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Beth Shaw

Active Tectonics of the Hellenic Subduction Zone

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Active Tectonics of the Hellenic Subduction Zone

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The object of my mission had sufficient interest in itself to excite a feeling of enthusiasm, from an anticipation of future utility, from the opportunity afforded me of studying some of the grander features of nature, and from the varied interests connected with the examination and exploration of a new field.

Thomas A.B. Spratt

Travels and Researches in Crete, 1865

Publications resulting from this thesis

The material described in Chap. 2 has been published as: Shaw et al. 2008, Eastern Mediterranean tectonics and tsunami hazard inferred from the AD 365 earthquake. *Nature Geoscience* 1, 268–276.

The material described in Chap. 3 has been published as: Shaw and Jackson 2010, Earthquake mechanisms and active tectonics of the Hellenic subduction zone. *Geophysical Journal International* doi:10.1111/j.1365-246X.2010.04551.x

The material described in Chap. 4 has been published as: Shaw et al. 2010, Radiometric dates of uplifted marine fauna in Greece: Implications for the interpretation of recent earthquake and tectonic histories using lithophagid dates. *Earth and Planetary Science Letters* 297, 395–404.

Supervisor's Foreword

Beth Shaw's thesis illustrates very well the progress, and unexpected benefits, of curiosity-driven science at its best, ranging widely over diverse fields of endeavour, from earthquake seismology, to coastal geomorphology, elastic dislocation modelling and the implications of marine ecology and biogeochemistry for radiocarbon dating. It is through making connections across such scientific disciplines that our view of the planet we live on can change profoundly. It is not an easy course of research to pursue, and requires determination, and some confidence, to follow clues without even knowing what they are clues to. This approach is not for the specialist who is comfortable only within the well-defined boundaries of a particular professional discipline, yet it is manifestly the way to find out about a planet that is constantly carrying out experiments without the courtesy of informing us first what those experiments are for.

The thesis began with a forensic investigation of a famous catastrophe of the Byzantine world, in which a tsunami destroyed Alexandria, the Nile delta, and other coastal settlements in Sicily and the Adriatic in AD 365. The prime suspect for causing the tsunami was an earthquake in the Hellenic subduction zone, but it was also known that the 40 mm/year convergence between Crete and Libya was mostly accommodated without earthquakes, which can only account for about 10% of the necessary motion. There is nothing particularly unusual about slip without earthquakes, even in other subduction zones, but it is generally thought to be a characteristic of the slip surface itself, which is either dominated by friction (and generates earthquakes) or not. If the Hellenic subduction zone generated occasional earthquakes of magnitude 8 or greater it could evidently behave in both ways, which was a puzzle. Another element in the mystery was the remarkable observation, first recorded by Captain Spratt RN in 1865, that the entire SW corner of Crete had been uplifted by up to 10 m since Roman times, but by what mechanism? Following these clues and resolving these puzzles was the first element of Beth's thesis and, like any reviewer reluctant to give away the plot of a detective story, I will not reveal the answer in this preface. It is sufficient to point out that its discovery involved an unusually broad spectrum of observations, arguments and techniques, including earthquake seismology, GPS, radiocarbon dating, dislocation and tsunami modelling and field observations of geomorphology.

Solving this first mystery of course revealed others. It showed how the convergence between Africa and Crete was accommodated near Crete, and how it was able to generate tsunamis. But what was the tsunami potential of the rest of the arc between the Ionian islands and Rhodes? How do the variations in earthquake mechanisms relate to the motions revealed by GPS measurements? How does the active faulting in the subduction zone connect with that in central Greece, and what happens at the eastern and western ends of the arc? These questions were answered in the second part of the thesis, which involved a re-evaluation of the earthquakes in the entire arc, a major effort in observational seismology, and a close examination of the GPS measurements over the last 10 years. Several important new insights were revealed by this investigation, which represented a step change in clarifying the patterns of earthquakes and what they were telling us.

