; Garzanti and Resentini, 2016).

670 The range of CIA values (Fig. 7a) is compatible with the petrographic
 671 observations, especially the abundance of clay matrix and plagioclase alteration
 672 (Torley and Robertson, 2018), in the late Triassic to early Cretaceous sandstones.
 673 The weathering trend is indicated in simplified form by the Th/U ratios here
 674 (McLennan et al., 1993) (see above and Supplementary material).

675 4.1.4. Sorting and recycling effects

676 On the ternary plot of Al_2O_3 -Zr-TiO₂ (Fig. 7c), Al_2O_3 strongly correlates with TiO₂/Zr.
 677 The resulting linear trend (Fig. 7c) is consistent with sorting-related fractionation of
 678 similar-composition protoliths (Garcia et al., 1991). Sediment recycling effects,
 679 especially enrichment in zircon are also indicated by the plot of Th/Sc vs. Zr/Sc (Fig.
 680 7d). The late Triassic sandstones cluster around the field of andesite and granite,
 681 supporting a felsic-dominated source. The late Jurassic-early Cretaceous sandstones,
 682 with relatively high Th/Sc and Zr/Sc ratios, mainly plot above the average ratios for
 683 UCC, which suggests relatively high zircon concentrations and thus sediment
 684 recycling (Fig. 7d).

685 Sorting and recycling effects, in principle, can be illustrated by La_N/Y_N vs.
 686 $\text{SiO}_2/\text{Al}_2\text{O}_3$. However, the late Triassic to early Cretaceous sandstones are
 687 characterised by enrichment of SiO_2 and depletion of Al_2O_3 and Na_2O owing to strong
 688 weathering. To avoid a misleading interpretation resulting from quartz dilution, the
 689 trace element ratios Ti/Zr and Zr/Sc were used to indicate sorting and recycling effects.
 690 The dominance of Precambrian zircons in both the Triassic and late Jurassic-early

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Cretaceous sandstones supports a recycled origin. These sediments were initially supplied from Precambrian basement in Gondwana (i.e., northeast Africa/Arabian-Nubian Shield) and first accumulated within late Precambrian-Paleozoic successions generally to the north, as exposed in southern Turkey. Clastic material was later eroded and reworked generally southwards into the Southern Neotethys during after late Triassic final continental break-up (Chen et al., 2019; Ustaömer et al., 2019). The lack of evidence of rapid recycling of zircon in the Mamonia Complex or the Moni Melange sandstones is consistent with a passive margin setting (e.g., Cawood et al., 2012).

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4.1.5. Provenance indicators

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On the La-Th-Sc diagram (Fig. 8a), the linear array shown by the late Triassic sandstones is consistent with a mixing of andesitic and upper crust-sourced material. The late Jurassic-early Cretaceous sandstones cluster around the Post-Archean Australian Shale (PAAS) field, suggesting a felsic-dominated source. Similar trends are evident in the La/Th vs. Hf diagram (Fig. 8b). Key trace-element ratios (e.g., La/Sc, Th/Sc and Th/Cr) also help to distinguish felsic vs. mafic sources (see Supplementary material). Although variable, the sandstones analysed are statistically within the range of the ratios of felsic-dominated rocks (see Supplementary material). Cr/Ni-related diagrams were not used because ophiolite-related (ultramafic) detritus was not observed petrographically (Robertson, 1977; Torley and Robertson, 2018). Also, the carbonate content of the late Triassic sandstones (CaO=2.8-43.3 wt%), and the

strongly weathered nature of the late Jurassic-early Cretaceous sandstones (i.e., very low K_2O , Na_2O and Al_2O_3), render discriminant function analysis using major elements unsuitable (the necessary recalculation is unreliable; see above). In addition, the detrital zircon data indicate a felsic-dominated source (Chen et al., 2019). The dominant Neoproterozoic zircon populations are compatible with the voluminous plutonic and volcanic rocks of this age within the northeast African/Arabian-Nubian region (Chen et al., 2019).

4.1.6. Tectonic setting of deposition

The late Triassic sandstones (8 low-silica and 11 high-silica) mainly plot in the collision field (Verma and Armstrong-Altrin, 2013), together with three samples (2 low-silica and 1 high-silica) in the continental rift field (Fig. 9a-b). The typical high-silica, late Jurassic-early Cretaceous sandstones (one sample with $SiO_2 > 95\%$ was excluded) plot in the collision field (Fig. 9b). In contrast, all of the sandstones plot within the passive margin setting (Fig. 9c-d) on the multi-dimensional discriminant function diagrams that utilise a combination of major elements and trace elements (Verma and Armstrong-Altrin, 2016). Verma and Armstrong-Altrin (2013) show statistically that such inter-field variation is unlikely to result from chemical changes including weathering, sediment transport, recycling and post-depositional processes. These authors also note that, when that is inconsistent with other geological evidence, the results may represent chemical inheritance from a pre-existing tectonic setting.

The UCC-normalised spider diagram (Fig. 9e) shows: (1) The late Triassic

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sandstones exhibit negative Nb-Ta anomalies and relatively high Nb/Nb* ratios (c. 0.35; $Nb/Nb^* = Nb_N / (Ni_N \cdot Ti_N)^{1/2}$). These ratios are slightly higher than those of passive margin greywackes (c. 0.29) but lower than those of passive margin sandstones involving relatively old, reworked continental crust (c. 0.5) (Floyd et al., 1991); (2) The late Triassic sandstones have positive V-Cr-Ni-Sc anomalies and relative depletion of Ti-Zr-Y, which reflect a relatively low heavy mineral content (mainly zircon); (3) The late Jurassic-early Cretaceous sandstones have positive normalised V-Cr-Ni anomalies (<1) and negative Nb anomalies, compatible with a passive margin setting; and (4) The relative depletions of Ti and Sc are suggestive of a minor mafic source contribution. Taken together, the UCC plots are comparable to those of greywackes from a passive margin setting.

64.2. Sandstones from Northern Cyprus: Kyrenia Range

4.2.1. Chemical classification

The latest Cretaceous-Miocene sandstones of the Kyrenia Range are characterised by restricted SiO_2/Al_2O_3 ratios, but highly variable Na_2O/K_2O ratios (Fig. 107a), resulting in a classification ~~as of~~ mainly litharenites or arkoses. The middle ~~to~~ -late Miocene sandstones (Mia Milia (Dağyolu) Formation) have relatively high Na_2O/K_2O but low SiO_2/Al_2O_3 ratios and so classify as greywackes. In the Herron scheme (Fig. 107b), the latest Cretaceous-Miocene sandstones are mainly Fe-sand, wacke,

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litharenite and sublitharenite. In contrast, the middle to- late Miocene sandstones (Mia Milia (Dağyolu) Formation) are enriched in ($\text{Al}_2\text{O}_3 > 10 \text{ wt\%}$), resulting in a Fe-shale composition.

4.2.2. Chemical composition and correlations–

The Kyrenia Range sandstones have a wide compositional range. SiO_2 varies from 14.7 to 70.2 wt%. The latest Cretaceous sandstones range in Al_2O_3 content from 4.8 to 5.2 wt%, whereas Na_2O and K_2O values are typically low ($< 1 \text{ wt\%}$). The middle Eocene sandstone exhibits lower SiO_2 , Na_2O and intermediate Al_2O_3 , K_2O values. The compositions of the late Eocene sandstones vary. The sandstones from the north of the Kyrenia Range have generally higher concentrations of SiO_2 , TiO_2 , Na_2O , K_2O and Al_2O_3 but lower CaO compared to those from the south of the range. The late Eocene-Oligocene sandstones are typically enriched in $\text{Fe}_2\text{O}_3 + \text{MgO}$, but depleted in Na_2O ($< 0.2 \text{ wt\%}$). Na_2O is extremely depleted ($< 0.2 \text{ wt\%}$) in the overlying Oligocene-Mid-Miocene sandstones (Panagra (Geçitköy) Formation). Although variable, Al_2O_3 and TiO_2 are relatively depleted. SiO_2 and Na_2O vary widely, together with relative enrichment of Al_2O_3 and K_2O in the middle Miocene sandstones (Trapeza (Esentepe) Formation). The late Miocene sandstones have the highest SiO_2 and K_2O concentrations, together with relative enrichment in Na_2O and Al_2O_3 . The middle-late Miocene sandstones (Mia Milia (Dağyolu) Formation) are characterised by relatively high values of TiO_2 , Na_2O , Al_2O_3 but low CaO .

~~Most of the formations are separated in the PCA biplot of major elements (Fig-~~

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~~8a). Sodium is relatively enriched in the sandstones of latest Cretaceous, late Eocene,~~
~~middle Miocene (i.e., Trapeza (Esentepe) and Davlos (Kaprıca) formations), and also~~
~~middle-late Miocene ages (i.e., Mia Milia (Dağyolu) Formation). Conversely, Si, P and~~
~~Mg are relatively enriched in the Oligocene, early Miocene and middle Miocene (i.e.,~~
~~Panagra (Göçitköy) Formation) sandstones. In addition, the late Miocene sandstones~~
~~are enriched in Ti, Al and K, coupled with depletion in Mn and Ca. Using the PCA (Fig.~~
~~8b), which excludes mobile elements and cement-influenced carbonate, a separation~~
~~of the late Eocene-Oligocene sandstones is possible as the sandstones from the~~
~~north of the Kyrenia Range are relatively enriched in Si, P, Y, Zr but depleted in Fe, Ni~~
~~and Cr compared to those from the south of the range. In addition, the late Miocene~~
~~sandstones from the north of the range are enriched in V, Cr, Fe and Ni compared to~~
~~those in the south. The late Eocene samples have a relatively consistent composition,~~
~~with enrichments in Ni, V, Fe and Cr. The middle-late Miocene sandstones (Mia Milia~~
~~(Dağyolu) Formation) are characterised by enrichments of Al, Ti and V.~~

The trace elements of the latest Cretaceous and the middle Eocene sandstones
 are similar in terms of high field strength elements ~~(HFSEs)~~ and transition metals,
 whereas large-ion lithophile elements (LILEs) are more varied (Fig. ~~9a11a~~). Minerals
 enriched in K, Rb, Sr (e.g., microcline, mica), as observed petrographically, can
 account for these differences (Robertson et al., 2012b, 2014). Higher in the
 succession, the late Eocene sandstones define an increasingly positive slope in their
 trace element patterns (Fig. ~~9b11b~~). The late Eocene-Oligocene sandstones exhibit
 variable compositions, with higher abundances of HFSEs and LILEs (compared to

transition elements) in the north of the range compared to the south (Fig. 9b11b).

Spider diagrams are 'smoother' in the overlying Oligocene-early Miocene sandstones

(Fig. 9e11c-d). The middle Miocene sandstones are relatively consistent in

composition. 'Troughs' in Nb, Zr and V are present, together with 'spikes' in Th, La, Y,

Sr and Ni (Fig. 9e11e). The middle-late Miocene sandstones also have relatively

constant compositions, with positive trace element slope patterns (Fig. 9f11f).—

Compared to UCC, all of the sandstones exhibit depletions in LILEs, such as Rb

and probably Ba. Strontium is generally depleted, with the exception of ~~the~~ middle

Miocene sandstones. Zirconium is generally depleted in the middle Miocene

sandstones, whereas Zr shows small relative enrichments in some of the Oligocene

sandstones. Yttrium contents spike relative to Ba and Zr. Transition elements (e.g., Sc,

V, Ni and Cr) are typically enriched in the middle Miocene sandstones with, after an

initial decrease, an overall ~~upward~~-increase upwards in the succession.

On chondrite-normalised plots of REEs, the sandstones show relatively evolved

patterns with variable-sized Eu anomalies (0.64-0.95) (Fig. 4012). The negative Eu

anomalies (<1) are consistent with the enrichment in plagioclase-rich volcanic lithic

fragments, as seen in both the latest Cretaceous sandstones (Robertson et al., 2012b)

and the Cenozoic sandstones (McCay and Robertson, 2012). The late Miocene

sandstones have the most fractionated LREE patterns, with $(La/Yb)_N=10.14-11.08$.

The late Eocene-Oligocene sandstones from south of the Kyrenia Range are similar

to the other sandstones, but with pronounced REE fractionation and lower REE

concentrations.

Most of the formations are separated in the PCA biplot of major elements (Fig. 813a). Sodium is relatively enriched in the sandstones of latest Cretaceous, late Eocene, middle Miocene (i.e., Trapeza (Esentepe) and Davlos (Kaplıca) formations), and also middle-late Miocene ages (i.e., Mia Milia (Dağyolu) Formation). Conversely, Si, P and Mg are relatively enriched in the Oligocene, early Miocene and middle Miocene (i.e., Panagra (Geçitköy) Formation) sandstones. In addition, the late Miocene sandstones are enriched in Ti, Al and K, coupled with depletion in Mn and Ca. Using the PCA (Fig. 813b), which excludes mobile elements and cement-influenced carbonate, a separation of the late Eocene-Oligocene sandstones is possible as the sandstones from the north of the Kyrenia Range are relatively enriched in Si, P, Y, Zr but depleted in Fe, Ni and Cr compared to those from the south of the range. In addition, the late Miocene sandstones from the north of the range are enriched in V, Cr, Fe and Ni compared to those in the south. The late Eocene samples have a relatively consistent composition, with enrichments in Ni, V, Fe and Cr. The middle-late Miocene sandstones (Mia Milia (Dağyolu) Formation) are characterised by enrichments of Al, Ti and V.

4.2.3. Weathering

CIA values vary from the lower to the upper part of the latest Cretaceous-Miocene succession, with an initial general rise and then decrease (Fig. 14a). The latest Cretaceous (Maastrichtian) base of the succession has relatively low (average) CIA values (~60), whereas values in the overlying late Eocene-middle Miocene

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succession range from 72 to 91. The CIA decreases significantly to 53 in the late Miocene sandstones, suggesting a lower degree of weathering, perhaps as a result of a relatively arid source area and/or rapid erosion/deposition. These sandstones, especially the middle-late Miocene Mia Milia (Dağyolu) Formation (up to 1.6 km thick), are interpreted as mainly mass-flows and high-density turbidity current deposits (McCay and Robertson 2012). Also, their lithoclastic nature is consistent with rapid erosion and transport from source to sink (with little subsequent reworking).

CIA values are relatively low in the lower part of the succession; i.e., the late Eocene-middle Miocene sandstones, from the south of the Kyrenia Range. In contrast, relatively high CIA values occur in the sandstones in the upper part of the succession; i.e., the late Miocene Davlos (Kaplıca) Formation, from the north of the range.

Na is depleted relative to other mobile elements (e.g., K, Mg, Ca, Rb, Sr and Ba). $\alpha^{Al}Na$ reaches 49 in the Oligocene, 10 in the early Miocene, but <6 in other sandstones (see Supplementary material). K and Rb are depleted relative to Ca. Relative depletion in Ba is moderate; i.e., up to ~3 in both the lower part (latest Cretaceous-late Eocene) and the upper part (late Miocene) of the succession. Depletion in Mg and Sr are relatively minor, seldom above 0.6. The following bulk-sediment mobility sequence is inferred: $\alpha^{Al}Na > \alpha^{Al}Rb > \alpha^{Al}Ba \geq \alpha^{Al}K > \alpha^{Al}Sr > \alpha^{Al}Mg > \alpha^{Al}Ca$. Although the sandstones from the Kyrenia range have notably high $\alpha^{Al}Na$, the observed, relatively lesser depletions $\alpha^{Al}Ca$, $\alpha^{Al}Sr$ and $\alpha^{Al}Mg$ suggest that the sediment composition was predominantly influenced by source rock composition rather than by weathering (e.g., Nesbitt et al., 1980). The main reason for

the compositional differences south and north of the Kyrenia Range are likely to be variable inputs of continental versus igneous (ophiolite-related) rock detritus (McCay and Robertson, 2012).

4.2.4. Sorting and recycling effects

On the ternary diagram of Al_2O_3 -Zr- TiO_2 (Fig. 14b), the latest Cretaceous-Oligocene sandstones have relatively low Zr, but high Al_2O_3 and TiO_2 . Relative enrichment in Zr, but depletion in Al_2O_3 and TiO_2 are recorded in the Oligocene-middle Miocene sandstones, suggesting increased sorting effects upwards in the succession. The middle-late Miocene sandstones are characterised by enrichment of Al_2O_3 and TiO_2 ; these are less well-sorted, as confirmed by optical petrography (McCay and Robertson, 2012).

On the Th/Sc vs. Zr/Sc diagram (Fig. 14c), the sandstones show great compositional variation, with Th/Sc ratios ranging from 0.04 to 0.5. The samples cluster from the compositions of average basalt to andesite, and plot below the average ratio of UCC, suggesting a dominant mafic to intermediate-composition volcanic source. Zr/Sc ratios are relatively low, varying from 0.5 to 14.6, suggesting an absence of significant sediment recycling/zircon concentration (McLennan et al., 1993). This is supported by the similar paleontologically and radiometrically (zircon U-Pb)-determined ages (Chen et al., 2019).

On the La_N/Y_N vs. $\text{SiO}_2/\text{Al}_2\text{O}_3$ diagram (Fig. 14d), the samples have a wide range of La_N/Y_N ratios (0.8-8.0) reflecting marked provenance variation. $\text{SiO}_2/\text{Al}_2\text{O}_3$ is

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relatively low (5.1-9.0, average=7.4) in the latest Cretaceous, to late Eocene-Oligocene. The ratio greatly increases to 7.2-20.2 (average=13) in the Oligocene-middle Miocene, then decreases to 3.9-8.0 (average=5.7) in the upper levels of the middle-late Miocene succession. The samples plot to the right of the diagram (Fig. 14d), which is suggestive of increased sorting and recycling in this direction (Roser and Korsch, 1999). Sorting and recycling processes significantly affected the Oligocene-middle Miocene sandstones (Fig. 14b, d), as suggested by the relatively high and constant CIA values (Fig. 14a). Together with the relatively univariable provenance variation (i.e., constant La_N/Y_N), the CIA values are likely to reflect the effects of prolonged weathering.

4.2.5. Provenance indicators

The north-Cyprus (Kyrenia Range) sandstones contain ophiolite-related lithics (see Supplementary material) (McCay and Robertson, 2012; Robertson et al., 2012b, 2014) and therefore, Cr and Ni are useful proxies for ultramafic detritus (Fig. 1). The latest Cretaceous to late Eocene-Oligocene sandstones have relative enrichments in Cr and Ni, high Cr/Ni and Cr/V ratios that are indicative of a mafic and/or ultramafic source (Fig. 15a-c). These sandstones also have significant abundances of lithics derived from ophiolite-related rocks, including basalt, diabase, gabbro and serpentinite. Such lithologies could have been derived from intact ophiolite or accretionary melange (McCay and Robertson, 2012; Robertson et al., 2012b, 2014). On the other hand, the Oligocene-late Miocene sandstones generally have low Cr and Ni values, low Cr/V

904 but high Th/Ni and Th/Sc ratios, which suggests a relatively high input of felsic
905 components (although some mafic detritus is not excluded) (Fig. 15b-d), in agreement
906 with petrographic evidence (McCay and Robertson, 2012). “Intermediate” Cr and Ni
907 concentrations, elevated Cr/Ni (>2) and Cr/Th (>90) but low Th/Sc (c. 0.1) ratios are
908 observed in the middle-late Miocene sandstones (Mia Milia (Dağyolu) Formation),
909 consistent with an increasing incorporation of mafic rock detritus (Fig. 15c-d), again
910 consistent with the petrographic evidence, including the presence of basaltic rocks
911 (McCay and Robertson, 2012).

