Geomorphological maps are crucially important in geomorphology studies, allowing the representation of topographic and geological data in an interpretative, dynamic and appealing way. In this paper, a medium-scale (1:70,000) geomorphological map is presented with the objective of facilitating the analysis and interpretation of the Plio-Quaternary landscapes of the Arrábida Chain, central-west Portugal. The map results from the combination of field and laboratory techniques, including aerial-photo interpretation, digital terrain data analysis and the morphometric study of landforms.

Keywords: geomorphological mapping; landscape evolution; Pliocene-Quaternary; Arrábida Chain; Portugal

1. Introduction
Geomorphological maps have been used in different fields of study and have proven to be crucial tools for the study of short and long-term landscape evolution (e.g. Pavlopoulos et al., 2007; Walstra, Heyvaert, & Verkinderen, 2010). Over the last decade significant developments have occurred in geomorphological mapping techniques through the increasing use of geographic information systems (GIS) and widespread availability of high-resolution, low-cost elevation data and satellite imagery (Napieralski, Barr, Kamp, & Kervyn, 2013). It is now possible to combine different methods and tools so that comprehensive geomorphological maps are generated, which may be validated by means of both GIS-based geomorphometry and field surveys.

In this paper a geomorphological map at a scale of 1:70,000 is presented, that focuses on the Plio-Quaternary landscape evolution of the Arrábida Chain, which is located in central-west Portugal. Geomorphological maps have accompanied most geomorphological studies of the Arrábida Chain performed over the last 30 years. These have been compiled, not only for particular sectors of the chain itself, but have also concentrated on specific geomorphological features (Alcoforado, 1981; Daveau & Azevedo, 1980–81; Pereira, 1988; Pereira, Borges, Soares, Santos, & Neves 2007; Regnauld, Fournier, & Ramos Pereira, 1995). Nevertheless, the Arrábida Chain lacks complete geomorphological coverage.
The main objectives of this paper are: (I) to contribute to the knowledge of the Plio-Quaternary tectonic geomorphology of the Arrábida mountain range by focusing attention on the identification of tectonically driven landforms; (II) to perform landform and drainage network analysis in order to detect the influence of tectonics on landscape evolution; (III) to create a geomorphological map for the chain that integrates information obtained by and extracted from photo-interpretation, field surveys and digital terrain analysis.

2. Methods

The geomorphological map was created through a combination of field surveys, aerial-photo interpretation, digital elevation modelling (DEM) and geomorphometry. The digital database combines published geological and tectonic maps (Kullberg, Kullberg, & Terrinha, 2000; Manuppella, Antunes, Pais, Ramalho, & Rey, 1999), aerial-photos at a scale of 1:25,000 (FAP flight no. 9, 1967 – sheets 453–454, 464 and 465), topographic maps (Carta Militar de Portugal, 1:25,000, number M888 – sheets 453–454, 464 and 465) and a DEM (spatial resolution 10 m) created through the interpolation of contour and point data retrieved from the 1:25,000 maps.

Landform mapping was performed by means of GIS tools. Aerial-photo interpretation allowed precise identification of landforms, particularly the extension of erosion surfaces and morphological anomalies (e.g. lineaments, drainage deflections) possibly connected with tectonic activity. In addition, for reasons of validation and analysis, potential erosion surfaces ($\leq 2^\circ$) were automatically extracted by applying a conditional function to the slope map following the method proposed by Calvet and Gunnell (2008). The obtained map was overlain with a classified DEM (10 m classes) allowing the altitudinal classification of each erosion surface through histogram analysis and the identification of local anomalies representing probable tectonic deformation (Jordan, 2003).

Tectonic control on topography was also evaluated by performing aggregate statistics on a $10 \times 10$ pixel matrix (maximum and minimum altitude, local relief and base level) and through the application of morphometric indices to the main catchments located within the study area (Catchment Asymmetry Index, Keller & Pinter, 2002; Elevation – Relief ratio, Pike & Wilson, 1971). The obtained results were translated into a point map that expresses the local tectonic component of uplift.

The final phase of research concerned map design. The symbols as well as the legend organisation are based on a morphogenetic classification of landforms following the work of Pellegrini et al. (1993) and Tricart (1970): brown – structure and structural landforms; blue – marine landforms and deposits; Red – slope landforms and deposits; green – fluvial landforms and deposits; pink – karst landforms and deposits; yellow – aeolian landforms and deposits; black and grey – anthropogenic landforms. Patterned polygons are used to represent surface deposits and dashed polygons to identify erosion surfaces. With the exception of the Plio-Quaternary deposits, lithological information was not included, as this would compromise map interpretation due to the superimposition of coloured symbols over filled and patched polygons. To allow an integrated analysis of both the geological and geomorphological data, however, a simplified geological map of the Arrábida Chain was placed in the bottom-right corner of the map. All geological data are derived from the work of Manuppella et al. (1999).