The final substantial element of the thesis involved an entirely different focus. Having established that SW Crete was indeed uplifted in a single event in AD 365, an outstanding puzzle was why some uplifted marine shells, which must have been killed in that event, gave the 'wrong' age when carbon-dated; usually too old by up to 1,000 years. This was more than a curiosity because the shells concerned are the best and most commonly preserved organisms in uplifted coastlines around much of the Mediterranean and Aegean, and are often used to estimate tectonic uplift rates. The AD 365 uplift event allowed Beth to investigate this effect and discover that it is related to the ecology and mode of life of the shells themselves, which incorporate old (radiocarbon-dead) carbon from host limestone into their shells during growth. Quantification of this effect reveals the limitations of these shells in understanding uplift rates in much wider tectonic contexts than Crete.

Other questions and puzzles have been revealed by this work and remain to be pursued. But the work reported here was substantially completed in 3 years, which is the intended duration of a Ph.D. study, and so a halt had to be called. But it is not a halt to the work's influence: all of it has now been published in professional journals, and I expect it will have an important effect on tectonic studies in the Mediterranean and other subduction zones for some time. No one could ask more of a thesis.

Cambridge, 19 January 2011 James Jackson

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Sincere thanks are due to my supervisor, James Jackson; without him this thesis could not have been written. I am extremely fortunate in having been able to discuss my work with Philip England, Dan McKenzie and Tom Higham, whose comments and advice have dramatically improved this thesis.

The tsunami modelling described here was carried out by Matthew Piggott and colleagues at Imperial College, London. Michael Floyd and Jean-Matthieu Nocquet supplied the GPS measurements that were used extensively in this thesis. Nic Ambraseys is an absolute mine of information concerning the historical record of the Mediterranean, and it was a great pleasure to discuss ancient descriptions of earthquakes with him. Microearthquake data was generously provided by Denis Hatzfeld and Thomas Meier.

Special thanks are also due to Martin Brasier, Norman Charnley, Jill Darrell, Owen Green, Liz Harper, Gideon Henderson, Mathew Lowe, Roberto Portela-Miguez, Richard Preece, Gareth Roberts, Brian Rosen, Alastair Sloan, Paul Taylor, Alex Thomas, Kathie Way, Tim Wright, and the staff of the NERC Radiocarbon centres in Oxford and East Kilbride.

I owe an enormous debt of gratitude to my friends in St John's College and at Bullard Laboratories. My family have been a continual source of support, and have always encouraged me to be curious about the world around me. Finally, my sincere thanks go to my husband, Richard, to whom I dedicate this thesis. Without his constant cheerfulness, encouragement and calm in the face of innumerable minor Ph.D. disasters, this thesis would probably not exist.

Contents

Chapter 1
Introduction

The Hellenic subduction zone plays a key role in the active tectonics of the Mediterranean, yet its tsunamigenic potential and details of its kinematics remain poorly understood. The subduction zone appears to be largely uncoupled, having accommodated just 10% of the Nubia-Aegean convergence in earthquakes in the last 100 years. However, the historical record contains evidence of devastating earthquakes and tsunamis, raising the possibility that the subduction zone interface fails in large magnitude earthquakes with a repeat time that is long compared with the period of observation. The focus of this thesis is an investigation of the kinematics of the region, beginning with a forensic investigation of the AD 365 earthquake, based on evidence found on the island of Crete.

Mesozoic Nubian lithosphere subducts to the North beneath overriding Aegean material in the Hellenic subduction zone (Fig. 1.1). Nubia is moving north towards Eurasia at just 5–10 mm/year, however due to the south-west motion of the Aegean with respect to Eurasia, 35 mm/year must be accommodated across the Hellenic subduction zone [1, 2].

The subducting slab appears as a relatively fast velocity anomaly to depths of at least 600 km [3–5] but is asesimic below 180 km depth [6]. At depth, the slab is almost semicircular in shape because of the highly arcuate trench system, but steepens dramatically from west to east [4, 7–11].