912 The above interpretations are consistent with the available U-Pb detrital zircon
913 age data (Chen et al., 2019). Sparse Turonian-Coniacian (94-87 Ma) zircon grains in
914 the late Cretaceous/Eocene sandstones are similar to the ages of supra-subduction
915 zone ophiolites and related accretionary melange in the region, including southern
916 Turkey (Chen et al., 2019). The abundant Santonian-Campanian-aged zircons in the
917 late Miocene sandstones are also suggestive of a source from subduction-related
918 igneous rocks, particularly granitic rocks in southeast Turkey (Chen et al., 2019).
919 Sporadic zircon with low Th/U ratios (<0.1) in the late Cretaceous/Eocene sandstones
920 could relate to exposures of greenschist-facies metamorphic rocks in southeast
921 Turkey (Chen et al., 2019). In addition, younger zircon grains (16-13 Ma) in
922 middle-late Miocene sandstones (Mia Milia (Dağyolu) Formation) probably relate to
923 air-fall tuff that is exposed locally in the Kyrenia Range (Chen et al., 2019).

924 4.2.6. Tectonic setting of deposition

925 The sandstones (20 out of 25 samples) mainly lie in the collisional field of Verma and
926 Armstrong-Altrin (2013) (Fig. 16a), whereas the middle-late Miocene (Mia Milia
927 (Dağyolu) Formation) sandstones plot in the arc field. In contrast, on other
928 multi-dimensional discrimination function diagrams (after Verma and Armstrong-Altrin,
929 2016), the majority of the samples plot in the passive margin field (Fig. 16b-c). The
930 contrasts in tectonic setting, as implied by the different discrimination diagrams,
931 largely reflect differing crustal influences on the (implied) tectonic setting. Much clastic
932 sediment is likely to have been derived via reworking of Paleozoic passive margin
933 shelf-successions exposed in southern and central Turkey, as inferred for the
934 southwest and south-Cyprus sandstones (see above).

936 5. Regional geological development

937 7. Discussion

938 7.1. Southern Cyprus sandstones: Mamonía Complex and Moni Melange

939 7.1.1 Weathering, sorting and recycling effects

940 Moderate weathering conditions are inferred for the late Triassic sandstones, with CIA
941 and PIA values of 52–77 (Fig. 11a) and 52–89, respectively (see Supplementary
942 material). CIX values of 65–80 are more restricted. The CIA values for most of the late
943 Triassic sandstones (excepting a few outliers) lie along a different trend from that
944 generally expected (Fig. 11a). This can be explained by potassium metasomatism,
945 specifically the conversion of aluminous clay minerals to illite and the replacement of
946 plagioclase by K-feldspar (McLennan et al., 1993; Fedo et al., 1995). Petrographic
947 observations indicate a variable clay matrix and plagioclase alteration in the late
948 Triassic sandstones (see Supplementary material in Torley and Robertson, 2018).
949 Oxidising depositional conditions are inferred, as reflected by the proxies of e.g., high
950 CIA, coupled with elevated Th/U but lower V/Cr and V/Sc ratios (Nesbitt and Young,
951 1982; Taylor and McLennan, 1985; Jones and Manning, 1994).

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952 ~~In contrast, the late Jurassic-early Cretaceous sandstones exhibit higher CIA (90-95)~~
953 ~~(Fig. 11a), PIA (98-99), CIW (98-99) and CIX (90-95) values (see Supplementary~~
954 ~~material). These higher values are likely to have resulted from CaO and Na₂O~~
955 ~~depletion, in response to intense or prolonged weathering of the source area (Nesbitt~~
956 ~~and Young, 1982). In addition, extreme textural maturity is indicated by the~~
957 ~~abundance of very well rounded grains (Robertson, 1977; Torley and Robertson,~~
958 ~~2018). The observed bimodal grain size variation is also indicative of reworking~~
959 ~~(Robertson, 1977; Robertson and Woodcock, 1979; Torley and Robertson, 2018).~~
960 ~~The combined textural and chemical evidence points to prolonged weathering in a~~
961 ~~tropical environment, coupled with reworking (e.g., Weltje et al., 1998). The early~~
962 ~~Cretaceous sandstone (Pareklisia Member) is chemically similar but has a lower CIA~~
963 ~~value (76) (Fig. 11a). This sample has a relatively high K₂O (possibly resulting from~~
964 ~~K-metasomatism), which shifts the point on the diagram towards illite (Fig. 11a).~~
965 ~~Although variable, the sandstones trend back to crustal source compositions~~
966 ~~(andesite and granodiorite), in line with the petrographic evidence, which is generally~~
967 ~~consistent with a felsic-dominated source (Robertson, 1977; Torley and Robertson,~~
968 ~~2018),—~~

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Na is strongly depleted relative to the other mobile elements (e.g., K, Mg, Ca, Rb, Sr and Ba). α_{AlNa} ranges from 32–83 in the late Jurassic–early Cretaceous sandstones, e. 33 in the early Cretaceous sandstones, and from 1–7 in the late Triassic sandstones (Fig. 11b). Ca is more depleted relative to K and Rb (Fig. 11b). There is little relative depletion in Mg, Sr and Ba (Fig. 11b), with α_{AlMg} , α_{AlSr} and α_{AlBa} rarely >2 . The following bulk-sediment mobility sequence is inferred: $\alpha_{AlNa} > \alpha_{AlCa} > \alpha_{AlK} \geq \alpha_{AlRb} > \alpha_{AlBa} \geq \alpha_{AlSr} > \alpha_{AlMg}$. The notably higher α_{AlNa} and α_{AlCa} (preferentially removed during weathering), together with the low values of α_{AlMg} (fixed in secondary clay minerals) and α_{AlBa} (absorbed onto clays), demonstrates that the sandstone composition is strongly influenced by weathering processes (e.g., Nesbitt et al., 1980; Garzanti and Resentini, 2016).

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980 On the ternary plot of Al_2O_3 -Zr- TiO_2 (Fig. 11c), Al_2O_3 strongly correlates with
981 TiO_2/Zr . The resulting linear trend (Fig. 11c) is consistent with sorting-related
982 fractionation of similar composition protoliths (Garcia et al., 1991). Sediment recycling
983 effects, especially enrichment in zircon are also indicated by the plot of Th/Sc vs.
984 Zr/Sc (Fig. 11d). The late Triassic sandstones cluster around the field of andesite and
985 granite, supporting a felsic-dominated source. The late Jurassic-early Cretaceous
986 sandstones, with relatively high Th/Sc and Zr/Sc ratios, mainly plot above the average
987 ratios for UCC, which suggests relatively high zircon concentrations and thus
988 sediment recycling (Fig. 11d). In addition, the dominance of Gondwana-derived
989 zircons in both the Triassic and early Cretaceous south-Cyprus sandstones supports
990 a recycled origin, probably sourced from Paleozoic sedimentary successions in
991 southern and central Turkey (Chen et al., 2019; Ustaömer et al., 2019).

992 7.1.2. Provenance indicators

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On the La-Th-Sc diagram (Fig. 12a), the linear array shown by the late Triassic sandstones is consistent with a mixing of andesitic rocks and upper crust-sourced material. The late Jurassic-early Cretaceous sandstones cluster around the Post-Archean Australian Shale (PAAS) field, suggesting a felsic-dominated provenance. Similar trends are evident in the La/Th vs. Hf diagram (Fig. 12b). Key trace element ratios (e.g., La/Sc, Th/Sc and Th/Cr) also help to distinguish felsic vs. mafic sources (see Supplementary material). Although variable, the sandstones analysed are statistically within the range of the ratios of felsic-dominated source rocks (see Supplementary material).

7.1.3. Tectonic setting of deposition

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1003 The late Triassic sandstones (8 low-silica and 11 high-silica) mainly plot in the
1004 collision field (Verma and Armstrong-Altrin, 2013), together with three samples (2
1005 low-silica and 1 high-silica) in the continental rift field (Fig. 13a-b). The typical
1006 high-silica, late Jurassic-early Cretaceous sandstones (one sample with $\text{SiO}_2 > 95\%$
1007 was excluded) plot in the collision field (Fig. 13b). In contrast, all of the sandstones
1008 plot within the passive margin setting (Fig. 13c-d) on the multi-dimensional
1009 discriminant function diagrams that utilise a combination of major elements and trace
1010 elements (Verma and Armstrong-Altrin, 2016). Verma and Armstrong-Altrin (2013)
1011 show statistically that such inter-field variation is unlikely to result from chemical
1012 changes including weathering, sediment transport, recycling and post-depositional
1013 processes. These authors also note that, when that are inconsistent with other
1014 geological evidence, the results may represent chemical inheritance from a
1015 pre-existing tectonic setting.

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1016 The UCC-normalised spider diagram (Fig. 13e) shows: (1) The late Triassic
 1017 sandstones exhibit negative Nb-Ta anomalies and relatively high Nb/Nb* ratios (c.
 1018 0.35; $Nb/Nb^* = NbN / (NiN \cdot TiN)^{1/2}$). These ratios are slightly higher than those of
 1019 passive margin greywackes (c. 0.29) but lower than those of passive margin
 1020 sandstones involving relatively old, reworked continental crust (c. 0.5) (Floyd et al.,
 1021 1991); (2) The late Triassic sandstones have positive V-Cr-Ni-Sc anomalies and
 1022 relative depletion of Ti-Zr-Y, which reflect a relatively low heavy mineral content
 1023 (mainly zircon); (3) The late Jurassic-early Cretaceous sandstones have positive
 1024 normalised V-Cr-Ni anomalies (<1) and negative Nb anomalies, compatible with a
 1025 passive margin setting; (4) The relative depletions of Ti and Sc are suggestive of a
 1026 minor mafic source contribution. Taken together, the dips in the UCC plots are
 1027 comparable to the overall trend of greywackes from a passive margin setting.

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1029 7.2. Northern Cyprus sandstones: Kyrenia Range

1030 7.2.1. Weathering, sorting and recycling

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1031 CIA values vary from the lower to the upper part of the latest Cretaceous-Miocene
1032 succession, with an initial general rise and then decrease (Fig. 14a). The latest
1033 Cretaceous (Maastrichtian) aged base of the succession has relatively low average
1034 CIA values (~60), whereas values in the overlying late Eocene-middle Miocene
1035 succession range from 72 to 91. The CIA decreases significantly to 53 in the late
1036 Miocene sandstones, suggesting a lower degree of weathering, perhaps as a result of
1037 a relatively arid source area and/or rapid erosion/deposition. These sandstones,
1038 especially the middle-late Miocene Mia Milia (Dağyolu) Formation (up to 1.6 km thick),
1039 are interpreted as mainly mass-flows and high-density turbidity current deposits
1040 (McCay and Robertson 2012). Also, their lithoclastic nature is consistent with rapidly
1041 erosion and transport from source to sink (with little subsequent reworking).
1042 CIA values are relatively low in the lower part of the succession; i.e. the late
1043 Eocene-middle Miocene sandstones, from the south of the Kyrenia Range. In contrast,
1044 relatively high CIA values occur in the sandstones in the upper part of the succession;
1045 i.e. the late Miocene Davlos (Kaprıca) Formation, from the north of the range.

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Na is depleted relative to other mobile elements (e.g., K, Mg, Ca, Rb, Sr and Ba). αAlNa reaches in 49 in the Oligocene, 10 in the early Miocene, but <6 in other sandstones. K and Rb are depleted relative to Ca. Relative depletion in Ba is moderate; i.e. up to ~3 in both the lower part (latest Cretaceous-late Eocene) and the upper part (late Miocene) of the succession. Depletion in Mg and Sr are relatively minor, seldom above 0.6. The following bulk-sediment mobility sequence is inferred: $\alpha\text{AlNa} > \alpha\text{AlRb} > \alpha\text{AlBa} > \alpha\text{AlK} > \alpha\text{AlSr} > \alpha\text{AlMg} > \alpha\text{AlCa}$. Although the sandstones from the Kyrenia range have notably high αAlNa , the observed, relatively lesser depletions αAlCa , αAlSr and αAlMg suggest that the sediment composition was predominantly influenced by source-rock composition rather than by weathering (e.g., Nesbitt et al., 1980). The main reason for the compositional differences south and north of the Kyrenia Range are likely to be the various abundances of continental versus igneous (ophiolite-related) rock detritus (McCay and Robertson, 2012).

On the ternary diagram of Al_2O_3 -Zr- TiO_2 (Fig. 14b), the latest Cretaceous-late Eocene-Oligocene sandstones have relatively low Zr, but high Al_2O_3 and TiO_2 concentrations. Relative enrichment in Zr, but depletion in Al_2O_3 and TiO_2 , are recorded in the Oligocene-middle Miocene sandstones, suggesting increasing sorting effects upwards in the succession. The middle-late Miocene sandstones are characterised by enrichments of Al_2O_3 and TiO_2 and are less well-sorted, as confirmed by optical petrography (McCay and Robertson, 2012).

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1066 On the Th/Sc vs. Zr/Sc diagram (Fig. 14c), the sandstones show great compositional
1067 variation, with Th/Sc ratios ranging from 0.04-0.5. The samples cluster from the
1068 compositions of average basalt to andesite, and plot below the average ratio of UCC,
1069 suggesting a dominant mafic to intermediate-composition volcanic source. Zr/Sc
1070 ratios are relatively low, varying from 0.5-14.6, suggesting an absence of significant
1071 sediment recycling/zircon concentration (McLennan et al., 1993).

1072 On the La_N/Y_N vs. SiO₂/Al₂O₃ diagram (Fig. 14d), the samples have a wide range of
1073 La_N/Y_N ratios (0.8-8.0) reflecting marked provenance variation. SiO₂/Al₂O₃ is
1074 relatively low (5.1-9.0, average=7.4) in the latest Cretaceous, to late
1075 Eocene-Oligocene. The ratio greatly increases to 7.2-20.2 (average=13) in the
1076 Oligocene-middle Miocene, then decreases to 3.9-8.0 (average=5.7) in the upper
1077 levels of the middle-late Miocene. The samples plot to the right of the diagram
1078 (Fig. 14d), which is suggestive of increasing sorting and recycling in this direction
1079 (Roser and Korsch, 1999). Sorting and recycling processes also affected the
1080 Oligocene-middle Miocene sandstones (Fig. 14b, d), as suggested by the relatively
1081 high and constant CIA values (Fig. 14a). Together with the relatively unvariable
1082 provenance variation (i.e., constant La_N/Y_N), the CIA values likely to reflect the
1083 effects of prolonged weathering.

1084 7.2.2. Chemical evidence of sediment provenance

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The latest Cretaceous to late Eocene-Oligocene sandstones have relative enrichments in Cr and Ni, high Cr/Ni and Cr/V ratios that are indicative of a mafic and/or ultramafic source (Fig. 15a-c). These sandstones also have significant abundances of lithics derived from ophiolite-related rocks, including basalt, diabase, gabbro and serpentinite. Such lithologies could have been derived either from intact ophiolite thrust sheets and/or accretionary melange (McCay and Robertson, 2012; Robertson et al., 2012b, 2014). On the other hand, the Oligocene-late Miocene sandstones generally have low Cr and Ni values, low Cr/V but high Th/Ni and Th/Sc ratios, which suggests a relatively high input of felsic components (although some mafic detritus is not excluded) (Fig. 15b-d), in agreement with petrographic evidence (McCay and Robertson, 2012). "Intermediate" Cr and Ni concentrations, elevated Cr/Ni (>2) and Cr/Th (>90) but low Th/Sc (c. 0.1) ratios are observed in the middle-late Miocene sandstones (Mia Milia (Dağyolu) Formation), consistent with an increasing incorporation of mafic rock detritus (Fig. 15c-d), again consistent with the petrographic evidence, including the presence of basaltic rocks (McCay and Robertson, 2012).

7.2.3 Tectonic setting of deposition

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1102 The sandstones (20 out of 25 samples) mainly lie in the collisional field of Verma and
1103 Armstrong-Altrin (2013) (Fig. 16a), whereas the middle-late Miocene (Mia Milia
1104 (Dağyolu) Formation) sandstones plot in the arc field. In contrast, on other
1105 multi-dimensional discrimination function diagrams (after Verma and Armstrong-Altrin,
1106 2016), the majority of the samples plot in the passive margin field (Fig. 16b-c). The
1107 differences in tectonic setting, as implied by the different discrimination diagrams,
1108 largely reflects the differing chemical influences on the implied tectonic setting. Much
1109 clastic sediment is likely to have been derived via reworking of Paleozoic passive
1110 margin shelf successions exposed in southern and central Turkey (see below). —

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1112 7.3. Relation to regional geological development

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1113 7.3.5.1. Triassic-Early early Cretaceous

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1114 Prior to the late Permian, the easternmost Mediterranean region formed part of the
1115 northern margin of Gondwana (Robertson and Woodcock, 1979, 1986; Şengör, 1984;
1116 Robertson et al., 2012a, b; Chen et al., 2019). Continental breakup took place during
1117 the late Permian-early Mesozoic, followed by opening of the Southern Neotethys (e.g.,
1118 Robertson and Dixon, 1984; Şengör, 1984; Stampfli and Borel, 2002; Barrier et al.,
1119 2018) (Fig. 17a, ~~b~~). The mixed clastic-carbonate facies of the Mamonia Complex,
1120 southwest Cyprus (Lapierre, 1975; Robertson and Woodcock, 1979; Torley and
1121 Robertson, 2018), and the detached sandstone blocks in the Moni Melange, southern

1122 Cyprus (Robertson, 1977) are interpreted as remnants of the South_-Neotethyan
1123 passive margin. Other tectonically emplaced remnants include similar marine facies in
1124 southern Turkey (Antalya Complex) (Robertson and Woodcock, 1982; Robertson et
1125 al., 2019b); southeast Turkey (Adiyaman area) (Robertson et al., 2016) and north
1126 Syria (Baer-Bassit) (Delaune-Mayère, 1984; Al-Riyami and Robertson, 2002) (Fig. 42).

1127 The extra restoration of the Mamonia Complex is debateable (Torley and Robertson,
1128 2018). However, the likely source was recycling from Paleozoic successions, as
1129 exposed in one or more of the most southerly microcontinental units, for example the
1130 Alanya Massif, generally to the north or the Tahtahlı Dağ (Kemer Zone; Antalya
1131 Complex), generally to the northwest (Figs. 2, 17a-b). These units were located to the
1132 south of a deep-water rift or small ocean basin (Robertson, 2000; Çetinkaplan et al.,
1133 2016; Robertson et al., 2019b) that separated such crustal fragments from the main
1134 Tauride continental block to the north.