The final map was converted to the 1:70,000 scale using a 50 m contour interval with spot elevations. To enhance the topographic contrast of the map a shaded-relief image was placed in the background of the map.

3. Geology and geomorphology of the Arrabida Chain

The Arrábida Chain is a small WSW-ENE trending Alpine orogenic belt of Miocene age, characterised by south verging folds and thrust planes connected to sinistral NNE-SSW and N-S strike-
slip faults. The southern flank of the massif plunges into the Atlantic Ocean through vertical sea cliffs, while the northern flank is connected to the alluvial plain of the paleo-Tagus River, exposing an almost complete sedimentary sequence of north-dipping strata from lower Jurassic to Pliocene is exposed (see main geomorphological map). Although relatively small, being 35 km in length, 7 km in width and with a maximum elevation of 501 m asl, the Arrábida Chain is the best example of the Alpine orogeny in Portugal (Ribeiro et al., 1990).

The main period of deformation of the Arrábida Chain occurred during the middle to upper-Miocene tectonic inversion of Triassic to Mesozoic structures, in response to the convergence between the African and the Eurasian plates (Kullberg et al., 2000). Two stages of ductile-fragile deformation are identified: (1) Burdigalian (17–16 Ma) – uplift and formation of the south-verging Formosinho anticline in response to N-S compression (Antunes, Elderfield, Legoinha, & Pais, 1995); and (2) upper Tortonian (8–7 Ma) – change in the shortening direction from N-S to NW-SE causing uplift in the eastern part of the chain and the formation of the St. Luis anticline (Choffat, 1908). Plio-Quaternary tectonic activity is associated with displacements along both E-W thrust faults and NNE-SSW to NNW-SSE sinistral strike-slip faults, together with a regional tilting towards NNW, in response to both the tectonic subsidence of the Tagus River basin and the uplift of the Arrábida Chain (Manuppella et al., 1999).

The Meso-Cenozoic sedimentation within the chain is characterised by a thick marine-fluvial sequence that reflects the complex tectonic and eustatic history of this sector of the Portuguese margin over the past 250 million years. The lower Jurassic sedimentation is characterised by an evaporitic sequence (i.e. marls and clay), followed by compact, oolitic and coral limestone of middle to upper Jurassic age. The upper Jurassic and Cretaceous deposits present strong lateral facies variations which are related to differences in the depositional environments between the western (marine) and the eastern (fluvial-marine) zones of the chain, where limestones crop out in the former and poorly consolidated sandstone and sandy-limestone in the later. Paleogene and Miocene sedimentation is characterised by coarse-grained conglomeratic deposits that reflect the first stages of uplift of the Arrábida Chain, and by shallow marine sequences (marls and coral limestone), referring to phases of marine transgression (Kullberg, Terrinha, Pais, Reis, & Legoinha, 2006).

Before its establishment along the Tagus gorge, the Tagus River flowed further southwards, reaching the Atlantic Ocean in the vicinity of the Arrábida Chain. Throughout the Pliocene and Pleistocene, sediment accommodation to the north of the chain was controlled by tectonic subsidence in the Tagus plain. As a consequence, Pliocene sedimentation (i.e. Fonte da Telha formation) is characterised by a thick (over 150 m) fluvial sequence, comprising yellow coloured, fine to coarse-grained sand with occasional pebble beds and sandy-clay intercalations (Azevedo, 1982).

The beginning of the Pleistocene is marked by the deposition of the Belverde formation, which signals the final stage of the paleo-Tagus River, before it migrated north and became established along the Tagus gorge. The Belverde formation comprises a poorly consolidated conglomeratic deposit, containing quartz and quartzite rounded pebbles in a sandy matrix (Azevedo, 1982). Pebble fabric within the Belverde formation indicates fluvial deposition in association with the E-W flow of the Tagus River, followed by later pebble reorganisation in response to marine transgression (Azevedo, 1982).

Following the Belverde formation, the Marco Furado formation (middle Pleistocene) is characterised by a medium consolidated heterometric deposit (30–40 m thick), containing angular clasts of quartz, quartzite, jasper, flint and schist within a sandy-clay matrix. Field studies suggest that this formation results from torrential flows exiting the Arrábida Chain through the existing north and southbound fluvial incisions (Azevedo, 1982).
Differences in the resistance of bedrock to erosion played a crucial role in the overall architecture of the Arrábida Chain. Positive relief, namely the Formosinho and St. Luís anticlines and the homoclinal ridges along the northern flank, are associated with outcrops of compact Jurassic, Cretaceous, Paleogene and Miocene limestone, while the main topographic depressions are developed within the Jurassic evaporates – diapiric depression of Sesimbra – and upper Jurassic and Cretaceous poorly consolidated continental sequences (see main geomorphological map).