The oceanic Moho of the downgoing African plate can be identified using receiver functions at depths of between 40 and 69 km beneath Crete [11–14]. It is possible to follow this interface to a depth of ∼100 km beneath Santorini [13], or to around 160 km beneath the volcanic arc generally and to 220 km beneath northern Greece [11]. Most receiver function studies recognise a low-velocity region between 20 and 50 km, which has been explained as due either to subjected sediments [12], or as serpentenised Aegean upper mantle [11, 14].

The subduction zone interface is aseismic between the surface and ∼15 km depth [15–17], with shallowly dipping thrust-faulting earthquakes observed at depths of 15–45 km. Such interface events reach a depth of 45 km beneath the SW corner of Crete, approximately 10 km above the receiver function estimates of African Moho

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depths in this area, consistent with the subduction zone interface coinciding with the top of the African oceanic crust.

The surface expression of the subduction zone is obscured by up to 10 km of deformed sediment. No true subduction zone trench can be recognised in the bathymetry, in that the interface fault is probably 'blind', projecting to the surface beneath the Mediterranean Ridge, a thick accretionary prism (Fig. 1.1). The prism is actively deforming and mud-volcanoes, landslides, salt domes and faults can be recognised on its surface [18–22]. The sediments of the accretionary prism contain a number of weak layers, including Messinian salt and Cretaceous shales along which sliding may occur [23, 24]. Bohnhoff et al. [25] carried out a wide-aperture seismic experiment, using a combination of OBS and onshore data. They observed material with the velocity of continental crust, which may be compacted sediments, thinning to the south of Crete to a minimum of 17 km, and observed the contact between this material and oceanic crust ∼100 km south of Crete, beneath the central Mediterranean Ridge.

A clear bathymetric escarpment 3 km deep, known as the Hellenic Trench, runs from the Ionian Islands to the south-west of Crete, splitting into at least three branches south of Crete, and continuing east to Rhodes as the Ptolemy, Pliny and Strabo trenches [18, 26, 27]. The Hellenic Trench is not the surface expression of the subduction interface, but may be a backstop to the accretionary prism.

Crete lies to the north-east of the Hellenic trench, and elevated marine deposits, deeply incised river gorges and the high, recent topography in an area affected by E-W extension suggest that the island has been rapidly uplifted since at least the Middle Miocene. Le Pichon and Angelier [28] suggested that the observed uplift results from sediment underplating. In spite of the great thickness (up to 10 km) of sediment entering the subduction zone, the isotopic composition of igneous material erupted from Santorini and Milos contain almost no sedimentary signature [29, 30], suggesting that the sediments are not subducted to depths at which melting occurs. In a more recent study, Zellmer et al. [31] found that their samples from Santorini could be modelled with the addition of a very small fraction of sediment-derived partial melt to the mantle wedge (0.2–0.4%). The buoyant sediments may be partially scraped off to form the accretionary prism, or subducted to shallow depths beneath Crete until they can be subducted no further, uplifting Crete by crustal thickening.

Despite being the most seismically active region in Europe, just 10% of the expected convergence between Nubia and the southern Aegean has been accommodated by earthquakes during the instrumental record [32]. The seismic deficit could be due to aseismic slip in the subduction zone, or due to the period of observation being short compared to the repeat time of large magnitude earthquakes that accommodate the majority of the convergence. To distinguish between these two possibilities, it is necessary to examine the long and rich historical record of the region. In Chap. 2, I address this question by carrying out a forensic study of the AD 365 earthquake which occurred close to the island of Crete (Fig. 1.1). I suggest that the subduction zone interface is largely aseismic, but that the Hellenic Trench is the surface expression of a splay fault which is capable of producing earthquakes larger