1135 The rRegional geological evidence ~~therefore overall~~ supports a passive margin
1136 setting for the late Triassic and the early Cretaceous sandstones, as follows:

1137 -(1) The sandstones were ultimately derived from felsic-dominated source rocks;
1138 i.e., andesitic to granitic. Suitable source rocks include late Precambrian-Cambrian
1139 low-grade meta-sedimentary rocks and felsic volcanic rocks, as exposed in the
1140 Precambrian inliers of Anatolia (e.g., Sultan Dağ)-(Göncüoğlu and Kozlu, 2000;
1141 Gürsu et al., 2004; Mackintosh and Robertson, 2012) (Figs. 42, 17a). Precambrian
1142 clastic material appears to have been reworked into Ordovician-Permian shelf sands
1143 that accumulated along the northern margin of Gondwana (Ustaömer et al., 2019;

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1144 Chen et al., 2019);

1145 (2) The source material shows increased weathering effects from the ~~Late-late~~
1146 Triassic to the late Jurassic-early Cretaceous, probably under oxidizing, tropical
1147 conditions. Carbonate-siliciclastic facies changed between the ~~Late-late~~ Triassic and
1148 the late Jurassic-early Cretaceous, consistent with a shift towards a relatively humid
1149 climate (Berra, 2012) along the near-equatorial northern margin of Gondwana (0-30°
1150 S):-

1151 (3) Sorting and recycling effects (polycyclic origin) increased over the same time
1152 interval. The late Triassic sandstones are mainly deep-water turbidites ~~that were and~~
1153 ~~some mass-flow-deposits that were~~ rapidly deposited without much reworking
1154 (Robertson and Woodcock, 1979; Torley and Robertson, 2018). Their input reflects
1155 continental rifting in southern Turkey ~~followed by regional passive margin~~
1156 ~~development~~ (Robertson and Woodcock, 1982; Barrier et al., 2018; Ustaömer et al.,
1157 2019; Robertson et al., 2019b).

1158 The late Jurassic-early Cretaceous sandstones mainly accumulated in response
1159 to mass-flow ~~and turbidity-current~~ processes (e.g., gravity-controlled sand flow).
1160 High-energy sorting took place in a shallow-marine, or more likely aeolian setting,
1161 followed by redeposition into a proximal but relatively deep-marine setting (Robertson
1162 and Woodcock, 1979; Torley and Robertson, 2018). Passive margin conditions largely
1163 persisted during this time interval although there are hints of tectonic re-activation ~~in~~
1164 ~~the form of localised related to renewed rifting and~~ alkaline magmatism ~~in the~~
1165 ~~Mamonia Complex (Robertson and Woodcock, 1979; Chan et al., 2008) and renewed~~

1166 rifting in the Levant (Homberg and Bachmann, 2010; Robertson et al., 2012a). The
1167 Late-late Jurassic-Early-early Cretaceous sandstones, therefore, experienced greater
1168 reworking than the Late-late Triassic sandstone, in agreement with the chemical
1169 indicators;

1170 (4) The tectonic discrimination of the Late-late Triassic sandstones suggests a
1171 continental collision setting, changing to a rift/passive margin setting by the late
1172 Jurassic-early Cretaceous (Fig. 439). The latter setting is consistent with the regional
1173 geology (see above), whereas the former appears to be inconsistent. However, this
1174 can be explained by chemical inheritance from the pre-existing tectonic setting. By
1175 the late Cambrian, collision was replaced by passive margin shelf conditions, with the
1176 main source being the Pan-African hinterland to the south (Göncüoğlu and Kozlu,
1177 2000). The Late-late Triassic sandstones were largely derived from source rocks that
1178 experienced late Pan-African collisional amalgamation, which included regional-scale
1179 plutonism and continental margin arc magmatism (e.g., Gürsu and Göncüoğlu, 2006,
1180 2008; Avigad et al., 2016; Ustaömer et al., 2019). By the late Cambrian, collision was
1181 replaced by passive margin shelf conditions, with the main source being the
1182 Pan-African hinterland to the south (Göncüoğlu and Kozlu, 2000).

1183 7.35.2. Latest Cretaceous-Neogene

1184 As part of the South Neotethyan region, tThe Kyrenia Range of northern Cyprus
1185 formed part of a subsiding carbonate platform, as part of the South Neotethyan
1186 continental margin,—during the Late-late Triassic-Cretaceous (Baroz, 1979;

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Robertson and Woodcock, 1986; Robertson et al., 2012a) (Fig. 17a-b). During the late Cretaceous, ~~the~~ Southern Neotethys began to subduct northwards beneath continental crust in southern Turkey (Robertson and Dixon, 1984; Robertson et al., 2012b; Çetinkaplan et al., 2016; Barrier et al., 2018) (Fig. 17c). The Kyrenia Range ~~the~~rebyn became part of the northerly active continental margin of ~~the~~ Southern Neotethys until collision during the late Miocene (Robertson et al., 2012a, b; McCay and Robertson, 2012), ~~followed by then~~ Pleistocene uplift (Palamakumbura et al., 2016). The main source of the late Cretaceous-late Miocene sandstones ~~studied~~ was the Tauride thrust belt that extends across southern and ~~southeastern-southeast~~ Turkey (Robertson et al., 2012a, b; McCay and Robertson, 2012; Chen et al., 2019) (Fig. 17c-e). ~~The~~The Kythrea (Değirmenlik) Fault, which today delineates the southern margin of the Kyrenia Range (near-basal thrust), was activated during the middle Miocene, ~~causing-creating a sub-basins to form~~ on either side of this lineament (McCay and Robertson, 2013). The resulting topographic ridge ~~allowed-favoured the deposition of~~ compositionally different sands ~~to be deposited~~ on either side of this feature (McCay, 2010; McCay and Robertson, 2012).

The ~~chemical evidence supports and adds to the regional geology is consistent~~ ~~with the~~ following inferences ~~from-for~~ the latest Cretaceous-Miocene regional geology~~chemical evidence~~:

(1) The compositions of ~~the~~ middle to late Miocene sandstones differ on both sides of the inferred E-W topographic ridge in the Kyrenia Range, with the more northerly sands being enriched in felsic detritus whereas the southerly ones are

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enriched in mafic detritus. Relatively the quartz-rich sands in the northerly sub-basin were mainly derived from continental and/or cover sedimentary rocks. In contrast, the more lithic-rich sands in the southerly sub-basin were preferentially derived from igneous rocks, as widely exposed in the South-Neotethyan suture zone of southeast Turkey (see below):

(2) Low sorting and low weathering effects characterise the late Eocene and the middle-late Miocene sandstones. Low sorting can be explained by the dominance of mass-flow or high-density turbidite deposition during both of these time intervals (McCay and Robertson, 2012; Robertson et al., 2014). The low-weathering signal is consistent with deposition soon after major tectonic events changed the surface topography and thus weathering and erosion in the source area. ~~First, the late Eocene sandstones accumulated soon after collision-related thrusting in southern Turkey (Şengör and Yılmaz, 1981; Pourteau et al., 2010; Barrier et al., 2018) and southward thrusting in the Kyrenia Range (Baroz, 1979; Robertson and Woodcock, 1986; Robertson and Kinnaird, 2016). Secondly, the middle-late Miocene sandstones accumulated during and after suturing of the Southern Neotethys in southeast Turkey, accompanied by regional-scale southward thrusting (Yalçın and Görür, 1984; Aktaş and Robertson, 1984; Yılmaz, 1993; Williams et al., 1995; Robertson et al., 2004, 2012b; Barrier et al., 2018). Suturing was followed by post-suture tightening, exhumation and surface uplift (Okay et al., 2010; Radeff et al., 2017). The paleocurrent data from the Late Eocene-Late Miocene turbidites in the Kyrenia Range indicate southerly flow (from southern Turkey) during the Late Eocene-Oligocene (Fig.~~

~~17d).~~ The Oligocene-middle Miocene sandstone plots indicate significant sorting effects and the highest CIA values (Fig. 14), consistent with 'normal' input from mainly felsic (continental) rocks. This Deposition took place ~~during in~~ a deep-water basin or trench~~period of sedimentation in a deep basin/trench~~ related to northward subduction ~~beneath Anatolia~~ (McCay and Robertson, 2012). The ~~paleocurrents switched to westerly flow during the Miocene (Fig. 17e) (McCay, 2010; McCay and Robertson, 2012). The provenance from the South-Neotethyan suture zone in southeast Turkey included~~middle-late Miocene sandstones show an increased input from emplaced mafic/ultramafic ophiolite-related rocks (McCay and Robertson, 2012), as indicated by the sandstone plots (Fig. 15);

(3) The chemical discrimination (e.g., Fig. 16) points to derivation from several different tectonic settings. For example, the inferred arc setting in the late Miocene sandstones (Fig. 16a) is consistent with the presence of petrographically observed mafic detritus that was derived from ophiolitic bodies and/or related melange, as exposed in the Taurides (e.g., Mersin ophiolite, Adana region; Berit ophiolite, Kahramanmaraş region) (Figs. 42, 17c). Also, the passive margin setting inferred for the late Eocene to middle Miocene sandstones is consistent with the erosion of km-thick ~~passive margin sediments, shelf successions that~~ including Paleozoic-early Mesozoic siliciclastic sediments, as exposed in the Taurides, and also Triassic-Cretaceous shallow-water platform carbonate, as exposed in the Kyrenia Range (see ~~the Appendix in the~~ supplementary material for e.g., detrital carbonate contents);

(4) The paleocurrent data from the late Eocene-late Miocene turbidites in the Kyrenia Range indicate southerly flow (from southern Turkey) during the late Eocene-Oligocene (Fig. 17d). The late Eocene sandstones accumulated soon after final collision-related thrusting in southern Turkey (Şengör and Yılmaz, 1981; Pourteau et al., 2010; Barrier et al., 2018) and southward thrusting in the Kyrenia Range (Baroz, 1979; Robertson and Woodcock, 1986; Robertson and Kinnaird, 2016).

However, the provenance is likely to have included Cadomian basement/cover, Permian-Triassic rift-related sedimentary and igneous rock, Jurassic-Cretaceous passive margin sediments and late Cretaceous ophiolite-related rocks, as widely exposed in southern Turkey. The source areas could possibly also have included clastic sediment from a more northerly oceanic basin (e.g., Mersin ophiolite and melange) (Fig. 17c-d). The paleocurrents switched to westerly flow during the middle-late Miocene (McCay, 2010; McCay and Robertson, 2012) (Fig. 17e). These sandstones accumulated during and after suturing of the Southern Neotethys in southeast Turkey, which was accompanied by regional-scale southward thrusting (Yalçın and Görür, 1984; Aktaş and Robertson, 1984; Yılmaz, 1993; Williams et al., 1995; Robertson et al., 2004, 2006; Barrier et al., 2018). Suturing was followed by post-suture tightening, exhumation and surface uplift (Okay et al., 2010; Radeff et al., 2017). During the middle to late Miocene, the provenance was therefore mainly from the east/northeast, from thrust sheets including ophiolites, as exposed extensively in the South Neotethyan suture zone in southeast Turkey (Robertson et al., 2004;

1275 ~~McCay and Robertson, 2012). Finally, it is not surprising that the tectonic setting~~
1276 ~~discrimination (Fig. 16) yielded inconsistent results because the Precambrian to~~
1277 ~~Recent (and thus the source rocks) in southern Turkey evolved from collisional (late~~
1278 ~~Precambrian-Cambrian), to passive margin (Ordovician-early Permian), to rift (late~~
1279 ~~Permian-early Jurassic), to passive margin (late Triassic-early Cretaceous-~~
1280 ~~interrupted by a pulse of crustal extension), to active margin (late~~
1281 ~~Cretaceous-Oligocene) and finally to (diachronous) collision (early Miocene-Recent),~~
1282 ~~with each stage leaving its distinctive petrographical/chemical signal in sand~~
1283 ~~composition.~~

1284 6. Conclusions

1285 We have presented and discussed a step-wide methodology (user's guide) for
1286 the description and interpretation of whole-rock chemical data for sandstones. This is
1287 most effective for areas where it builds on a large body of existing field and laboratory
1288 evidence. We have then applied the user's guide to a specific example (case history)
1289 of Mesozoic-Cenozoic sandstones in the development of the Southern Neotethys
1290 ocean in Cyprus. The resulting body of interpretation add significantly to
1291 understanding of the regional geological development, such that we advocate more
1292 routine application of the chemical methods involved.

1293 8. For the Cyprus sandstones:

- 1294 ● Weathering process greatly influenced the composition of the late Triassic and
1295 late Jurassic-early Cretaceous southern Cyprus sandstones (Mamonia Complex and

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1296 Moni Melange).

1297 • Temporally increased weathering and sediment recycling/sorting ~~processes~~,

1298 together with a general felsic-dominated origin are inferred for the late Triassic and

1299 the late Jurassic-early Cretaceous.

1300 • Intensive and/or prolonged source-area weathering is indicated for the late

1301 Cretaceous to late Eocene-Oligocene sandstones in the Kyrenia Range, northern

1302 Cyprus.

1303 • In contrast, the chemical indices for the Oligocene to Miocene sandstones are

1304 consistent with rapid weathering, transport and deposition (without much ~~sea-floor~~

1305 reworking) ~~of as~~ turbidity currents and/or mass-flow deposits.

1306 • Relatively high degrees of sorting are recorded in the Oligocene-middle Miocene

1307 sandstones, consistent with dominant accumulation from suspension flows (turbidity

1308 currents).

1309 • The late Eocene-late Miocene sandstones have relatively abundant felsic

1310 material of 'normal' continental crust origin (with probable admixture of mafic detritus),

1311 which is consistent with accumulation in a subduction trench setting, ~~(indicated by~~

1312 ~~other geological evidence)~~. In contrast, the late Cretaceous to late Eocene-Oligocene

1313 sandstones have an increasing mafic-ultramafic ophiolite-related detrital input, related

1314 to a source of emplaced ophiolite-related rocks, which, taking account of paleocurrent

1315 data, can be linked with the South Neotethyan suture zone of southeast Turkey.

1316 • The sandstone compositions represent the combined influences of late

1317 Precambrian-Cambrian collision/amalgamation of Cadomian basement, and then

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1318 deposition in continental shelf (Ordovician-early Permian), rift (late Permian-early
1319 Jurassic), passive margin (late Triassic-early Cretaceous) (interrupted by a pulse of
1320 crustal extension), active margin (late Cretaceous-Oligocene) and finally diachronous
1321 continental collision settings (late Miocene-Recent in Cyprus).

1322 ~~• Our chemical data add usefully to the interpretation of the Cyprus sandstones,~~
1323 ~~over and above that available from other methods, including field sedimentology,~~
1324 ~~optical microscopy and X-ray diffraction. We advocate routine inclusion of chemical~~
1325 ~~analysis/interpretation in the study of sandstones and we have developed and applied~~
1326 ~~a 'user's guide' to facilitate this.~~

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1327

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1846 Listing of Figures

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1847 Fig. 1. Flowchart showing suggested steps in the description and description of
1848 whole-rock chemical data for sandstones, including key plots and methods that can
1849 be used at individual steps.

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1851 Fig. 42. Outline tectonic map of the Eastern Mediterranean region, including the main
1852 tectonic units mentioned in the text. Tectonic framework is modified from Robertson et
1853 al. (2012a). Note the locations of Mamonia Complex (southwest Cyprus), the Moni
1854 Melange (southern Cyprus) and the Kyrenia Range (northern Cyprus) in Cyprus (red
1855 box).

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1857 Fig. 23. Stratigraphy of the Mamonia Complex (southwest Cyprus), the Moni Melange
1858 (southern Cyprus) and the Kyrenia Range (northern Cyprus). Main sources of
1859 information: Robertson and Woodcock (1979), Robertson (1977); and McCay and
1860 Robertson (2012). The positions of the sandstones analysed in this study are marked
1861 by red stars.

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1863 Fig. 3. Suggested flowchart of plots and methods, ideally used sequentially, that aid
1864 the interpretation of chemical data for sandstones. See the text for discussion.

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1866 Fig. 4. Comparative chemical plots for the sandstones analysed: late Triassic
1867 (Vlamborous Formation); late Jurassic-early Cretaceous of the Mamonia Complex

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1868 (Episkopi Formation, including Akamas Member), southwest Cyprus; also early
1869 Cretaceous sandstone of the Moni Melange (Pareklisia Member), southern Cyprus. (a)
1870 $\text{Na}_2\text{O}/\text{K}_2\text{O}$ versus $\text{SiO}_2/\text{Al}_2\text{O}_3$ discrimination diagram (after Pettijohn et al., 1972); (b)
1871 $\text{Fe}_2\text{O}_3/\text{K}_2\text{O}$ versus $\text{SiO}_2/\text{Al}_2\text{O}_3$ diagram (after Herron, 1988).

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1872
1873 ~~Fig. 5. Binary compositional plots for the late Triassic (Vlamborous Formation) and the~~
1874 ~~late Jurassic-early Cretaceous (Episkopi Formation, including Akamas Member)~~
1875 ~~sandstones of the Mamonia Complex, southwest Cyprus; also early Cretaceous~~
1876 ~~sandstone (Pareklisia Member) of the Moni Melange, southern Cyprus. (a) The first~~
1877 ~~two principal components of the principal component analysis (PCA) based on the~~
1878 ~~centred log-ratio (clr)-transformed concentrations of the major and trace elements; (b)~~
1879 ~~The first and second principal components of the PCA are based on the~~
1880 ~~clr-transformed concentrations of a subset of the elements that is assumed to be less~~
1881 ~~affected by diagenesis and leaching (e.g., Nesbitt and Young, 1984; Bhatia and Crook,~~
1882 ~~1986).~~

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1883
1884 Fig. 65. (a, b) Selected major and trace element concentrations for the late Triassic
1885 (Vlamborous Formation) and the late Jurassic-early Cretaceous (Episkopi Formation,
1886 including the Akamas Member) sandstones of the Mamonia Complex, southwest
1887 Cyprus; also early Cretaceous sandstone (Pareklisia Member) of the Moni Melange,
1888 southern Cyprus, normalised to upper continental crust (UCC). The normalising
1889 values are from Rudnick and Gao (2003), and Hu and Gao (2008); (c, d) REE

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concentrations, normalised to chondrite; normalising values from Taylor and McLennan (1985).

Fig. 6. Binary compositional plots for the late Triassic (Vlamborous Formation) and the late Jurassic-early Cretaceous (Episkopi Formation, including Akamas Member) sandstones of the Mamonia Complex, southwest Cyprus; also early Cretaceous sandstone (Pareklisia Member) of the Moni Melange, southern Cyprus. (a) The first two principal components of the principal component analysis (PCA) based on the centred log-ratio (clr)-transformed concentrations of the major and trace elements; (b) The first and second principal components of the PCA are based on the clr-transformed concentrations of a subset of the elements that is assumed to be less affected by diagenesis and leaching (e.g., Nesbitt and Young, 1984; Bhatia and Crook, 1986).

Fig. 447. (a) Ternary diagram (after Nesbitt and Young, 1984) of molecular proportions of Al_2O_3 -($\text{CaO}^*+\text{Na}_2\text{O}$)- K_2O for the late Triassic (Vlamborous Formation) and the late Jurassic-early Cretaceous (Episkopi Formation, including Akamas Member) sandstones of the Mamonia Complex, southwest Cyprus; also the early Cretaceous sandstone (Pareklisia Member) of the Moni Melange, southern Cyprus. Black arrow indicates the general weathering trend (McLennan et al., 1993), and the brown arrow diagenetic K-metasomatism (smectite-illite transformation; Fedo et al., 1995). Open/solid boxes represent compositions of various rock types (McLennan et al.,

1993); (b) Different mobility of diverse alkali and alkaline-earth metals in the above sandstones; α values are normalised to UCC (Rudnick and Gao, 2003; Hu and Gao, 2008); (c) Ternary Al_2O_3 -Zr-TiO₂ plot for the same sandstones (after Garcia et al., 1991); the post-Archean Australia Shale (PAAS) data are from McLennan et al. (1993). Blue arrow shows possible sorting effects (Garcia et al., 1991); (d) Th/Sc vs. Zr/Sc diagram (after McLennan et al., 1993). Black solid circles indicate the average compositions of granite, andesite and basalt (after Condie, 1993). Grey square represents the average compositions of UCC (Rudnick and Gao, 2003; Hu and Gao, 2008). The purple arrow indicates compositional variations and the green arrow sedimentary recycling effects (i.e., zircon addition).