Tectonic control on topography is expressed by faults scarps along the southern flanks of the Formosinho and S. Luís anticlines, and through tectonic compartments along NNW-SSE faults, which occur perpendicularly to the northern homoclinal ridges. Recent fault activity is evidenced by a vertical offset affecting the Marco Furado formation (Azevedo, 1982), together with relative uplift of the eastern blocks.

Long-term uplift is further expressed in the form of four erosion surfaces (L1 - 190–220 m; L2 - 140–170 m; L3 - 70–110 m; L4 - 30–50 m) that are perched above the present-day drainage network (see main geomorphological map). There are no absolute ages for these erosional surfaces, with current knowledge based on relative dating methods. The age of the uppermost level (L1) (known as the Plataforma do Cabo level) is difficult to determine due to its lack of stratigraphic references (Ribeiro, 1935; Daveau & Azevedo, 1980–81; Cabral, 1993). Nevertheless, the fact that the L1 cuts the northern flank of the St. Luís anticline, suggests a post Tortonian age and possible association with the high sea level stands of upper Miocene and/or Pliocene date: i.e. – from 6 to 5 Ma and/or 3.5 to 2.5 Ma (Dowsett & Cronin, 1990; Miller et al., 2005).

The intermediate surface (L2) descends from the northern edge of the upper level (L1) and towards the top of the homoclinal ridges. Its morphology and lateral extension suggest an association with a degradation phase of L1 connected with a northerly directed flow of surface waters from the higher sector of the chain towards the paleo-Tagus river alluvial plain during upper Pliocene-lower Pleistocene time (Daveau & Azevedo, 1980–81).

The external level (L3) cuts the Pliocene terrain and the Belverde Formation along the northern flank of the Arrábida Chain and is fossilised by the torrential deposits of the Marco Furado formation. The lack of absolute ages for the Belverde (lower Pleistocene) and Marco Furado (middle Pleistocene) formations hinders the definition of a specific timeframe for the L3 event. Furthermore, the unknown thickness of the Belverde formation throughout the northern flank of the Arrábida Chain hampers the attribution of a lower Pleistocene age for L2, since the marine transgression registered in the Belverde formation and the fluvial processes responsible for the deposition of the Marco Furado formation might have modelled the original surface.

The lowest level (L4) represents a degradation of L3 in response to Pleistocene sea level variations, which eventually led to the formation of the Lagoa de Albufeira during the Holocene.

Along the south-central and western sectors of the L1 the Jurassic limestone is highly karstified forming large depressions oriented along fractures and structural bedding. Drainage network incision within the central and eastern sectors of the Arrábida Chain has deeply incised the L1 and L2 following the less competent units of the Upper Jurassic. U-shaped valleys, as well as glacis slopes, are associated with concave valley-slope sections where slope degradation and debris accumulation is notorious.

Geomorphic evidences of uplift along the southern and western sectors of the chain are preserved in the form of uplifted marine terraces. A complete discussion of each level is beyond the scope of this work and further information may be found in Pereira (1988), Regnauld et al. (1995), Manuppella et al. (1999) and Pereira et al. (2007).
4. Conclusion

The combination of a complex tectonic setting within a highly variable lithological context has led to a landscape dominated by tectonic/structural landforms. During Plio-Pleistocene times, the topography of the Arrábida Chain adjusted to sea-level fluctuations and tectonic uplift mainly through drainage network incision.

The definition of three, well-established erosion surfaces emphasises the existence of two possible morphodynamic settings: (I) the presence of phases of increased tectonic uplift (or subsidence in the Tagus basin) followed by periods of tectonic quiescence where erosion prevails; or (II) the presence of steady uplift conditions intercalated by phases of increased erosion. The proximity to the Atlantic Ocean and to the paleo-Tagus alluvial plain suggests that phases of increased erosion might be connected high sea-level stands of the upper-Miocene and Plio-Quaternary. Only the L2 indicates that erosion occurred in association with the northerly directed flow of surface waters.

The geomorphological map presented in this paper is a contribution for the interpretation of the Plio-Quaternary landscape evolution of the Arrábida Chain. An empirical validation of landform location and geometry was obtained through the use of both field and laboratory techniques. The map establishes a baseline that can easily be adapted for various forms of applied geomorphological research (e.g. morphotectonics, geoheritage and geotourism).

Software

The geomorphological map was constructed using both GIS and graphic-design software. Geomorphological data were collected, analyzed and drawn on ArcGis 9.2. Aerial photo-interpretation was performed on Ilwis 3.3 using the ‘Epipolar Stereo-pair’ tool. The final map was designed in Macromedia FreeHand MX.

Map design

Map design aims for a simple, accurate and appealing representation of the geomorphology of the Arrábida Chain following the methodology described in section 2. Taking into account the orientation of the chain we opted for placing map title, authors names and scale info in the top-right corner of the map. Legend is placed in the bottom of the map to allow an easy interpretation and identification of landforms in the map. Coordinate representation is similar to the topographic maps used in this study.

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