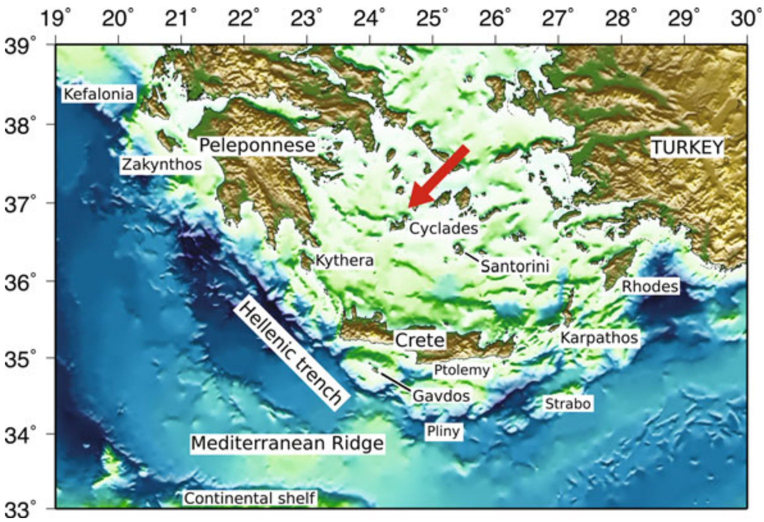

Fig. 1.1 Major topographic and bathymetric features of the Hellenic subduction zone. *Red arrow* represents velocity of the south Aegean relative to the Nubian (North African) plate

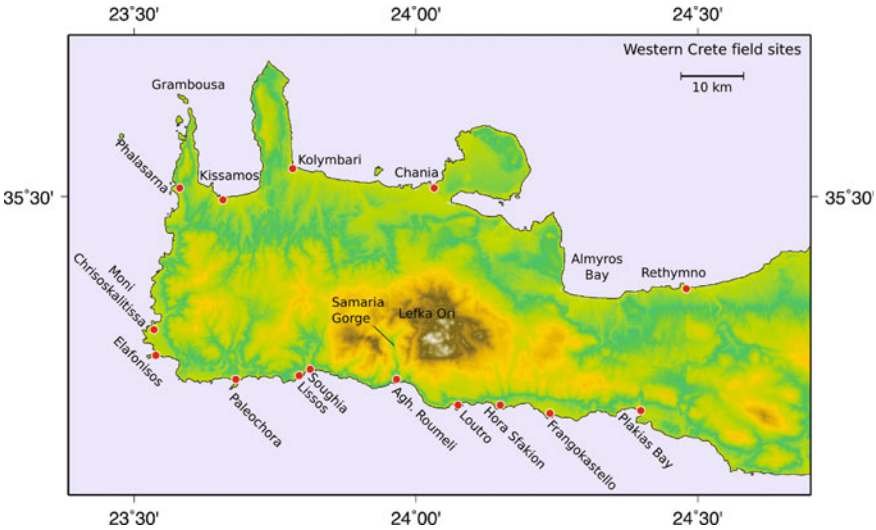

Fig. 1.2 Important field sites and towns in western Crete, referred to throughout this thesis

than magnitude 8 and tsunamis that travel throughout the Eastern Mediterranean, and estimate the approximate repeat time for earthquakes of this magnitude.

Further questions related to the kinematics of the region remain, and in Chap. 3, I use teleseismic waveform modelling to elucidate the structure of the Hellenic subduction zone, focusing in particular on the processes occurring at its ends, and suggest a connection between the Hellenic subduction zone and normal faulting and block rotation in Central Greece.

In Chap. 4, I carry out a detailed study of the utility and reliability of corals, bryozoans and lithophagids for constraining tectonic uplift using radiocarbon dating. This study arose from radiocarbon dates described in Chap. 2 which show that lithophagids may record incorrect uplift dates. In this chapter, I confirm that lithophagid dates are offset from the date of uplift and investigate possible reasons for this offset, discussing colonisation order, preservation potential, and incorporation of detrital carbonate in their shells. This study has important general implications for radiocarbon dating tectonic events.

In order to investigate the potential of topography and geomorphology for constraining the history and configuration of uplift in Crete, I present digital elevation models (DEMs) of uplifted marine terraces and river profiles constructed using kinematic GPS in Chap. 5. I discuss the long term uplift rate of Crete and the accuracy of DEMs constructed in this way. Important field sites, referred to throughout the thesis, are shown in (Fig. 1.2).

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