Fig. 428. Comparative plots for provenance discrimination for the late Triassic (Vlamborous Formation) and the late Jurassic-early Cretaceous (Episkopi Formation, including the Akamas Member) of the Mamonia Complex, W Cyprus; also the early Cretaceous sandstone (Pareklisia Member) of the Moni Melange, southern Cyprus. (a) Ternary plot of La-Th-Sc. The values of potential source rocks (grey squares) are from McLennan and Taylor (1984); (b) La/Th vs. Hf diagram (after Floyd and Leveridge, 1987). See text for explanation.

Fig. 439. Tectonic discriminations for the late Triassic (Vlamborous Formation) and the late Jurassic-early Cretaceous (Episkopi Formation, including Akamas Member) sandstones of the Mamonia Complex, southwest Cyprus; also the early Cretaceous

sandstone (Pareklisia Member) of the Moni Melange, southern Cyprus. (a) Multi-dimensional diagram for the low-silica ($35\% < \text{SiO}_2 < 63\%$) and (b) the high-silica ($63\% < \text{SiO}_2 < 95\%$) sandstones (after Verma and Armstrong-Altrin, 2013); (c, d) Multi-dimensional discriminant function diagrams for active vs. passive margin settings; after Verma and Armstrong-Altrin (2016); (e) UCC-normalised multi-element patterns for average sandstone compositions; also for greywacke (averaged) from different tectonic environments (after Floyd et al., 1991). UCC-normalising values from Rudnick and Gao (2003) and Hu and Gao (2008).

Fig. 710. Binary compositional plots for the latest Cretaceous-late Miocene sandstones from the Kyrenia Range, northern Cyprus. The formations from which the sandstones were collected are listed below. (a) $\text{Na}_2\text{O}/\text{K}_2\text{O}$ versus $\text{SiO}_2/\text{Al}_2\text{O}_3$ discrimination diagram (after Pettijohn et al., 1972); (b) $\text{Fe}_2\text{O}_3/\text{K}_2\text{O}$ versus $\text{SiO}_2/\text{Al}_2\text{O}_3$ diagram (after Herron, 1988). Open symbols represent samples from the northerly sub-basin (north of the Kyrenia Range); filled symbols represent samples from the southerly sub-basin (south of the Kyrenia Range).

~~Fig. 8. Binary compositional plots for the latest Cretaceous-late Miocene sandstones from the Kyrenia Range. The formations from which the sandstones are derived are listed below. (a) The first two principal components of the PCA based on the clr transformed concentrations of the major and trace elements; (b) The first and second principal components of the PCA are based on the clr transformed~~

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1956 ~~concentrations of a subset of the elements that is assumed to be less affected by~~
1957 ~~diagenesis and leaching.~~

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1959 Fig. ~~9~~11. Upper continental crust (UCC)-normalised spider plots for the latest
1960 Cretaceous-late Miocene sandstones from the Kyrenia Range. The formations from
1961 which the sandstones were collected are listed below (data from Rudnick and Gao,
1962 2003; Hu and Gao, 2008). The element order is after Condie et al. (1992).

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1964 Fig. ~~40~~12. Chondrite-normalised REE spider plots for the latest Cretaceous-late
1965 Miocene sandstones from the Kyrenia Range. The formations from which the
1966 sandstones came are listed ~~below~~.

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1969 Fig. 813. Binary compositional plots for the latest Cretaceous-late Miocene
1970 sandstones from the Kyrenia Range. The formations from which the sandstones are
1971 derived are listed below. (a) The first two principal components of the PCA based on
1972 the clr-transformed concentrations of the major and trace elements; (b) The first and
1973 second principal components of the PCA are based on the clr-transformed
1974 concentrations of a subset of the elements that is assumed to be less affected by
1975 diagenesis and leaching.

1976 ~~Fig. 11. (a) Ternary diagram (after Nesbitt and Young, 1984) of molecular proportions~~
1977 ~~of Al_2O_3 , $(CaO^* + Na_2O)$, K_2O for the late Triassic (Vlamborous Formation) and the late~~

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1978 Jurassic-early Cretaceous (Episkopi Formation, including Akamas Member)
 1979 sandstones of the Mamonía Complex, southwest Cyprus; also the early Cretaceous
 1980 sandstone (Pareklisia Member) of the Moni Melange, southern Cyprus. Black arrow
 1981 indicates the general weathering trend (McLennan et al., 1993), and the brown arrow
 1982 diagenetic K metasomatism (smectite illite transformation; Fodor et al., 1995).
 1983 Open/solid boxes represent compositions of various rock types (McLennan et al.,
 1984 1993); (b) Different mobility of diverse alkali and alkaline earth metals in the above
 1985 sandstones; α values are normalised to UCC (Rudnick and Gao, 2003; Hu and Gao,
 1986 2008); (c) Ternary Al_2O_3 -Zr-TiO₂ plot for the same sandstones (after Garcia et al.,
 1987 1991); the post-Archean Australia Shale (PAAS) data are from McLennan et al. (1993).
 1988 Blue arrow shows possible sorting effects (Garcia et al., 1991); (d) Th/Sc vs. Zr/Sc
 1989 diagram (after McLennan et al., 1993). Black solid circles indicate the average
 1990 compositions of granite, andesite and basalt (after Condie, 1993). Grey square
 1991 represents the average compositions of UCC (Rudnick and Gao, 2003; Hu and Gao,
 1992 2008). The purple arrow indicates compositional variations and the green arrow
 1993 sedimentary recycling effects (i.e., zircon addition).
 1994
 1995 Fig. 12. Comparative plots for provenance discrimination for the late Triassic
 1996 (Vambersou Formation) and the late Jurassic-early Cretaceous (Episkopi Formation,
 1997 including the Akamas Member) of the Mamonía Complex, W Cyprus; also the early
 1998 Cretaceous sandstone (Pareklisia Member) of the Moni Melange, southern Cyprus. (a)
 1999 Ternary plot of La-Th-Sc. The values of potential source rocks (grey squares) are from

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2000 ~~McLennan and Taylor (1984); (b) La/Th vs. Hf diagram (after Floyd and Leveridge,~~
2001 ~~1987). See text for explanation.~~

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2002
2003 ~~Fig. 13. Tectonic discriminations for the late Triassic (Vlamborou Formation) and the~~
2004 ~~late Jurassic-early Cretaceous (Episkopi Formation, including Akamas Member)~~
2005 ~~sandstones of the Mamonia Complex, southwest Cyprus; also the early Cretaceous~~
2006 ~~sandstone (Parokklisia Member) of the Moni Melange, southern Cyprus. (a)~~
2007 ~~Multi-dimensional diagram for the low-silica ($35\% < \text{SiO}_2 < 63\%$) and (b) the high-silica~~
2008 ~~($63\% < \text{SiO}_2 < 95\%$) sandstones (after Verma and Armstrong-Altrin, 2013); (c, d)~~
2009 ~~Multi-dimensional discriminant function diagrams for active vs. passive margin~~
2010 ~~settings; after Verma and Armstrong-Altrin (2016); (e) UCC-normalised multi-element~~
2011 ~~patterns for average sandstone compositions; also for greywacke (averaged) from~~
2012 ~~different tectonic environments (after Floyd et al., 1991). UCC-normalising values~~
2013 ~~from Rudnick and Gao (2003) and Hu and Gao (2008).~~

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2014
2015 ~~Fig. 14. Comparative plots indicating possible weathering, sorting and recycling~~
2016 ~~effects for the latest Cretaceous-late Miocene sandstones from the Kyrenia Range.~~

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2017 The formations from which the sandstones came are listed below. (a)
2018 Al_2O_3 -($\text{CaO}^* + \text{Na}_2\text{O}$)- K_2O ternary diagram (after Nesbitt and Young, 1984). Black
2019 arrow indicates general weathering trend (McLennan et al., 1993) and the brown
2020 arrow diagenetic K-metasomatism (i.e., smectite-illite transformation) (Fedo et al.,
2021 1995). Open/solid boxes represent compositions of various rock types (McLennan et

al., 1993); (b) Ternary $\text{Al}_2\text{O}_3\text{-Zr-TiO}_2$ plot (after Garcia et al., 1991). Blue arrow represents possible sorting effects; (c) Th/Sc vs. Zr/Sc diagram (after McLennan et al., 1993). Black solid circles indicate the average compositions of granite, andesite and basalt (after Condie, 1993). Grey square represents average compositions of UCC (Rudnick and Gao, 2003; Hu and Gao, 2008). Purple arrow indicates compositional variations; green arrow indicates sedimentary recycling (zircon addition) effects; (d) La_N/Y_N vs. $\text{SiO}_2/\text{Al}_2\text{O}_3$ plot (after Roser and Korsch, 1999). Purple arrow indicates compositional variations and the green arrow sedimentary sorting and recycling effects.

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Fig. 15. Discrimination diagrams to identify ultramafic-mafic-felsic provenances for the latest Cretaceous-Late Miocene sandstones from the Kyrenia Range. The source formations are listed below. (a) Cr vs. Ni diagram. High concentrations of Cr (>150 ppm) and Ni (>100 ppm), together with Cr/Ni ratios (1.3-1.5; grey shaded) are indicative of ultramafic provenance; Cr/Ni ratios (>2; orange arrow) typify input of mafic volcanic rocks (Garver et al., 1996); (b) Cr/V vs. Y/Ni diagram (after McLennan et al., 1993). Red arrow represents possible mafic or ultramafic sources; (c) V-Ni-Th plot (after Bracciali et al., 2007). Black shaded areas represent the compositions of the felsic, mafic and ultramafic rocks; (d) Th/Sc vs. Cr/Th diagram (after Taylor and McLennan, 1985). Grey arrow indicates a felsic provenance and the orange arrow an input of mafic volcanic rocks.

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2044 Fig. 16 Tectonic discrimination for the latest Cretaceous-~~Late~~-late Miocene
2045 sandstones from the Kyrenia Range. The formations from which the sandstones are
2046 derived are listed below. (a) Multi-dimensional tectonic discrimination diagram for
2047 settings with $35\% < \text{SiO}_2 < 63\%$ (after Verma and Armstrong-Altrin, 2013); (b, c)
2048 Multi-dimensional discriminant function diagrams to separate active vs. passive
2049 margin settings (after Verma and Armstrong-Altrin, 2016).

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2051 Fig. 17. Plate tectonic sketch maps showing the development of the easternmost
2052 Mediterranean during late Triassic-late Miocene, simplified from Robertson et al.
2053 (2012a). (a) late Triassic; (b) late Jurassic-early Cretaceous; (c) latest Cretaceous; (d)
2054 middle Eocene; and (e) middle Miocene. The likely source and transport directions of
2055 the sandstones studied chemically are indicated, based on available geological
2056 evidence. The chemical data allow a better understanding of provenance, weathering,
2057 transport, deposition and diagenesis but cannot by themselves be used to create such
2058 detailed plate tectonic reconstructions.

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2060 Listing of Tables

2061 Table 1. Weathering indices derived for the sandstones analysed.

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2064 Listing of Supplementary material

2065 ~~Supplementary Appendix A. Additional explanation of chemical methods.~~

2066 ~~Supplementary Table 1. Weathering indices derived for the sandstones analysed.~~

2067 Supplementary Table 21. Major element oxides, trace elements and rare earth

2068 elements for the sandstones analysed from Cyprus.

2069 Supplementary Table 32. Petrographic summary of the related sandstones analysed

2070 from Cyprus.

2071 Supplementary Table 43. Range of elemental ratios of the sandstones analysed from

2072 Cyprus, compared to the corresponding range of ratios in sediments derived from

2073 felsic and mafic rocks.

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1 User's guide to the interpretation of sandstones using whole-rock chemical data,
2 exemplified by sandstones from Triassic to Miocene passive and active margin
3 settings from the Southern Neotethys in Cyprus

4

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12

13 Abstract

14 Sandstone geochemistry provides useful insights into source-rock weathering,
15 erosion, sedimentary transport, deposition, diagenesis and provenance. We identify
16 and discuss useful geochemical methods and plots for the description and
17 interpretation of whole-rock chemical data for a wide range of sandstone
18 compositions, which we present as a user's guide. As a test, we apply this to late
19 Triassic-late Miocene sandstones from two contrasting depositional-tectonic settings
20 in Cyprus that are already extensively documented and interpreted. The chemical
21 approach adds useful information/interpretation and deserves to be used more widely.

22 Late Triassic-early Cretaceous sandstones in southwest and southern Cyprus
23 (Mamonia Complex and Moni Melange) were ultimately derived from felsic-dominated
24 source rocks (e.g., granodiorite) that became more weathered through time, as
25 conditions became more humid; sorting and recycling effects increased over the same
26 time interval. The sandstones were mainly recycled from Paleozoic siliciclastic shelf
27 deposits in southernmost Turkey (Taurides) during the rift/passive margin
28 development of the Southern Neotethys. For the late Cretaceous-late Miocene
29 sandstones in northern Cyprus (Kyrenia Range), the chemical signals are more
30 complex related to a more variable provenance. Paleocurrent and other geological
31 evidence support initial supply during the late Eocene-Oligocene from a mostly felsic
32 continental source to the north in southern Turkey, with accumulation in a trench-type
33 setting in north Cyprus, related to northward subduction. Paleocurrent data for during
34 and after early-middle Miocene indicate sediment westward supply, including

mafic/ultramafic material from ophiolite-related rocks, related to suturing of the Southern Neotethys in southeast Turkey. Overall, sandstone composition in Cyprus was strongly influenced by the regional Cadomian basement that was amalgamated during the late Precambrian-Cambrian Pan-African orogeny.

Keywords: user's guide; sandstone geochemistry; Cyprus; weathering and recycling; provenance; Southern Neotethys

1. Introduction

Clastic sediments, as the products of mechanical and chemical processes, provide important clues concerning many aspects of sedimentary geology (e.g., Dickinson, 1970; McLennan et al., 1993; Weltje and von Eynatten, 2004; Basu et al., 2016). Petrographic analysis of major framework constituents and petrofacies using the optical microscope is critical to the successful study of physical erosion, provenance (source units), paleogeography and tectonic setting (e.g., Dickinson and Suczek, 1979; Marsaglia and Ingersoll, 1992; Critelli et al., 1997, 2003; Marsaglia et al., 2016; Critelli, 2018; Garzanti, 2019).

It is widely accepted that a combination of field and laboratory techniques enhances the understanding of sedimentary geology (e.g., Dickinson and Suczek, 1979; McLennan et al., 1993; Critelli, 2018; Garzanti, 2019). However, literature survey suggests that one of these techniques, whole-rock chemical analysis, is not

nowadays routinely applied to the study of sandstones but mainly undertaken by specialists in sedimentary geochemistry. Possible reasons for this may include the extra time and expense involved in chemical analysis and interpretation, a belief that the results might not add much to the overall interpretation, and the plethora of existing chemical plots and diagrams with different objectives that can be off-putting.

Here, we present a user's guide that can help the non-specialist to enhance the interpretation of sandstones using chemical evidence. For igneous rocks, users' guides have long been available that allow earth scientists to obtain useful information, for example on eruptive tectonic setting, by making use of chemical discriminant diagrams and plots, especially when combined with optical microscopy and other techniques (e.g., Pearce and Cann, 1973; Pearce and Norry, 1979; Pearce, 1996). Although many aspects of sandstones can be interpreted using other methods (e.g., sedimentary structures and optical petrography), our present study, confirms that the whole-rock chemical analysis of sandstones does indeed provide useful additional information, especially concerning climate, diagenesis and provenance. We recommend the routine chemical analysis of sandstones using a combination of major and trace elements, including rare earth elements (REEs).

Here, we take a whole-rock chemical dataset for the Triassic to Miocene sandstones of Cyprus as a case history. This, together with relevant sedimentological, petrographic and geochronological data (e.g., Robertson, 1977; McCay and Robertson, 2012; Trolley and Robertson, 2018; Chen et al., 2019), illustrates the value of whole-rock sandstone geochemistry in understanding the geological development

of the Southern Neotethys and its margins.

The chemical analysis of sandstones particularly helps with an understanding of chemical weathering (climate-related), diagenesis, provenance, paleogeography and tectonic setting (Roser and Korsch, 1985, 1986, 1988; McLennan et al., 1993; Garver et al., 1996; Cullers, 2000). Chemical composition can change in identifiable ways during sand generation, transportation, deposition and recycling (Singh and Rajamani, 2001; Ryan and Williams, 2007; Caracciolo et al., 2012; von Eynatten and Dunkl, 2012; Verma and Armstrong-Altrin, 2013, 2016). The interpretation of chemical data is most effective when the stratigraphy, age and structure of a study area are well known, and where petrographic, X-ray diffraction (XRD) and geochemical analysis techniques are used together (Weltje and von Eynatten, 2004; Critelli et al., 2008; Basu et al., 2016; Chen and Robertson, 2019). For fine-grained clastic sediments (mudrocks), identification of constituents can best be achieved using both XRD and chemical composition (e.g., Palamakumbura and Robertson, 2019).

2. User's guide to interpreting sandstone chemical composition

Below, we suggest a series of steps for the interpretation of sandstones in which different diagrams provide complementary information and interpretation (Fig. 1).

2.1. Step 1: screening (grain-size and composition) and chemical classification

The first step is to select samples for appropriate grain-size and compositions of interest. Samples with inappropriate grain-size and, or unusual or irrelevant

compositions can then be excluded from further study.

Grain-size can significantly influence the chemical composition of terrigenous sediments. However, the selection of equivalent grain-sizes (i.e., fine to medium-grained sandstone; 63-250 μm) and the use of element ratios minimises the effects of grain size and mineral fractionation (Wronkiewicz and Condie, 1987; Cullers, 1995, 2000; Weltje and von Eynatten, 2004). In our study, we collected medium-grained sandstones and make extensive use of element ratios.

The sandstones can then be classified using two schemes in conjunction; i.e., binary plots of log ratios of $\text{Na}_2\text{O}/\text{K}_2\text{O}$ vs. $\text{SiO}_2/\text{Al}_2\text{O}_3$ (Pettijohn scheme; Pettijohn et al., 1972) and $\text{Fe}_2\text{O}_3/\text{K}_2\text{O}$ vs. $\text{SiO}_2/\text{Al}_2\text{O}_3$ (Herron scheme; Herron, 1988). Key element ratios include: (1) $\text{SiO}_2/\text{Al}_2\text{O}_3$, which reflects mineralogical maturity in clastic sediments (Pettijohn et al., 1972). This ratio increases as quartz is progressively concentrated at the expense of less resistant phases during weathering, transport or recycling (Maynard et al., 1982; Roser and Korsch, 1999); (2) $\text{Na}_2\text{O}/\text{K}_2\text{O}$ characterizes the relative abundance of feldspars (e.g., plagioclase vs. K-feldspar); and (3) $\text{Fe}_2\text{O}_3/\text{K}_2\text{O}$ indicates mineralogical stability (lithic vs. feldspathic fragments) (Herron, 1988). For log-ratios, where the data set contains zeros; i.e., below detection limits of X-ray fluorescence (XRF) spectrometry or inductively coupled plasma mass spectrometry (ICP-MS), an arbitrary value of 0.65 times the detection limit can be set (Martín-Fernández et al., 2003).

2.2. Step 2: Whole-rock chemical composition

The next step is to gain an understanding of the bulk chemical composition. A useful first step is to plot binary variation, for example of key major elements (e.g., Al_2O_3 , SiO_2 , Fe_2O_3 , MgO) against other components, equivalent to the widely used Harker diagrams for igneous rocks (Harker, 1909). This can be supplemented using specific bivariate plots, for example of major and trace elements ($\text{Na}_2\text{O}+\text{K}_2\text{O}$ vs. SiO_2 of Le Bas et al., 1986) (e.g., Chen and Robertson, 2019). It is useful then to plot the sandstone composition against that of average chondrite and also of upper continental crust (UCC) for selected major elements (e.g., K and P) and trace elements (e.g., REEs) (Taylor and McLennan, 1985; Rudnick and Gao, 2003). As for igneous rocks, certain trace elements; i.e., high field strength elements (HFSEs), e.g., Ti, Zr, Y and heavy rare earth elements (HREEs), are particularly useful as they are relatively immobile and little affected by diagenesis or low-grade metamorphism, as is well understood in the study of igneous rocks (Cann, 1970; Pearce and Cann, 1971, 1973).

Chemical correlations can also be identified using principal component analysis (PCA) of the major and trace element data (Aitchison, 2003). This can be carried out by means of a centred log-ratio (clr) transformation. Multivariate observations (points) and variables (rays) are displayed as a compositional plot (Gabriel, 1971). The length of each ray is proportional to the variance of the corresponding element in the dataset. The angle between the two rays of c. 0° , 90° , and 180° and shows whether the

relevant elements are directly correlated, uncorrelated or inversely correlated. This approach can be refined by plotting a second PCA that excludes highly mobile elements; e.g., K, Rb, Ba, Sr, Mn and Na. Where carbonate cement is present, Ca should be excluded; also Mg if a high-magnesium cement is present.

2.3. Step 3: Role of weathering and alteration

The next step is to assess the importance of weathering and alteration that could have taken place in the source area and, or during sediment transport. Chemical alteration can also take place during burial diagenesis (e.g., Tucker, 2001).

Variable degrees of chemical weathering in the source area strongly affect the major-element composition and the mineralogy of siliciclastic sediments (e.g., Nesbitt and Young, 1982; Taylor and McLennan, 1985; McLennan, 1993; Fedo et al., 1995).

The intensity of chemical weathering affecting a source rock is mainly controlled by the source-rock composition, climatic conditions, duration of weathering, and rate of uplift/exhumation (e.g., Wronkiewicz and Condie, 1987; Scarciglia et al., 2007, 2016).

Chemical indices have been introduced to evaluate weathering effects quantitatively (e.g., Nesbitt and Young, 1982; Harnois, 1988; Fedo et al., 1995; Garzanti et al., 2013a, b, 2014a, b).

The mobility of elements during chemical weathering and post-depositional chemical diagenesis of source materials can be evaluated using the Al_2O_3 -($\text{CaO}^*+\text{Na}_2\text{O}$)- K_2O molecular proportion diagram and the Chemical Index of Alteration (CIA of Nesbitt and Young, 1982). Chemical indices can customised to

circumvent problems associated with anomalous enrichment in potassium, such as the Chemical Index of Weathering (CIW of Harnois, 1988), the Plagioclase Index of Alteration (PIA of Fedo et al., 1995), the modified Chemical Index of Alteration (CIX of Garzanti et al., 2014a, b), the Weathering Index (WIP of Parker, 1970), and the α^{Al} values (Garzanti et al., 2013a, b). These indices can be utilised individually, or preferably together, to infer weathering effects. The formulae used to calculate the weathering indices are given in Table 1.

Oxidation, one of the major reactions in chemical weathering, influences the oxidation state of some elements (e.g., U^{4+} to U^{6+}) (Taylor and McLennan, 1985). Oxidising conditions can be inferred using proxies; e.g., elevated Th/U (>3.8 ; Taylor and McLennan, 1985), but lower V/Cr (<2 ; Jones and Manning, 1994) and V/Sc (<9 ; Kimura and Watanabe, 2001). The Th/U vs. Th diagram that can be used to help evaluate successive cycles of weathering and redeposition (McLennan et al., 1993) works in the same way mathematically.

2.4. Step 4: Role of sedimentary sorting and recycling

Sorting/recycling processes strongly fractionate mineralogical components (e.g., clays, zircon) and therefore significantly influence bulk sediment composition (Garcia et al., 1991; McLennan et al., 1993). Sedimentary sorting and recycling processes affect the energy, rate, and/or duration of deposition, as well as transport processes (e.g., debris-flow, aeolian). Such processes can also fractionate chemical components within sediments; e.g., clay minerals (Al_2O_3), Ti-oxides (TiO_2), zircon (Zr)

and quartz (SiO_2) (Garcia et al., 1991). The related Al_2O_3 -Zr-TiO₂ plot eliminates weathering effects and can, therefore, highlight sorting-related fractionation (Garcia et al., 1991). By comparison, Zr/Sc usefully indicates petrogenetic evolution and sedimentary zircon concentration (McLennan et al., 1993). A combination of Th/Sc ratio (as in the Th/Sc vs. Zr/Sc plot), together with comparisons with the igneous differentiation trend and the model source evolution trend (e.g., Roser and Korsch, 1999; Roser et al., 2002) can, therefore, help to indicate sorting and recycling effects.

2.5. Step 5: Provenance indicators

The chemical compositions of sedimentary rocks can help indicate their provenance (Dickinson and Suczek, 1979; Roser and Korsch, 1988; von Eynatten et al., 2012). Major and trace element compositions, including SiO_2 , Al_2O_3 , Fe_2O_3 + MgO, K_2O , Na_2O , TiO_2 , Th, Sc, Zr, Cr, Ni, Co, V, Y, La, and Eu anomalies, have been used to infer sediment provenance (Roser and Korsch, 1988; McLennan and Taylor, 1991).

Major-element compositions can be significantly affected during alteration and diagenesis (see above) and, therefore, are not ideal provenance indicators, although some ratios ($\text{SiO}_2/\text{Al}_2\text{O}_3$, $\text{K}_2\text{O}/\text{Na}_2\text{O}$, $\text{Al}_2\text{O}_3/\text{TiO}_2$) have been widely used for this purpose (Pettijohn et al., 1972; Roser and Korsch, 1988; Fyffe and Pickerill, 1993). Trace elements, which are relatively immobile during sedimentary processes (see above) are generally considered to be useful for provenance determination (e.g., Taylor and McLennan, 1985; Floyd and Leveridge, 1987; Wronkiewicz and Condie, 1987; McLennan et al., 1993; Cullers, 1995). Zr, Th, Hf and REEs are mainly derived

203 from felsic rocks, as they are highly incompatible during most igneous melting and
204 fractionation processes (McLennan, 1989; Cullers, 1995; Varga et al., 2007). However,
205 sediments derived from mafic or ultramafic sources have relative enrichments in Sc,
206 Co, Cr and Ni, representing their more compatible behaviour (Garver and Scott, 1995;
207 Zimmermann and Bahlburg, 2003). Therefore, key trace-element ratios (e.g., La/Co,
208 Th/Co, Th/Cr, La/Sc and Th/Sc) help to distinguish compositional differences (e.g.,
209 Taylor and McLennan, 1985; Cullers, 1995, 2000). Combinations of the above ratios
210 are commonly used for provenance analysis, for example, the La-Th-Sc diagram and
211 its variants (Taylor and McLennan, 1985; Jahn and Condie, 1995).

212 The progressive dissection of a magmatic arc and erosion of its basement
213 increases the Hf content via release of zircon (Floyd and Leveridge, 1987). Therefore,
214 La/Th vs. Hf can discriminate between different arc compositions and sources (and
215 can also be related to framework modal analysis) (Floyd and Leveridge, 1987).

216 Chromium and Ni are widely used to indicate ultramafic components in clastic
217 sediments. Enrichments of Cr (>150 ppm), Ni (>100 ppm), Cr/Ni (1.3-1.5) (Garver and
218 Scott, 1995; Garver et al., 1996), together with elevated Cr/V (McLennan et al., 1993)
219 suggest an ultramafic rock provenance (i.e., ophiolite-related sources). The addition
220 of Th (e.g., V-Ni-Th and Th/Sc vs. Cr/Th diagrams; Bracciali et al., 2007; Taylor and
221 McLennan, 1985) can help to indicate contributions from ultramafic, mafic or felsic
222 rocks.

223 2.6. Step 6: Tectonic setting of deposition

224 Some widely used chemical plots have shortcomings for tectonic discrimination (e.g.,
225 Ryan and Williams, 2007; von Eynatten and Dunkl, 2012; Verma and Armstrong-Altrin,
226 2013, 2016; Basu et al., 2016; Chen, 2018). Major element-related diagrams can help
227 indicate tectonic setting (Bhatia, 1983) and tectonic discrimination based on trace
228 elements (e.g., La-Th-Sc, Th-Co-Zr) (Bhatia and Crook, 1986). However, the
229 database used to construct the original template diagrams has limitations. The
230 comparative tectonic settings used, represented by the Paleozoic of Eastern Australia
231 (an ancient orogen), are inevitably interpretative; the database is restricted (<100
232 samples), and the presence of either authigenic or allogenic carbonate required
233 recalculation prior to plotting of the diagrams, which is potentially problematic.

234 More recently, new diagrams have been developed using a more consistent
235 statistical treatment of the compositional data, a larger number of analyses and a
236 greater variety of comparative source lithologies (e.g., Armstrong-Altrin and Verma,
237 2005; Ryan and Williams, 2007; von Eynatten and Dunkl, 2012; Verma and
238 Armstrong-Altrin, 2013, 2016). The recently proposed diagrams of Verma and
239 Armstrong-Altrin (2013, 2016), based on multicomponent algorithms (i.e., $\log_e$ -ratio
240 transformation of 10 major elements with SiO_2 or isometric log-ratio transformation of
241 10 major elements and 6 trace elements) are effective where sandstones have a wide
242 range of compositions and are likely to encompass several different settings.
243 Diagrams using a selected (customised) combination of relatively immobile major and

244 trace elements can best determine tectonic setting (e.g., Robertson and
245 Palamakumbura, 2019).

246 It should be noted that any discriminated tectonic setting refers to the source area
247 and not necessarily the depositional setting (e.g., Verma and Armstrong-Altrin, 2013,
248 2016). In some cases, for example, long-lived subduction zone both source and sink
249 may have similar sources (e.g., volcanic arc). In other settings, the depositional
250 setting may postdate and be entirely different from the source area setting (e.g.,
251 sandstones above an unconformity).

252 2.7. Step 7: Synthesis including additional evidence

253 In practice, the above six steps provide complementary information requiring them to
254 be evaluated together. Interpretations are most effective when a wide suite of
255 chemical plots are used in conjunction, especially in cases in which the field
256 sedimentological context is well understood and in which detailed optical petrography
257 has been carried out (e.g., statistically valid point-counting) (e.g., Caracciolo et al.,
258 2012; Scarciglia et al., 2016; Chen and Robertson, 2019).

259 The interpretation is greatly enhanced when other methods and resulting data
260 are used in conjunction. Some examples are as follows: (1) The chemical analyses of
261 heavy minerals (e.g., zircon, rutile, pyroxene) can help to identify specific
262 provenances (Morton and Hallsworth, 1994; Bahlburg and Floyd, 1999; Tucker, 2001;
263 von Eynatten and Dunkl, 2012); (2) Microprobe and, or ion probe analysis of selected
264 grains. For example, the composition of clinopyroxene, plagioclase or volcanic glass

can help indicate magma type and thus provenance (e.g., Nisbet and Pearce, 1977; Bryant et al., 2003; Deer et al., 2013; Chen and Robertson, 2019). Also, the Cr composition of chrome spinel can be used to help constrain the original tectonic setting of an ultramafic rock (Pober and Faupl, 1988; Mange and Morton, 2007; von Eynatten and Dunkl, 2012); (3) The U-Pb age spectra of detrital zircon and/or rutile help to identify sandstone provenance and how it may have evolved through time (e.g., Gehrels et al., 1995; Fedo et al., 2003; Meinhold, 2010; von Eynatten and Dunkl, 2012); (4) Lu-Hf isotopic data (combined with U-Pb data) can provide additional clues to crustal origin, growth and recycling (Knudsen et al., 2001; Meinhold, 2010; Ustaömer et al., 2019); and (5) Apatite/zircon fission track ages can help identify the provenance terranes via the timing of uplift (Wagner, 1968).

In addition, the source area of metamorphic rocks can be further elucidated using methods such as tourmaline/garnet major element composition and rutile geochemistry/geochronology (Meinhold, 2010; von Eynatten and Dunkl, 2012).

However, further consideration of such methods is beyond our present scope which focusses on bulk chemical composition.

3. Selected case history: Mesozoic-Cenozoic sandstones related to South Neotethys

To test the application and effectiveness of our user's guide to sandstone whole-rock chemical analysis, as explained above, we now take the example of a classic geological region, the island of Cyprus, in the easternmost Mediterranean. Compositionally variable sandstones of a large age range are exposed in Cyprus,

related to the Mesozoic-Cenozoic geological development of the Southern Neotethys, the most southerly strand of the Tethys in the Eastern Mediterranean region (e.g., Robertson, 1998; Stampfli and Borel, 2002; Barrier et al., 2018). In this region, the paleogeography and tectonic setting are relatively well known and where the sandstones have already been studied in some detail, both sedimentologically (e.g., facies analysis, paleocurrent evidence) and petrographically (e.g., optical petrography and point-counting) (Robertson, 1977; McCay and Robertson, 2012; Torley and Robertson, 2018). Some U-Pb dating of detrital zircons is also available (Chen et al., 2019). Here, we focus on terrigenous sandstones. Sandstones with different compositions, such as ophiolite-derived sandstones, volcanoclastic sandstones and mixed carbonates-siliciclastics ideally require a different selection of diagrams/methods (e.g., Caracciolo et al., 2011; Perri et al., 2012). For this reason, we exclude late Cretaceous volcanoclastic sandstones in west Cyprus (Robertson, 1977) for which whole-rock chemical data are also available (Chen and Robertson, 2019).

The main objectives of our chemical study of the Cyprus sandstones, as presented below are as follows: (1) To determine the nature and extent of weathering of possible source rocks; (2) To evaluate the influence of sedimentary processes on sediment chemical composition; (3) To shed light on the provenance and paleogeography; and (4) To evaluate alternative possible controls of chemical composition in relation to the tectonic development of Cyprus and the Southern Neotethys in the eastern Mediterranean region.

3.1. Cyprus geology in a nutshell

The outline below is based on several overview contributions (e.g., Robinson and Malpas, 1990; Robertson and Xenophontos, 1993; Robertson, 1998; Göncüoğlu and Kozlu, 2000; Pearce and Robinson, 2010; Cyprus Geological Survey Department, 2020). Cyprus comprises three litho-tectonic assemblages ('terranes'), the Troodos Massif (central), the Mamonia Complex (in the west), and the Kyrenia Range (in the north) (Fig. 2). During the late Precambrian, the area that is now Cyprus formed part of the Cadomian orogen along the northern margin of the Pan-African continent. During most of the Paleozoic, the area formed part of a wide continental shelf bordering Gondwana with oceans (Rheic and Paleotethys) to the north. During the Permian-Triassic, the continental borderland rifted to form the Southern Neotethys. In conjunction, several continental fragments rifted and drifted northwards. As a result, these continental units, including crust that is now in Cyprus, became isolated from direct input of clastic sediment from the Pan-African basement to the south, whereas compositionally similar metamorphic and igneous material became available from the north. Several interconnected rift and small ocean basins existed during the Mesozoic. Clastic sediment supply was probably derived mainly from the most southerly of the rifted continental fragments, such as the Alanya Massif and/or the Antalya Complex (e.g., Tahtalı Dağ) (Fig. 2) and accumulated in Cyprus within the Mamonia Complex and the Moni Melange in the west and south of the island. During the Jurassic and/or early Cretaceous, the Southern Neotethys reached its widest extent. Incipient closure

during the late Cretaceous (c. 90 Ma) triggered subduction and the genesis of ophiolites, including the Troodos Massif in Cyprus above a subduction zone. The Southern Neotethys subducted northwards during late Cretaceous to Miocene resulting in voluminous clastic sediment accumulation, as studied here, in a trench setting, now exposed in the Kyrenia Range, northern Cyprus. Further crustal shortening was accommodated along a subduction zone south of Cyprus. Today, the island is in an incipient collisional setting between the Eurasian and African plates.

The Mesozoic sandstones discussed here, accumulated during the passive margin stage of opening of the Southern Neotethys (Mamonia Complex and Moni Melange), whereas the late Mesozoic-Cenozoic sandstones (Kyrenia Range) accumulated in trench-type setting related to subduction, making an interesting comparison.

3.2. Sampling and data analysis

In total, 68 samples of sandstone were selected for major and trace element analysis, made up of 31 samples from the Mamonia Complex (southwest Cyprus), one from the Moni Melange (southern Cyprus) and 36 from the Kyrenia Range (northern Cyprus). We used a combination of previously collected samples, together with some additional samples to give a more complete coverage. The samples mainly come from logged successions that cover the range of compositions and ages. Medium-grained sandstones were analysed preferentially to minimise grain-size and mineral fractionation effects (e.g., Wronkiewicz and Condie, 1987; Cullers, 1995, 2000). Major

and trace elements were analysed by XRF spectrometry at the School of GeoSciences, University of Edinburgh, using the methods explained by Fitton et al. (1998) and Fitton and Godard (2004). Accuracy and precision are typically c. 5%.

In addition, five samples of sandstone from the Mamonia Complex, one from the Moni Melange and 19 samples from the Kyrenia Range were analysed for selected trace elements and a full set of REEs by ICP-MS at the ACME Analytical Laboratories, Vancouver. A larger number of samples was utilised for the Kyrenia range sandstones than the Mamonia Complex/Moni Melange sandstones because of their greater compositional range based on petrographic study (McCay and Robertson, 2012). For detailed information on the procedures, geostandards and precision for the elements analysed, see <http://acmelab.com>. All of the analytical data for the major, trace and REEs are listed in the Supplementary material.

3.3. Sandstones of the Mamonia Complex, SW Cyprus and the Moni Melange, S Cyprus

The Mamonia Complex in southwest Cyprus and Moni Melange in southern Cyprus represent remnants of rifted passive margins of the Southern Neotethys (Robertson, 1977; Robertson and Woodcock, 1979). Triassic-Cretaceous sandstones occur in the Mamonia Complex, southwest Cyprus (Ealey and Knox, 1975; Lapierre, 1975; Robertson and Woodcock, 1979; Torley and Robertson, 2018), with equivalents in the Moni Melange, southern Cyprus (Robertson, 1977) (Fig. 3). The Moni Melange is a collection of blocks of sedimentary and igneous rocks including some serpentinite, in

a matrix of late Cretaceous deep-water argillaceous sediments. Some of the sandstones are similar in age and petrography to those in the Mamonia Complex. The Moni Melange is basically a more deformed and disaggregated equivalent of the Mamonia Complex and restores as a part of the same Mesozoic passive margin (Robertson, 1977).

Data available for the sandstones of the Mamonia Complex mainly concern lithostratigraphy (Robertson and Woodcock, 1979), depositional processes, paleoenvironments and diagenesis (Torley and Robertson, 2018). The age of deposition is mainly inferred from macro- and micro-paleontological studies of interbedded deep-sea sediments (e.g., radiolarites) (Ealey and Knox, 1975; Lapierre, 1975; Robertson and Woodcock, 1979; Bragin and Kyrlov, 1996; Bragin, 2007). Data are also available for the chemical composition of interbedded mudrocks and metalliferous sediments (Robertson and Boyle, 1983; Torley and Robertson, 2018). For the sandstones of the Moni Melange, southern Cyprus, facies and petrographic data are likewise published, coupled with a tentative age assignment using sporomorphs from interbedded mudrocks (Robertson, 1977). In addition, recent U-Pb dating of detrital zircons in the late Triassic and late Jurassic-early Cretaceous sandstones of the Mamonia Complex and also the early Cretaceous sandstones from the Moni Melange indicates an ultimate source from the northeast African/Arabian-Nubian Shield area (Chen et al., 2019), today to the southeast of Cyprus. However, following rifting of the Southern Neotethys, the probable source was in one or more of the microcontinental fragments that were located to the north in

393 Anatolia (Turkey). The clastic sediment probably reached Cyprus via reworking of
394 Paleozoic successions exposed in the Taurides (Chen et al., 2019; Ustaömer et al.,
395 2019).

396 3.4. Sandstones of the Kyrenia Range, N Cyprus

397 The Kyrenia Range, northern Cyprus, represents part of the northerly active
398 continental margin of the Southern Neotethys (Robertson and Woodcock, 1986;
399 Robertson et al., 2012a, 2014; Chen et al., 2019). Sandstones are well exposed along
400 the northern and southern flanks of the Kyrenia Range, mainly ranging in age from
401 latest Cretaceous (Maastrichtian) to late Miocene (Tortonian) (Fig. 3). Information
402 from geological mapping and lithostratigraphy (Ducloz, 1972; Baroz, 1979; Robertson
403 and Woodcock, 1986; Hakyemez et al., 2000) is supplemented by recent studies of
404 depositional facies and petrography for sandstones of latest Cretaceous (Robertson
405 et al., 2012b), early-middle Eocene (Robertson et al., 2014) and late Eocene-late
406 Miocene age (McCay and Robertson, 2012). These sandstones are mainly dated
407 using microfossils in interbedded mudrocks and pelagic/hemipelagic sediments
408 (Baroz, 1979; McCay et al., 2013), coupled with strontium isotopes (McCay et al.,
409 2013). XRD data are available for interbedded mudrocks (McCay and Robertson,
410 2012). Microfossil, XRD and chemical data have also been published for mudrocks
411 and manganese deposits of specifically early Messinian age (Robertson et al., 2019a).
412 In addition, preliminary U-Pb dating has been carried out on detrital zircons of
413 sandstones of latest Cretaceous, Eocene and middle Miocene age (Chen et al., 2019).

Paleocurrent data and lithological comparisons suggest that the source areas were located in the Taurides of southern Turkey, both to the north and northeast (McCay and Robertson, 2012; Chen et al., 2019).

4. Application of the user's guide to the Cyprus sandstones

Having obtained the chemical data, we carried out the seven-step evaluation and interpretation, as explained in the user's guide (see Section 2) (Fig. 1). The samples discussed below passed the initial screening step; i.e., are of suitable grain size and composition to proceed usefully.

4.1. Southwest/southern Cyprus sandstones: Mamonia Complex and Moni Melange

4.1.1. Chemical classification

The late Triassic sandstones (Vlambouros Formation, Mamonia Complex) show relatively consistent $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios, whereas the late Jurassic-early Cretaceous sandstones (i.e., Episkopi Formation including Akamas Member, Mamonia Complex; Pareklisia Member, Moni Melange) have variable $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios and relative depletion in Na (Fig. 4a). As a result, the late Triassic sandstones are subarkoses and the late Jurassic-early Cretaceous sandstones are mainly quartz arenites. In the Herron scheme (Fig. 4b), the late Triassic sandstones are litharenites or sublitharenites, whereas the late Jurassic-early Cretaceous sandstones (with variable $\text{Fe}_2\text{O}_3/\text{K}_2\text{O}$) are mainly Fe-sand and quartz arenite.

The above geochemical classification of the sandstones is generally consistent

with their petrographic descriptions (Robertson, 1977; Robertson and Woodcock, 1979; Torley, 2015; Torley and Robertson, 2018). The relatively low $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios are likely to have resulted from high mobility of Na_2O during chemical weathering, diagenesis and/or secondary alteration (e.g., Gaillardet et al., 1999; Varga et al., 2007).

4.1.2. Chemical composition and correlations

The late Triassic sandstones have variable SiO_2 contents (18.9-85.9 wt%), low K_2O (<2.0 wt%), Na_2O (<0.7 wt%), TiO_2 (<0.8 wt%) and P_2O_5 (<0.1 wt%). Al_2O_3 values are variable (1.3-7.7 wt%). CaO is generally high (2.8-43.3 wt%), consistent with the petrographically observed abundances of fine-grained micritic lithics and carbonate fragments (both skeletal and non-skeletal) (Torley and Robertson, 2018). In contrast, the late Jurassic-early Cretaceous sandstones are characterised by extremely high and uniform SiO_2 (91.5-98.2 wt%), together with low CaO (<0.5 wt%), K_2O (<0.2 wt%) and Na_2O (<0.01 wt%).

When selected trace element concentrations for the sandstones are normalised to upper continental crust (UCC) (Fig. 5a-b), the late Triassic sandstones are seen to be characterised by relatively low and scattered elemental abundances (e.g., Ba, Th, U), together with small relative enrichments in Zr and Hf (0.2-2×UCC). The main influence is likely to be detrital zircon, in line with petrographic observations (Torley and Robertson, 2018; Chen et al., 2019). The late Jurassic-early Cretaceous sandstones are poor in trace elements, with the exception of Zr, K and Sr (probably

also P) and show pronounced negative anomalies, whereas Th and U are relatively enriched.

The chondrite-normalised REE patterns confirm the presence of light rare earth elements (LREEs) enrichment in the sandstones (Fig. 5c-d). The late Triassic sandstones have higher concentrations of REEs in relation to UCC, and also moderate Eu depletion ($\text{Eu}/\text{Eu}^*=0.65$). The early Cretaceous sandstone (Pareklisia Member) has lower REE concentrations ($\Sigma\text{REE}=36.3$ ppm), together with significant Eu depletion ($\text{Eu}/\text{Eu}^*=0.5$).

The PCA biplot of major elements (Fig. 6a), reveals a clear separation between the late Triassic sandstones and the late Jurassic-early Cretaceous sandstones. Potassium, Na, Ca and loss on ignition (LOI) are relatively high in the late Triassic sandstones, whereas Si, Ti, Al and Fe relatively enriched in the late Jurassic-early Cretaceous ones. The three principal components of the PCA, excluding mobile elements and carbonates (Fig. 6b), together account for 86% of the total variability. Specifically, the late Triassic sandstones are enriched in Ni, Sc, V, Cr, Al and Fe but are depleted in Si, Zr and Nb compared to the late Jurassic-early Cretaceous sandstones.

4.1.3. Weathering

Moderate weathering conditions are inferred for the late Triassic sandstones (Vlambouros Formation) with CIA and PIA values of 52-77 (Fig. 7a) and 52-89, respectively (see Supplementary material). CIX values of 65-80 are more restricted.

The CIA values for most of the late Triassic sandstones (excepting a few outliers) lie along a different trend from that generally expected (Fig. 7a). This can be explained by potassium metasomatism, specifically the conversion of aluminous clay minerals to illite and the replacement of plagioclase by K-feldspar (McLennan et al., 1993; Fedo et al., 1995). Petrographic observations indicate the presence of a variable clay matrix and also of plagioclase alteration in the late Triassic sandstones (see Supplementary material in Torley and Robertson, 2018). Oxidising depositional conditions are inferred, as represented by the proxies of e.g., high CIA, coupled with elevated Th/U but lower V/Cr and V/Sc ratios (Nesbitt and Young, 1982; Taylor and McLennan, 1985; Jones and Manning, 1994).

In contrast, the late Jurassic-early Cretaceous sandstones (Episkopi Formation including Akamas Member) exhibit higher CIA (90-95) (Fig. 7a), PIA (98-99), CIW (98-99) and CIX (90-95) values (see Supplementary material). These higher values are attributed to CaO and Na₂O depletion, in response to intense or prolonged weathering of the source area (Nesbitt and Young, 1982). In addition, extreme textural maturity is indicated by the abundance of very well-rounded grains (Robertson, 1977; Torley and Robertson, 2018). The bimodal grain-size variation, as previously described and illustrated, is also indicative of reworking (Robertson, 1977; Robertson and Woodcock, 1979; Torley and Robertson, 2018). The combined textual and chemical evidence point to prolonged weathering in a tropical environment, coupled with reworking (e.g., Weltje et al., 1998). The early Cretaceous sandstone of the Moni Melange (Pareklisia Member) is chemically similar but has a lower CIA value (76) (Fig.

7a). This sample has a relatively high K/Al ratio (possibly resulting from K-metasomatism), which shifts the point on the diagram towards illite (Fig. 7a). Although variable, the sandstones trend back to crustal source compositions (andesite and granodiorite), in line with the petrographic evidence, which is generally consistent with a felsic-dominated source (Robertson, 1977; Torley and Robertson, 2018),

Na is strongly depleted relative to the other mobile elements (e.g., K, Mg, Ca, Rb, Sr and Ba). $\alpha^{Al}Na$ ranges from 32-83 in the late Jurassic-early Cretaceous sandstones, c. 33 in the early Cretaceous sandstones, and from 1-7 in the late Triassic sandstones (Fig. 7b). Ca is more depleted relative to K and Rb (Fig. 7b). There is little relative depletion in Mg, Sr and Ba, with $\alpha^{Al}Mg$, $\alpha^{Al}Sr$ and $\alpha^{Al}Ba$ rarely >2 (Fig. 7b). The following bulk-sediment mobility sequence is inferred: $\alpha^{Al}Na \gg \alpha^{Al}Ca > \alpha^{Al}K \geq \alpha^{Al}Rb > \alpha^{Al}Ba \geq \alpha^{Al}Sr > \alpha^{Al}Mg$. The notably higher $\alpha^{Al}Na$ and $\alpha^{Al}Ca$ (preferentially removed during weathering), together with the low values of $\alpha^{Al}Mg$ (fixed in secondary clay minerals) and $\alpha^{Al}Ba$ (absorbed onto clays), demonstrates that the sandstone composition is strongly influenced by weathering processes (e.g., Nesbitt et al., 1980; Garzanti and Resentini, 2016).

The range of CIA values (Fig. 7a) is compatible with the petrographic observations, especially the abundance of clay matrix and plagioclase alteration (Torley and Robertson, 2018), in the late Triassic to early Cretaceous sandstones. The weathering trend is indicated in simplified form by the Th/U ratios here (McLennan et al., 1993) (see above and Supplementary material).

4.1.4. Sorting and recycling effects

On the ternary plot of Al_2O_3 -Zr- TiO_2 (Fig. 7c), Al_2O_3 strongly correlates with TiO_2/Zr . The resulting linear trend (Fig. 7c) is consistent with sorting-related fractionation of similar-composition protoliths (Garcia et al., 1991). Sediment recycling effects, especially enrichment in zircon are also indicated by the plot of Th/Sc vs. Zr/Sc (Fig. 7d). The late Triassic sandstones cluster around the field of andesite and granite, supporting a felsic-dominated source. The late Jurassic-early Cretaceous sandstones, with relatively high Th/Sc and Zr/Sc ratios, mainly plot above the average ratios for UCC, which suggests relatively high zircon concentrations and thus sediment recycling (Fig. 7d).

Sorting and recycling effects, in principle, can be illustrated by La_N/Y_N vs. $\text{SiO}_2/\text{Al}_2\text{O}_3$. However, the late Triassic to early Cretaceous sandstones are characterised by enrichment of SiO_2 and depletion of Al_2O_3 and Na_2O owing to strong weathering. To avoid a misleading interpretation resulting from quartz dilution, the trace element ratios Ti/Zr and Zr/Sc were used to indicate sorting and recycling effects. The dominance of Precambrian zircons in both the Triassic and late Jurassic-early Cretaceous sandstones supports a recycled origin. These sediments were initially supplied from Precambrian basement in Gondwana (i.e., northeast Africa/Arabian-Nubian Shield) and first accumulated within late Precambrian-Paleozoic successions generally to the north, as exposed in southern Turkey. Clastic material was later eroded and reworked generally southwards into the

541 Southern Neotethys during after late Triassic final continental break-up (Chen et al.,
542 2019; Ustaömer et al., 2019). The lack of evidence of rapid recycling of zircon in the
543 Mamonia Complex or the Moni Melange sandstones is consistent with a passive
544 margin setting (e.g., Cawood et al., 2012).

545 4.1.5. Provenance indicators

546 On the La-Th-Sc diagram (Fig. 8a), the linear array shown by the late Triassic
547 sandstones is consistent with a mixing of andesitic and upper crust-sourced material.
548 The late Jurassic-early Cretaceous sandstones cluster around the Post-Archean
549 Australian Shale (PAAS) field, suggesting a felsic-dominated source. Similar trends
550 are evident in the La/Th vs. Hf diagram (Fig. 8b). Key trace-element ratios (e.g., La/Sc,
551 Th/Sc and Th/Cr) also help to distinguish felsic vs. mafic sources (see Supplementary
552 material). Although variable, the sandstones analysed are statistically within the range
553 of the ratios of felsic-dominated rocks (see Supplementary material). Cr/Ni-related
554 diagrams were not used because ophiolite-related (ultramafic) detritus was not
555 observed petrographically (Robertson, 1977; Torley and Robertson, 2018). Also, the
556 carbonate content of the late Triassic sandstones (CaO=2.8-43.3 wt%), and the
557 strongly weathered nature of the late Jurassic-early Cretaceous sandstones (i.e., very
558 low K₂O, Na₂O and Al₂O₃), render discriminant function analysis using major elements
559 unsuitable (the necessary recalculation is unreliable; see above). In addition, the
560 detrital zircon data indicate a felsic-dominated source (Chen et al., 2019). The
561 dominant Neoproterozoic zircon populations are compatible with the voluminous

plutonic and volcanic rocks of this age within the northeast African/Arabian-Nubian region (Chen et al., 2019).

4.1.6. Tectonic setting of deposition

The late Triassic sandstones (8 low-silica and 11 high-silica) mainly plot in the collision field (Verma and Armstrong-Altrin, 2013), together with three samples (2 low-silica and 1 high-silica) in the continental rift field (Fig. 9a-b). The typical high-silica, late Jurassic-early Cretaceous sandstones (one sample with $\text{SiO}_2 > 95\%$ was excluded) plot in the collision field (Fig. 9b). In contrast, all of the sandstones plot within the passive margin setting (Fig. 9c-d) on the multi-dimensional discriminant function diagrams that utilise a combination of major elements and trace elements (Verma and Armstrong-Altrin, 2016). Verma and Armstrong-Altrin (2013) show statistically that such inter-field variation is unlikely to result from chemical changes including weathering, sediment transport, recycling and post-depositional processes. These authors also note that, when that is inconsistent with other geological evidence, the results may represent chemical inheritance from a pre-existing tectonic setting.

The UCC-normalised spider diagram (Fig. 9e) shows: (1) The late Triassic sandstones exhibit negative Nb-Ta anomalies and relatively high Nb/Nb* ratios (c. 0.35; $\text{Nb/Nb}^* = \text{Nb}_N / (\text{Ni}_N \cdot \text{Ti}_N)^{1/2}$). These ratios are slightly higher than those of passive margin greywackes (c. 0.29) but lower than those of passive margin sandstones involving relatively old, reworked continental crust (c. 0.5) (Floyd et al., 1991); (2) The late Triassic sandstones have positive V-Cr-Ni-Sc anomalies and relative depletion of

Ti-Zr-Y, which reflect a relatively low heavy mineral content (mainly zircon); (3) The late Jurassic-early Cretaceous sandstones have positive normalised V-Cr-Ni anomalies (<1) and negative Nb anomalies, compatible with a passive margin setting; and (4) The relative depletions of Ti and Sc are suggestive of a minor mafic source contribution. Taken together, the UCC plots are comparable to those of greywackes from a passive margin setting.

4.2. Northern Cyprus sandstones: Kyrenia Range

4.2.1. Chemical classification

The latest Cretaceous-Miocene sandstones of the Kyrenia Range are characterised by restricted $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios, but highly variable $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios (Fig. 10a), resulting in a classification of mainly litharenites or arkoses. The middle to late Miocene sandstones (Mia Milia (Dağyolu) Formation) have relatively high $\text{Na}_2\text{O}/\text{K}_2\text{O}$ but low $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios and so classify as greywackes. In the Herron scheme (Fig. 10b), the latest Cretaceous-Miocene sandstones are mainly Fe-sand, wacke, litharenite and sublitharenite. In contrast, the middle to late Miocene sandstones (Mia Milia (Dağyolu) Formation) are enriched in ($\text{Al}_2\text{O}_3 > 10$ wt%), resulting in a Fe-shale composition.

4.2.2. Chemical composition and correlations

The Kyrenia Range sandstones have a wide compositional range. SiO_2 varies from 14.7 to 70.2 wt%. The latest Cretaceous sandstones range in Al_2O_3 content from 4.8

603 to 5.2 wt%, whereas Na₂O and K₂O values are typically low (<1 wt%). The middle
604 Eocene sandstone exhibits lower SiO₂, Na₂O and intermediate Al₂O₃, K₂O values. The
605 compositions of the late Eocene sandstones vary. The sandstones from the north of
606 the Kyrenia Range have generally higher concentrations of SiO₂, TiO₂, Na₂O, K₂O and
607 Al₂O₃ but lower CaO compared to those from the south of the range. The late
608 Eocene-Oligocene sandstones are typically enriched in Fe₂O₃+MgO, but depleted in
609 Na₂O (<0.2 wt%). Na₂O is extremely depleted (<0.2 wt%) in the overlying
610 Oligocene-Mid-Miocene sandstones (Panagra (Geçitköy) Formation). Although
611 variable, Al₂O₃ and TiO₂ are relatively depleted. SiO₂ and Na₂O vary widely, together
612 with relative enrichment of Al₂O₃ and K₂O in the middle Miocene sandstones (Trapeza
613 (Esentepe) Formation). The late Miocene sandstones have the highest SiO₂ and K₂O
614 concentrations, together with relative enrichment in Na₂O and Al₂O₃. The middle-late
615 Miocene sandstones (Mia Milia (Dağyolu) Formation) are characterised by relatively
616 high values of TiO₂, Na₂O, Al₂O₃ but low CaO.

617 The trace elements of the latest Cretaceous and the middle Eocene sandstones
618 are similar in terms of high field strength elements and transition metals, whereas
619 large-ion lithophile elements (LILEs) are more varied (Fig. 11a). Minerals enriched in
620 K, Rb, Sr (e.g., microcline, mica), as observed petrographically, can account for these
621 differences (Robertson et al., 2012b, 2014). Higher in the succession, the late Eocene
622 sandstones define an increasingly positive slope in their trace element patterns (Fig.
623 11b). The late Eocene-Oligocene sandstones exhibit variable compositions, with
624 higher abundances of HFSEs and LILEs (compared to transition elements) in the

north of the range compared to the south (Fig. 11b). Spider diagrams are 'smoother' in the overlying Oligocene-early Miocene sandstones (Fig. 11c-d). The middle Miocene sandstones are relatively consistent in composition. 'Troughs' in Nb, Zr and V are present, together with 'spikes' in Th, La, Y, Sr and Ni (Fig. 11e). The middle-late Miocene sandstones also have relatively constant compositions, with positive trace element slope patterns (Fig. 11f). Compared to UCC, all of the sandstones exhibit depletions in LILEs, such as Rb and probably Ba. Strontium is generally depleted, with the exception of middle Miocene sandstones. Zirconium is generally depleted in the middle Miocene sandstones, whereas Zr shows small relative enrichments in some of the Oligocene sandstones. Yttrium contents spike relative to Ba and Zr. Transition elements (e.g., Sc, V, Ni and Cr) are typically enriched in the middle Miocene sandstones with, after an initial decrease, an overall increase upwards in the succession.

On chondrite-normalised plots of REEs, the sandstones show relatively evolved patterns with variable-sized Eu anomalies (0.64-0.95) (Fig. 12). The negative Eu anomalies (<1) are consistent with the enrichment in plagioclase-rich volcanic lithic fragments, as seen in both the latest Cretaceous sandstones (Robertson et al., 2012b) and the Cenozoic sandstones (McCay and Robertson, 2012). The late Miocene sandstones have the most fractionated LREE patterns, with $(La/Yb)_N=10.14-11.08$. The late Eocene-Oligocene sandstones from south of the Kyrenia Range are similar to the other sandstones, but with pronounced REE fractionation and lower REE concentrations.

Most of the formations are separated in the PCA biplot of major elements (Fig. 13a). Sodium is relatively enriched in the sandstones of latest Cretaceous, late Eocene, middle Miocene (i.e., Trapeza (Esentepe) and Davlos (Kaplıca) formations), and also middle-late Miocene ages (i.e., Mia Milia (Dağyolu) Formation). Conversely, Si, P and Mg are relatively enriched in the Oligocene, early Miocene and middle Miocene (i.e., Panagra (Geçitköy) Formation) sandstones. In addition, the late Miocene sandstones are enriched in Ti, Al and K, coupled with depletion in Mn and Ca. Using the PCA (Fig. 13b), which excludes mobile elements and cement-influenced carbonate, a separation of the late Eocene-Oligocene sandstones is possible as the sandstones from the north of the Kyrenia Range are relatively enriched in Si, P, Y, Zr but depleted in Fe, Ni and Cr compared to those from the south of the range. In addition, the late Miocene sandstones from the north of the range are enriched in V, Cr, Fe and Ni compared to those in the south. The late Eocene samples have a relatively consistent composition, with enrichments in Ni, V, Fe and Cr. The middle-late Miocene sandstones (Mia Milia (Dağyolu) Formation) are characterised by enrichments of Al, Ti and V.

4.2.3. Weathering

CIA values vary from the lower to the upper part of the latest Cretaceous-Miocene succession, with an initial general rise and then decrease (Fig. 14a). The latest Cretaceous (Maastrichtian) base of the succession has relatively low (average) CIA values (~60), whereas values in the overlying late Eocene-middle Miocene

668 succession range from 72 to 91. The CIA decreases significantly to 53 in the late
 669 Miocene sandstones, suggesting a lower degree of weathering, perhaps as a result of
 670 a relatively arid source area and/or rapid erosion/deposition. These sandstones,
 671 especially the middle-late Miocene Mia Milia (Dağyolu) Formation (up to 1.6 km thick),
 672 are interpreted as mainly mass-flows and high-density turbidity current deposits
 673 (McCay and Robertson 2012). Also, their lithoclastic nature is consistent with rapid
 674 erosion and transport from source to sink (with little subsequent reworking).

675 CIA values are relatively low in the lower part of the succession; i.e., the late
 676 Eocene-middle Miocene sandstones, from the south of the Kyrenia Range. In contrast,
 677 relatively high CIA values occur in the sandstones in the upper part of the succession;
 678 i.e., the late Miocene Davlos (Kaplıca) Formation, from the north of the range.

679 Na is depleted relative to other mobile elements (e.g., K, Mg, Ca, Rb, Sr and Ba).
 680 $\alpha^{Al}Na$ reaches 49 in the Oligocene, 10 in the early Miocene, but <6 in other
 681 sandstones (see Supplementary material). K and Rb are depleted relative to Ca.
 682 Relative depletion in Ba is moderate; i.e., up to ~3 in both the lower part (latest
 683 Cretaceous-late Eocene) and the upper part (late Miocene) of the succession.
 684 Depletion in Mg and Sr are relatively minor, seldom above 0.6. The following
 685 bulk-sediment mobility sequence is inferred: $\alpha^{Al}Na > \alpha^{Al}Rb > \alpha^{Al}Ba \geq \alpha^{Al}K > \alpha^{Al}Sr > \alpha^{Al}Mg > \alpha^{Al}Ca$. Although the sandstones from the Kyrenia range have notably
 686 high $\alpha^{Al}Na$, the observed, relatively lesser depletions $\alpha^{Al}Ca$, $\alpha^{Al}Sr$ and $\alpha^{Al}Mg$ suggest
 687 that the sediment composition was predominantly influenced by source rock
 688 composition rather than by weathering (e.g., Nesbitt et al., 1980). The main reason for
 689

the compositional differences south and north of the Kyrenia Range are likely to be variable inputs of continental versus igneous (ophiolite-related) rock detritus (McCay and Robertson, 2012).

4.2.4. Sorting and recycling effects

On the ternary diagram of Al_2O_3 -Zr- TiO_2 (Fig. 14b), the latest Cretaceous-Oligocene sandstones have relatively low Zr, but high Al_2O_3 and TiO_2 . Relative enrichment in Zr, but depletion in Al_2O_3 and TiO_2 are recorded in the Oligocene-middle Miocene sandstones, suggesting increased sorting effects upwards in the succession. The middle-late Miocene sandstones are characterised by enrichment of Al_2O_3 and TiO_2 ; these are less well-sorted, as confirmed by optical petrography (McCay and Robertson, 2012).

On the Th/Sc vs. Zr/Sc diagram (Fig. 14c), the sandstones show great compositional variation, with Th/Sc ratios ranging from 0.04 to 0.5. The samples cluster from the compositions of average basalt to andesite, and plot below the average ratio of UCC, suggesting a dominant mafic to intermediate-composition volcanic source. Zr/Sc ratios are relatively low, varying from 0.5 to 14.6, suggesting an absence of significant sediment recycling/zircon concentration (McLennan et al., 1993). This is supported by the similar paleontologically and radiometrically (zircon U-Pb)-determined ages (Chen et al., 2019).

On the La_N/Y_N vs. $\text{SiO}_2/\text{Al}_2\text{O}_3$ diagram (Fig. 14d), the samples have a wide range of La_N/Y_N ratios (0.8-8.0) reflecting marked provenance variation. $\text{SiO}_2/\text{Al}_2\text{O}_3$ is

relatively low (5.1-9.0, average=7.4) in the latest Cretaceous, to late Eocene-Oligocene. The ratio greatly increases to 7.2-20.2 (average=13) in the Oligocene-middle Miocene, then decreases to 3.9-8.0 (average=5.7) in the upper levels of the middle-late Miocene succession. The samples plot to the right of the diagram (Fig. 14d), which is suggestive of increased sorting and recycling in this direction (Roser and Korsch, 1999). Sorting and recycling processes significantly affected the Oligocene-middle Miocene sandstones (Fig. 14b, d), as suggested by the relatively high and constant CIA values (Fig. 14a). Together with the relatively univariable provenance variation (i.e., constant La_N/Y_N), the CIA values are likely to reflect the effects of prolonged weathering.

4.2.5. Provenance indicators

The north-Cyprus (Kyrenia Range) sandstones contain ophiolite-related lithics (see Supplementary material) (McCay and Robertson, 2012; Robertson et al., 2012b, 2014) and therefore, Cr and Ni are useful proxies for ultramafic detritus (Fig. 1). The latest Cretaceous to late Eocene-Oligocene sandstones have relative enrichments in Cr and Ni, high Cr/Ni and Cr/V ratios that are indicative of a mafic and/or ultramafic source (Fig. 15a-c). These sandstones also have significant abundances of lithics derived from ophiolite-related rocks, including basalt, diabase, gabbro and serpentinite. Such lithologies could have been derived from intact ophiolite or accretionary melange (McCay and Robertson, 2012; Robertson et al., 2012b, 2014). On the other hand, the Oligocene-late Miocene sandstones generally have low Cr and Ni values, low Cr/V

but high Th/Ni and Th/Sc ratios, which suggests a relatively high input of felsic components (although some mafic detritus is not excluded) (Fig. 15b-d), in agreement with petrographic evidence (McCay and Robertson, 2012). “Intermediate” Cr and Ni concentrations, elevated Cr/Ni (>2) and Cr/Th (>90) but low Th/Sc (c. 0.1) ratios are observed in the middle-late Miocene sandstones (Mia Milia (Dağyolu) Formation), consistent with an increasing incorporation of mafic rock detritus (Fig. 15c-d), again consistent with the petrographic evidence, including the presence of basaltic rocks (McCay and Robertson, 2012).

The above interpretations are consistent with the available U-Pb detrital zircon age data (Chen et al., 2019). Sparse Turonian-Coniacian (94-87 Ma) zircon grains in the late Cretaceous/Eocene sandstones are similar to the ages of supra-subduction zone ophiolites and related accretionary melange in the region, including southern Turkey (Chen et al., 2019). The abundant Santonian-Campanian-aged zircons in the late Miocene sandstones are also suggestive of a source from subduction-related igneous rocks, particularly granitic rocks in southeast Turkey (Chen et al., 2019). Sporadic zircon with low Th/U ratios (<0.1) in the late Cretaceous/Eocene sandstones could relate to exposures of greenschist-facies metamorphic rocks in southeast Turkey (Chen et al., 2019). In addition, younger zircon grains (16-13 Ma) in middle-late Miocene sandstones (Mia Milia (Dağyolu) Formation) probably relate to air-fall tuff that is exposed locally in the Kyrenia Range (Chen et al., 2019).

4.2.6. Tectonic setting of deposition

The sandstones (20 out of 25 samples) mainly lie in the collisional field of Verma and Armstrong-Altrin (2013) (Fig. 16a), whereas the middle-late Miocene (Mia Milia (Dağyolu) Formation) sandstones plot in the arc field. In contrast, on other multi-dimensional discrimination function diagrams (after Verma and Armstrong-Altrin, 2016), the majority of the samples plot in the passive margin field (Fig. 16b-c). The contrasts in tectonic setting, as implied by the different discrimination diagrams, largely reflect differing crustal influences on the (implied) tectonic setting. Much clastic sediment is likely to have been derived via reworking of Paleozoic passive margin shelf-successions exposed in southern and central Turkey, as inferred for the southwest and south-Cyprus sandstones (see above).

5. Regional geological development

5.1. Triassic-early Cretaceous

Prior to the late Permian, the easternmost Mediterranean region formed part of the northern margin of Gondwana (Robertson and Woodcock, 1979, 1986; Şengör, 1984; Robertson et al., 2012a, b; Chen et al., 2019). Continental breakup took place during the late Permian-early Mesozoic, followed by opening of the Southern Neotethys (e.g., Robertson and Dixon, 1984; Şengör, 1984; Stampfli and Borel, 2002; Barrier et al., 2018) (Fig. 17a-b). The mixed clastic-carbonate facies of the Mamonia Complex,

southwest Cyprus (Lapierre, 1975; Robertson and Woodcock, 1979; Torley and Robertson, 2018), and the detached sandstone blocks in the Moni Melange, southern Cyprus (Robertson, 1977) are interpreted as remnants of the South Neotethyan passive margin. Other tectonically emplaced remnants include similar marine facies in southern Turkey (Antalya Complex) (Robertson and Woodcock, 1982; Robertson et al., 2019b); southeast Turkey (Adiyaman area) (Robertson et al., 2016) and north Syria (Baer-Bassit) (Delaune-Mayère, 1984; Al-Riyami and Robertson, 2002) (Fig. 2). The extra restoration of the Mamonia Complex is debateable (Torley and Robertson, 2018). However, the likely source was recycling from Paleozoic successions, as exposed in one or more of the most southerly microcontinental units, for example the Alanya Massif, generally to the north or the Tahtahlı Dağ (Kemer Zone; Antalya Complex), generally to the northwest (Figs. 2, 17a-b). These units were located to the south of a deep-water rift or small ocean basin (Robertson, 2000; Çetinkaplan et al., 2016; Robertson et al., 2019b) that separated such crustal fragments from the main Tauride continental block to the north.

The regional geological evidence overall supports a passive margin setting for the late Triassic and the early Cretaceous sandstones, as follows:

(1) The sandstones were ultimately derived from felsic-dominated source rocks; i.e., andesitic to granitic. Suitable source rocks include late Precambrian-Cambrian low-grade meta-sedimentary rocks and felsic volcanic rocks, as exposed in the Precambrian inliers of Anatolia (e.g., Sultan Dağ) (Göncüoğlu and Kozlu, 2000; Gürsu et al., 2004; Mackintosh and Robertson, 2012) (Figs. 2, 17a). Precambrian clastic

material appears to have been reworked into Ordovician-Permian shelf sands that accumulated along the northern margin of Gondwana (Ustaömer et al., 2019; Chen et al., 2019);

(2) The source material shows increased weathering effects from the late Triassic to the late Jurassic-early Cretaceous, probably under oxidizing, tropical conditions. Carbonate-siliciclastic facies changed between the late Triassic and the late Jurassic-early Cretaceous, consistent with a shift towards a relatively humid climate (Berra, 2012) along the near-equatorial northern margin of Gondwana (0-30° S);

(3) Sorting and recycling effects (polycyclic origin) increased over the same time interval. The late Triassic sandstones are mainly deep-water turbidites and some mass-flow-deposits that were rapidly deposited without much reworking (Robertson and Woodcock, 1979; Torley and Robertson, 2018). Their input reflects continental rifting in southern Turkey followed by regional passive margin development (Robertson and Woodcock, 1982; Barrier et al., 2018; Ustaömer et al., 2019; Robertson et al., 2019b).

The late Jurassic-early Cretaceous sandstones mainly accumulated in response to mass-flow and turbidity-current processes (e.g., gravity-controlled sand flow). High-energy sorting took place in a shallow-marine, or more likely aeolian setting, followed by redeposition into a proximal but relatively deep-marine setting (Robertson and Woodcock, 1979; Torley and Robertson, 2018). Passive margin conditions largely persisted during this time interval although there are hints of tectonic re-activation in the form of localised alkaline magmatism in the Mamonia Complex (Chan et al., 2008)

and renewed rifting in the Levant (Homberg and Bachmann, 2010; Robertson et al., 2012a). The late Jurassic-early Cretaceous sandstones, therefore, experienced greater reworking than the late Triassic sandstone, in agreement with the chemical indicators;

(4) The tectonic discrimination of the late Triassic sandstones suggests a continental collision setting, changing to a rift/passive margin setting by the late Jurassic-early Cretaceous (Fig. 9). The latter setting is consistent with the regional geology (see above), whereas the former appears to be inconsistent. However, this can be explained by chemical inheritance from the pre-existing tectonic setting. The late Triassic sandstones were largely derived from source rocks that experienced late Pan-African collisional amalgamation, which included regional-scale plutonism and continental margin arc magmatism (e.g., Gürsu and Göncüoğlu, 2006, 2008; Avigad et al., 2016; Ustaömer et al., 2019).

5.2. Latest Cretaceous-Neogene

The Kyrenia Range of northern Cyprus formed part of a subsiding carbonate platform, as part of the South Neotethyan continental margin, during the late Triassic-Cretaceous (Baroz, 1979; Robertson and Woodcock, 1986; Robertson et al., 2012a) (Fig. 17a-b). During the late Cretaceous, Southern Neotethys began to subduct northwards beneath continental crust in southern Turkey (Robertson and Dixon, 1984; Robertson et al., 2012b; Çetinkaplan et al., 2016; Barrier et al., 2018) (Fig. 17c). The Kyrenia Range thereby became part of the northerly active continental

margin of Southern Neotethys until collision during the late Miocene (Robertson et al., 2012a, b; McCay and Robertson, 2012), then Pleistocene uplift (Palamakumbura et al., 2016). The main source of the late Cretaceous-late Miocene sandstones was the Tauride thrust belt that extends across southern and southeast Turkey (Robertson et al., 2012a, b; McCay and Robertson, 2012; Chen et al., 2019) (Fig. 17c-e). The Kythrea (Değirmenlik) Fault, which today delineates the southern margin of the Kyrenia Range (near-basal thrust), was activated during the middle Miocene, creating sub-basins on either side of this lineament (McCay and Robertson, 2013). The resulting topographic ridge favoured the deposition of compositionally different sands on either side of this feature (McCay, 2010; McCay and Robertson, 2012).

The chemical evidence supports and adds to the following inferences for the latest Cretaceous-Miocene regional geology:

(1) The compositions of middle to late Miocene sandstones differ on both sides of the inferred E-W topographic ridge in the Kyrenia Range, with the more northerly sands being enriched in felsic detritus whereas the southerly ones are enriched in mafic detritus. Relatively the quartz-rich sands in the northerly sub-basin were mainly derived from continental and/or cover sedimentary rocks. In contrast, the more lithic-rich sands in the southerly sub-basin were preferentially derived from igneous rocks, as widely exposed in the South Neotethyan suture zone of southeast Turkey (see below);

(2) Low sorting and low weathering effects characterise the late Eocene and the middle-late Miocene sandstones. Low sorting can be explained by the dominance of

mass-flow or high-density turbidite deposition during both of these time intervals (McCay and Robertson, 2012; Robertson et al., 2014). The low weathering signal is consistent with deposition soon after major tectonic events changed the surface topography and thus weathering and erosion in the source area. The Oligocene-middle Miocene sandstone plots indicate significant sorting effects and the highest CIA values (Fig. 14), consistent with 'normal' input from mainly felsic (continental) rocks. Deposition took place in a deep-water basin or trench related to northward subduction (McCay and Robertson, 2012). The middle-late Miocene sandstones show an increased input from emplaced mafic/ultramafic ophiolite-related rocks (McCay and Robertson, 2012), as indicated by the sandstone plots (Fig. 15);

(3) The chemical discrimination (e.g., Fig. 16) points to derivation from several different tectonic settings. For example, the inferred arc setting in the late Miocene sandstones (Fig. 16a) is consistent with the presence of petrographically observed mafic detritus that was derived from ophiolitic bodies and/or related melange, as exposed in the Taurides (e.g., Mersin ophiolite, Adana region; Berit ophiolite, Kahramanmaraş region) (Figs. 2, 17c). Also, the passive margin setting inferred for the late Eocene to middle Miocene sandstones is consistent with the erosion of km-thick shelf successions that include Paleozoic-early Mesozoic siliciclastic sediments, as exposed in the Taurides, and also Triassic-Cretaceous shallow-water platform carbonate, as exposed in the Kyrenia Range (see Supplementary material for e.g., detrital carbonate contents);

(4) The paleocurrent data from the late Eocene-late Miocene turbidites in the

881 Kyrenia Range indicate southerly flow (from southern Turkey) during the late
882 Eocene-Oligocene (Fig. 17d). The late Eocene sandstones accumulated soon after
883 final collision-related thrusting in southern Turkey (Şengör and Yılmaz, 1981;
884 Pourteau et al., 2010; Barrier et al., 2018) and southward thrusting in the Kyrenia
885 Range (Baroz, 1979; Robertson and Woodcock, 1986; Robertson and Kinnaird, 2016).
886 However, the provenance is likely to have included Cadomian basement/cover,
887 Permian-Triassic rift-related sedimentary and igneous rock, Jurassic-Cretaceous
888 passive margin sediments and late Cretaceous ophiolite-related rocks, as widely
889 exposed in southern Turkey. The source areas could possibly also have included
890 clastic sediment from a more northerly oceanic basin (e.g., Mersin ophiolite and
891 melange) (Fig. 17c-d). The paleocurrents switched to westerly flow during the
892 middle-late Miocene (McCay, 2010; McCay and Robertson, 2012) (Fig. 17e). These
893 sandstones accumulated during and after suturing of the Southern Neotethys in
894 southeast Turkey, which was accompanied by regional-scale southward thrusting
895 (Yalçın and Görür, 1984; Aktaş and Robertson, 1984; Yılmaz, 1993; Williams et al.,
896 1995; Robertson et al., 2004, 2006; Barrier et al., 2018). Suturing was followed by
897 post-suture tightening, exhumation and surface uplift (Okay et al., 2010; Radeff et al.,
898 2017). During the middle to late Miocene, the provenance was therefore mainly from
899 the east/northeast, from thrust sheets including ophiolites, as exposed extensively in
900 the South Neotethyan suture zone in southeast Turkey (Robertson et al., 2004;
901 McCay and Robertson, 2012).

6. Conclusions

We have presented and discussed a step-wide methodology (user's guide) for the description and interpretation of whole-rock chemical data for sandstones. This is most effective for areas where it builds on a large body of existing field and laboratory evidence. We have then applied the user's guide to a specific example (case history) of Mesozoic-Cenozoic sandstones in the development of the Southern Neotethys ocean in Cyprus. The resulting body of interpretation add significantly to understanding of the regional geological development, such that we advocate more routine application of the chemical methods involved.

For the Cyprus sandstones:

- Weathering process greatly influenced the composition of the late Triassic and late Jurassic-early Cretaceous southern Cyprus sandstones (Mamonia Complex and Moni Melange).
- Temporally increased weathering and sediment recycling/sorting, together with a general felsic-dominated origin are inferred for the late Triassic and the late Jurassic-early Cretaceous.
- Intensive and/or prolonged source-area weathering is indicated for the late Cretaceous to late Eocene-Oligocene sandstones in the Kyrenia Range, northern Cyprus.
- In contrast, the chemical indices for the Oligocene to Miocene sandstones are consistent with rapid weathering, transport and deposition (without much reworking) as turbidity currents and/or mass-flow deposits.

● Relatively high degrees of sorting are recorded in the Oligocene-middle Miocene sandstones, consistent with dominant accumulation from suspension flows (turbidity currents).

● The late Eocene-late Miocene sandstones have relatively abundant felsic material of 'normal' continental crust origin (with probable admixture of mafic detritus), which is consistent with accumulation in a subduction trench setting. In contrast, the late Cretaceous to late Eocene-Oligocene sandstones have an increasing mafic-ultramafic ophiolite-related detrital input, related to a source of emplaced ophiolite-related rocks, which, taking account of paleocurrent data, can be linked with the South Neotethyan suture zone of southeast Turkey.

● The sandstone compositions represent the combined influences of late Precambrian-Cambrian collision/amalgamation of Cadomian basement, and then deposition in continental shelf (Ordovician-early Permian), rift (late Permian-early Jurassic), passive margin (late Triassic-early Cretaceous) (interrupted by a pulse of crustal extension), active margin (late Cretaceous-Oligocene) and finally diachronous continental collision settings (late Miocene-Recent in Cyprus).

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1446 Listing of Figures

1447 Fig. 1. Flowchart showing suggested steps in the description and description of
1448 whole-rock chemical data for sandstones, including key plots and methods that can
1449 be used at individual steps.

1450

1451 Fig. 2. Outline tectonic map of the Eastern Mediterranean region, including the main
1452 tectonic units mentioned in the text. Tectonic framework is modified from Robertson et
1453 al. (2012a). Note the locations of Mamonia Complex (southwest Cyprus), the Moni
1454 Melange (southern Cyprus) and the Kyrenia Range (northern Cyprus) in Cyprus (red
1455 box).

1456

1457 Fig. 3. Stratigraphy of the Mamonia Complex (southwest Cyprus), the Moni Melange
1458 (southern Cyprus) and the Kyrenia Range (northern Cyprus). Main sources of
1459 information: Robertson and Woodcock (1979), Robertson (1977); and McCay and
1460 Robertson (2012). The positions of the sandstones analysed in this study are marked
1461 by red stars.

1462

1463 Fig. 4. Comparative chemical plots for the sandstones analysed: late Triassic
1464 (Vlamborous Formation); late Jurassic-early Cretaceous of the Mamonia Complex
1465 (Episkopi Formation, including Akamas Member), southwest Cyprus; also early
1466 Cretaceous sandstone of the Moni Melange (Pareklisia Member), southern Cyprus. (a)
1467 $\text{Na}_2\text{O}/\text{K}_2\text{O}$ versus $\text{SiO}_2/\text{Al}_2\text{O}_3$ discrimination diagram (after Pettijohn et al., 1972); (b)

1468 $\text{Fe}_2\text{O}_3/\text{K}_2\text{O}$ versus $\text{SiO}_2/\text{Al}_2\text{O}_3$ diagram (after Herron, 1988).

1469

1470 Fig. 5. (a, b) Selected major and trace element concentrations for the late Triassic
1471 (Vlamborous Formation) and the late Jurassic-early Cretaceous (Episkopi Formation,
1472 including the Akamas Member) sandstones of the Mamonia Complex, southwest
1473 Cyprus; also early Cretaceous sandstone (Pareklisia Member) of the Moni Melange,
1474 southern Cyprus, normalised to upper continental crust (UCC). The normalising
1475 values are from Rudnick and Gao (2003), and Hu and Gao (2008); (c, d) REE
1476 concentrations, normalised to chondrite; normalising values from Taylor and
1477 McLennan (1985).

1478

1479 Fig. 6. Binary compositional plots for the late Triassic (Vlamborous Formation) and the
1480 late Jurassic-early Cretaceous (Episkopi Formation, including Akamas Member)
1481 sandstones of the Mamonia Complex, southwest Cyprus; also early Cretaceous
1482 sandstone (Pareklisia Member) of the Moni Melange, southern Cyprus. (a) The first
1483 two principal components of the principal component analysis (PCA) based on the
1484 centred log-ratio (clr)-transformed concentrations of the major and trace elements; (b)
1485 The first and second principal components of the PCA are based on the
1486 clr-transformed concentrations of a subset of the elements that is assumed to be less
1487 affected by diagenesis and leaching (e.g., Nesbitt and Young, 1984; Bhatia and Crook,
1488 1986).

1489

Fig. 7. (a) Ternary diagram (after Nesbitt and Young, 1984) of molecular proportions of Al_2O_3 -($\text{CaO}^*+\text{Na}_2\text{O}$)- K_2O for the late Triassic (Vlamborous Formation) and the late Jurassic-early Cretaceous (Episkopi Formation, including Akamas Member) sandstones of the Mamonia Complex, southwest Cyprus; also the early Cretaceous sandstone (Pareklisia Member) of the Moni Melange, southern Cyprus. Black arrow indicates the general weathering trend (McLennan et al., 1993), and the brown arrow diagenetic K-metasomatism (smectite-illite transformation; Fedo et al., 1995). Open/solid boxes represent compositions of various rock types (McLennan et al., 1993); (b) Different mobility of diverse alkali and alkaline-earth metals in the above sandstones; α values are normalised to UCC (Rudnick and Gao, 2003; Hu and Gao, 2008); (c) Ternary Al_2O_3 -Zr- TiO_2 plot for the same sandstones (after Garcia et al., 1991); the post-Archean Australia Shale (PAAS) data are from McLennan et al. (1993). Blue arrow shows possible sorting effects (Garcia et al., 1991); (d) Th/Sc vs. Zr/Sc diagram (after McLennan et al., 1993). Black solid circles indicate the average compositions of granite, andesite and basalt (after Condie, 1993). Grey square represents the average compositions of UCC (Rudnick and Gao, 2003; Hu and Gao, 2008). The purple arrow indicates compositional variations and the green arrow sedimentary recycling effects (i.e., zircon addition).

Fig. 8. Comparative plots for provenance discrimination for the late Triassic (Vlamborous Formation) and the late Jurassic-early Cretaceous (Episkopi Formation, including the Akamas Member) of the Mamonia Complex, W Cyprus; also the early

1512 Cretaceous sandstone (Pareklisia Member) of the Moni Melange, southern Cyprus. (a)
1513 Ternary plot of La-Th-Sc. The values of potential source rocks (grey squares) are from
1514 McLennan and Taylor (1984); (b) La/Th vs. Hf diagram (after Floyd and Leveridge,
1515 1987). See text for explanation.

1516

1517 Fig. 9. Tectonic discriminations for the late Triassic (Vlamborou Formation) and the
1518 late Jurassic-early Cretaceous (Episkopi Formation, including Akamas Member)
1519 sandstones of the Mamonia Complex, southwest Cyprus; also the early Cretaceous
1520 sandstone (Pareklisia Member) of the Moni Melange, southern Cyprus. (a)
1521 Multi-dimensional diagram for the low-silica ($35\% < \text{SiO}_2 < 63\%$) and (b) the high-silica
1522 ($63\% < \text{SiO}_2 < 95\%$) sandstones (after Verma and Armstrong-Altrin, 2013); (c, d)
1523 Multi-dimensional discriminant function diagrams for active vs. passive margin
1524 settings; after Verma and Armstrong-Altrin (2016); (e) UCC-normalised multi-element
1525 patterns for average sandstone compositions; also for greywacke (averaged) from
1526 different tectonic environments (after Floyd et al., 1991). UCC-normalising values
1527 from Rudnick and Gao (2003) and Hu and Gao (2008).

1528

1529 Fig. 10. Binary compositional plots for the latest Cretaceous-late Miocene sandstones
1530 from the Kyrenia Range, northern Cyprus. The formations from which the sandstones
1531 were collected are listed below. (a) $\text{Na}_2\text{O}/\text{K}_2\text{O}$ versus $\text{SiO}_2/\text{Al}_2\text{O}_3$ discrimination
1532 diagram (after Pettijohn et al., 1972); (b) $\text{Fe}_2\text{O}_3/\text{K}_2\text{O}$ versus $\text{SiO}_2/\text{Al}_2\text{O}_3$ diagram (after
1533 Herron, 1988). Open symbols represent samples from the northerly sub-basin (north

of the Kyrenia Range); filled symbols represent samples from the southerly sub-basin (south of the Kyrenia Range).

Fig. 11. Upper continental crust (UCC)-normalised spider plots for the latest Cretaceous-late Miocene sandstones from the Kyrenia Range. The formations from which the sandstones were collected are listed below (data from Rudnick and Gao, 2003; Hu and Gao, 2008). The element order is after Condie et al. (1992).

Fig. 12. Chondrite-normalised REE spider plots for the latest Cretaceous-late Miocene sandstones from the Kyrenia Range. The formations from which the sandstones came are listed.

Fig. 13. Binary compositional plots for the latest Cretaceous-late Miocene sandstones from the Kyrenia Range. The formations from which the sandstones are derived are listed below. (a) The first two principal components of the PCA based on the clr-transformed concentrations of the major and trace elements; (b) The first and second principal components of the PCA are based on the clr-transformed concentrations of a subset of the elements that is assumed to be less affected by diagenesis and leaching.

Fig. 14. Comparative plots indicating possible weathering, sorting and recycling effects for the latest Cretaceous-late Miocene sandstones from the Kyrenia Range.

The formations from which the sandstones came are listed below. (a) Al_2O_3 -($\text{CaO}^*+\text{Na}_2\text{O}$)- K_2O ternary diagram (after Nesbitt and Young, 1984). Black arrow indicates general weathering trend (McLennan et al., 1993) and the brown arrow diagenetic K-metasomatism (i.e., smectite-illite transformation) (Fedo et al., 1995). Open/solid boxes represent compositions of various rock types (McLennan et al., 1993); (b) Ternary Al_2O_3 -Zr- TiO_2 plot (after Garcia et al., 1991). Blue arrow represents possible sorting effects; (c) Th/Sc vs. Zr/Sc diagram (after McLennan et al., 1993). Black solid circles indicate the average compositions of granite, andesite and basalt (after Condie, 1993). Grey square represents average compositions of UCC (Rudnick and Gao, 2003; Hu and Gao, 2008). Purple arrow indicates compositional variations; green arrow indicates sedimentary recycling (zircon addition) effects; (d) $\text{La}_\text{N}/\text{Y}_\text{N}$ vs. $\text{SiO}_2/\text{Al}_2\text{O}_3$ plot (after Roser and Korsch, 1999). Purple arrow indicates compositional variations and the green arrow sedimentary sorting and recycling effects.

Fig. 15. Discrimination diagrams to identify ultramafic-mafic-felsic provenances for the latest Cretaceous-Late Miocene sandstones from the Kyrenia Range. The source formations are listed below. (a) Cr vs. Ni diagram. High concentrations of Cr (>150 ppm) and Ni (>100 ppm), together with Cr/Ni ratios (1.3-1.5; grey shaded) are indicative of ultramafic provenance; Cr/Ni ratios (>2; orange arrow) typify input of mafic volcanic rocks (Garver et al., 1996); (b) Cr/V vs. Y/Ni diagram (after McLennan et al., 1993). Red arrow represents possible mafic or ultramafic sources; (c) V-Ni-Th

plot (after Bracciali et al., 2007). Black shaded areas represent the compositions of the felsic, mafic and ultramafic rocks; (d) Th/Sc vs. Cr/Th diagram (after Taylor and McLennan, 1985). Grey arrow indicates a felsic provenance and the orange arrow an input of mafic volcanic rocks.

Fig. 16 Tectonic discrimination for the latest Cretaceous-late Miocene sandstones from the Kyrenia Range. The formations from which the sandstones are derived are listed below. (a) Multi-dimensional tectonic discrimination diagram for settings with $35\% < \text{SiO}_2 < 63\%$ (after Verma and Armstrong-Altrin, 2013); (b, c) Multi-dimensional discriminant function diagrams to separate active vs. passive margin settings (after Verma and Armstrong-Altrin, 2016).

Fig. 17. Plate tectonic sketch maps showing the development of the easternmost Mediterranean during late Triassic-late Miocene, simplified from Robertson et al. (2012a). (a) late Triassic; (b) late Jurassic-early Cretaceous; (c) latest Cretaceous; (d) middle Eocene; and (e) middle Miocene. The likely source and transport directions of the sandstones studied chemically are indicated, based on available geological evidence. The chemical data allow a better understanding of provenance, weathering, transport, deposition and diagenesis but cannot by themselves be used to create such detailed plate tectonic reconstructions.

1599 Listing of Tables

1600 Table 1. Weathering indices derived for the sandstones analysed.

1601

1602 Listing of Supplementary material

1603 Supplementary Table 1. Major element oxides, trace elements and rare earth
1604 elements for the sandstones analysed from Cyprus.

1605 Supplementary Table 2. Petrographic summary of the related sandstones analysed
1606 from Cyprus.

1607 Supplementary Table 3. Range of elemental ratios of the sandstones analysed from
1608 Cyprus, compared to the corresponding range of ratios in sediments derived from
1609 felsic and mafic rocks.

1610

Highlights

- User's guide to interpret sandstone chemical composition
- Weathering, sorting and recycling effects identified
- Provenance variation linked to different sources in southern Turkey

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● late Triassic Vlamboouros Formation

● late Jurassic-early Cretaceous Episkopi Formation

● late Jurassic-early Cretaceous Akamas Member (Episkopi Formation)

● early Cretaceous Pareklisia Member

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- latest Cretaceous Kiparisso Vouno (Alevkaya Tepe) Mbr. ○ middle Eocene Kalograia Ardana (Bahçeli–Ardahan) Fm. ○ late Eocene Kythrea (Büyüktepe) Conglomerate
☆ late Eocene-Oligocene Bellapais (Beylerbeyi) Fm. + Oligocene Klepini (Arapköy) Fm. × early Miocene Flamoudi (Tirmen) Fm.
★ middle Miocene Panagra (Geçitköy) Fm. ▽ middle Miocene Trapeza (Esentepe) Fm. ○ late Miocene Davlos (Kaplıca) Fm. ◆ middle to late Miocene Mia Milia (Dağyolu) Fm.

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- latest Cretaceous Kiparisso Vouno (Alevkaya Tepe) Mbr.
- middle Eocene Kalograia Ardana (Bahçeli–Ardahan) Fm.
- late Eocene Kythrea (Büyüktepe) Conglomerate
- ★ late Eocene-Oligocene Bellapais (Beylerbeyi) Fm.
- + Oligocene Klepini (Arapköy) Fm.
- × early Miocene Flamoudi (Tirmen) Fm.
- ◇ middle Miocene Panagra (Geçitköy) Fm.
- ◇ middle Miocene Trapeza (Esentepe) Fm.
- ◇ late Miocene Davlos (Kaplıca) Fm.
- ◇ middle to late Miocene Mia Milia (Dağyolu) Fm.

Fig. 14

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Fig. 17

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a late Triassic

b late Jurassic-early Cretaceous

c latest Cretaceous (Maastrichtian)

d middle Eocene

e middle Miocene

- AR Arabia
- C Cyprus (general area)
- ER Eurasia
- ES Eratosthenes Seamount
- NA North Africa
- SNT Southern Neotethys (ocean)
- TA Tauride continental unit
- ▲ Subduction zone
- △ Regional thrust zone
- + Spreading axis
- Transform and strike-slip zone
- ← Clastic sediment supply to N&S Cyprus
- Continental crust
- Oceanic crust
- Ophiolitic rocks

Table 1
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Index	Formula	Reference
CIA	$\text{Al}_2\text{O}_3/(\text{Al}_2\text{O}_3+\text{CaO}^*+\text{Na}_2\text{O}+\text{K}_2\text{O})\times 100$	Nesbitt and Yound (1982)
CIX	$\text{Al}_2\text{O}_3/(\text{Al}_2\text{O}_3+\text{Na}_2\text{O}+\text{K}_2\text{O})\times 100$	Garzanti et al. (2014a, b)
CIW	$\text{Al}_2\text{O}_3/(\text{Al}_2\text{O}_3+\text{CaO}^*+\text{Na}_2\text{O})\times 100$	Harnois (1988)
PIA	$(\text{Al}_2\text{O}_3-\text{K}_2\text{O})/(\text{Al}_2\text{O}_3+\text{CaO}^*+\text{Na}_2\text{O}-\text{K}_2\text{O})\times 100$	Fedo et al. (1995)
WIP	$(\text{CaO}^*/0.7+2\text{Na}_2\text{O}/0.35+2\text{K}_2\text{O}/0.25+\text{MgO}/0.9)\times 100$	Parker (1970)
$\alpha^{\text{Al}}\text{E}$	$(\text{Al}/\text{E})_{\text{sample}}/(\text{Al}/\text{E})_{\text{UCC}}$, being E a mobile element (Ca, Na, K, Rb, Sr or Ba)	Garzanti et al. (2013a, b)

Note: CaO* is the amount of CaO incorporated in the silicate fraction of the rock.

Supplementary Table 2

[Click here to download Supplementary material for on-line publication only: Supplementary Table 2.xlsx](#)

Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: