Structural Investigations/Observations along a Low-angle Normal Fault and their Implication for the Geology on Northwest Kea – Examining a Major Shear Zone

(Western Cyclades, Greece)
View to the area of the Otzias Bay Detachment from the NE.

Kea – a small island south of the Greek mainland.
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Abstract

Detailed geological mapping on the island of Kea (Western Cyclades, Greece) combined with recent structural observations have identified a large-scale low-angle fault system within the (Miocene) extensional regime of the Aegean region. This thesis focuses on a hitherto unrecognised/undescribed brittle-ductile low-angle normal fault in northern Kea, which is part of a domed, normal fault system formed under ductile (calcite) to brittle (dolomite) conditions.

Consistent shear sense indicators within the shear zone, predominantly SC-fabrics and clast geometries give evidence for top-to-SSW sense of movement in contrast to the opposed NNE extension kinematics of the Western Cyclades. Structural investigations on Kea reveal pervasive sub-horizontal foliation and tight to isoclinal, recumbent to moderately inclined folds as well as superposition of fold patterns which lead to the formation of refold structures in the study area. In this work, the tectono- and lithostratigraphy of the island is divided into a footwall and a fault-rock zone.

The footwall is predominantly represented by greenschist-facies chlorite-epidote bearing schists with varying contents of chlorite, quartz, biotite, epidote group minerals, actinolite, muscovite, calcite and opaques (ore) and metabasitic schists intercalated with calcitic mylonitic marbles with thin quartz layers and quartzitic schists/quartzites. Phyllonitic schists and cataclastic schists are observed around marble (mega-) boudins, thought to represent higher strain zones within the footwall unit.

A conspicuous horizon of phyllonites associated with lenses of serpentinite and locally talc-schists, occurring in both the footwall and the ‘hanging-wall’-cataclasite of the fault-rock zone, form the topmost part of the footwall, possibly forming a transition to the fault zone. The fault-rock zone comprises calcitic ultra-mylonitic marble and, as a dominant feature, the ‘hanging-wall’-cataclasite associated with re-mobilised cataclasite. To the top of this sometimes strongly ankeritised dolomite occurs.

In general, early stage extension-related deformation involved ductile processes dominating within the pelitic and calcitic footwall and ductile/brittle conditions dominating within the calcite/dolomitic footwall fault-rock zone.

In later exhumation, a multi-stage (e.g. protracted) brittle fault-system of widely spaced high-angle faults and steeply dipping to sub-vertical hydro-fracture veins (filled either by, ore-rich fluid products, quartz or calcite) developed. These cross-cut the footwall and fault-rock zone lithologies. While the high-angle (sub-horizontal) normal fault system is characterized by two distinctly oriented sets, acting as weakening zones and fluid migration pathways, the sub-vertical hydro-fracture veins predominantly occur in the footwall.

A description of the tectono-/lithostratigraphy allows to place Kea into the greater geodynamic context of the Aegean region/Cyclades.
**Zusammenfassung**

Im Zuge einer detaillierten geologischen Kartierung mit besonderer Berücksichtigung strukturgeologischer Beobachtungen auf der Insel Kea (Westliche Kykladen, Griechenland), wurde ein System von flachen Abschiebungen innerhalb des extensionellen Regimes der Ägäis identifiziert. Diese Diplomarbeit konzentriert sich auf eine im nördlichen Kea bisher unbeschriebene spröd-duktile Abschiebung, die einen Teil eines gewölbten Systems aus Abschiebungen, entstanden unter duktilen (Kalzit) bis spröden (Dolomit) Bedingungen, darstellt.


In dieser Arbeit ist die Tektono- und Lithostratigraphie der Insel in einen Bereich der ‚footwall’ – dem Liegenden, und ‚fault-rock zone’ – einer Zone aufgebaut aus Störungsgesteinen, unterteilt.


Eine Beschreibung der Tektono-/Lithostratigraphie ermöglicht es Kea in einen größeren geodynamischen Zusammenhang mit der Ägäische Raum und den Kykladen zu setzen.
1. Introduction

In the course of this masters (Diploma-) thesis, within the framework of Project ACCEL (see chapter 1.1), a new geological map was compiled. I mapped and examined the north-western edge of the island of Kea. On the basis of measurements taken, samples collected and observations made, a new map and geodynamic model to fit the data is presented.

The Island is dominated by high- and low-angle extensional faults. Our recent studies demonstrated that the Miocene extensional event with consistent and pervasive SW/SSW-directed shear is observed throughout the whole island and has also been documented on Kythnos and Serifos (Western Cyclades).

In NW Kea there is a major low-angle normal fault here termed the Otzias Bay Detachment (OBD); a focus in this study.

1.1 The start-up of Project ACCEL

Project ACCEL - Aegean Core Complexes along an Extending Lithosphere – is represented by an international Team of scientists and students who investigate exhumed brittle-ductile low- and high-angle normal faults on the Islands of Serifos, Kea and Kithnos, all of which are located in the Western Cyclades.

Inducement to the project and motivation to investigate the island of the Western Cyclades in the first place was the fact that the geodynamic history of these is almost unknown. Whereas the Eastern Cycladic islands have seen a range of models evolved and based on detailed investigations, Serifos, Kea and Kithnos lack comprehensive geological data.

Investigations on the island of Serifos in the course of three diploma theses (Iglseder 2005; Zámolyi 2006; Rambousek 2007) gave evidence for a metamorphic core complex associated with at least two (of higher and lower grade) south-directed detachment-type shear zones.

To add to the developed models and seeking to explain the Cenozoic geodynamic history of the Aegean and to round the picture of the entire area we thought it important to look into the geology and tectonics of Kea by means of (re-)mapping (see chapter 3.2), sampling (see tectono-/lithostratigraphy in 3.3), low to high temperature thermogeochronometry/geochronology (see 3.4.3.1) and fault/flow analysis (see chapter 3.4 and 4.1) so as to quantify the so far widely unknown geodynamic history.

Furthermore the geological map of Kea compiled by Davis 1972 had aroused our interest as non-metamorphic rocks on top of metamorphosed units have been mapped which were interpreted by Davis as a thrust-geometry (overthrust) in contrast to the broadly common low-angled normal fault geometries dominating the very well investigated islands of the Eastern Cyclades.

Principal investigator and head of project ACCEL is Dr. Bernhard Grasemann (University of Vienna).

Furthermore international based collaborators are M. Bohnhoff (GFZ Potsdam, Germany), E. Draganits (Vienna University of Technology), D.A. Schneider (University of Ottawa, Canada), D. Stöckli (University of Kansas, USA), A. Kiliais (Aristotle University Thessaloniki, Greece), A. Ganas (National Observatory of Athens, Greece) and P.I. Tsombos (IGME, Greece).

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2. Geological setting – Greece and the Aegean

As part of the greater orogenic belt system, generated from the continental collision of the Eurasian plate with the African, Arabian and Indian plates, Greece and the Aegean region are situated in an area of high seismic activity and in geological timescale ‘recent’ deformation and ongoing geodynamic processes.

2.1 Overview of the geology of Greece and the geodynamic setting of the Cyclades

In the eastern Mediterranean, extending/thinning crust of the greater Aegean region involves a complex interplay of (1) Gulf of Corinth rift-expansion, (2) west- & southward retreat of the Hellenic Trench, (3) westward impingement of the Anatolian Plate, and/or (4) propagation of the Anatolian Fault system into the Aegean. Observable effects of these are: a dramatic rotational pattern of present day surface displacement velocities, intense seismicity, and intensely developed active or ancient fault systems.

Due to the widespread extension/thinning (Lister et al. 1984) and the interplay of the widening Gulf of Corinth in the northwest (e.g. Markis 1978; Bonhoff et al. 2001; Endrun et al. 2005), a retreat of the Hellenic trench system to the south (McKenzie 1970; Angelier et al. 1982; Royden 1993; Papazachos et al. 2000) accompanied by gravitational collapse (e.g. Le Pichon et al. 1995) and associated rotation of back-arc crustal blocks (Walcott & White 1998) fault systems evolved/form within the Aegean Sea causing the formation of metamorphic core complexes (see chapter 2.3) on some island characterised by asymmetric ductile to brittle fault systems (e.g. Lister et al. 1984; Gautier et al. 1993; Jolivet et al. 1994) some of which are intruded by syn-tectonic plutons (Lister & Baldwin 1993; Iglseder 2008) and detachment-like low-angled normal fault geometries (e.g. Lister & Baldwin 1993; Jolivet et al. 1994; Iglseder 2008, see chapter 2.3).

The Aegean (micro-)plate, framed by the Eurasian and Apulian plate in the north and northwest, the Anatolian micro-plate in the northeast and the African plate in the south, is represented by the Attic-Cycladic Crystalline (see chapter 2.2). Evidence for the non-metamorphic cover of the Aegean (micro-)plate is found on continental Greece, the island of Eubia and also in the Cyclades.

Due to the plate tectonic background with the Hellenic subduction zone system and the other features described above, the entire region and geodynamics are dominated by the highest present-day seismic activity in Europe (e.g. Papazachos 1973; Jackson et al. 1992; Papaionnou & Papazachos 2000; Bonhoff et al. 2004; Faccenna et al. 2006) and finds its expression in earthquake activity and known from former times, also in tsunami hazards.
A strong regional rotational component (e.g. Clarke et al. 1998; McClusky et al. 2000; Reilinger et al. 2006) is the result of the southward extension and westward movement plus rotation of the Anatolian region (relative to Europe).

These geodynamic events left an imprint on the Cycladic Islands as seen in the geological expression in rocks revealing metamorphic events.

Within the Aegean region two tectono-metamorphic events are distinguished.

An early metamorphic event - M1 - characterised by blueschist-facies metamorphism in the Eocene (e.g. Dürr et al. 1978; Papanikolaou 1978; Altherr et al. 1982; Lister & Forster 1996; Forster & Lister 2005), later got overprinted by - M2 - greenschist-facies metamorphism in the Late Oligocene to Miocene coeval with the Aegean (post-)orogenic extension (e.g. Jolivet et al. 1998 & 2001; Ring 1999; 2001 & 2003; Gessner et al. 2002). Overprint intensity slightly varies throughout the affected island.

The metamorphic history of the M1 event is locally still present. The blueschist formation, a decompression deformation at 40-80 km depth (e.g. Altherr et al. 1982; Bröcker et al. 1993; Ring & Layer 2003), is present as relicts of blueschists and in some localities glaucophane crop out on the islands of e.g. Serifos, Syros, Sifnos, Tinos, Ios and Milos. There, marbles, metapelites and metabasites underwent a HP/LT blueschist-facies metamorphism.

In terms of structural features associated with M2, is a well developed dynamically recrystallised myonitic foliation and mineral orientations define a lineation. Furthermore several islands host predominantly I-type granitoid plutonism (e.g. Iglseder 2008), syn-
post-kinematic with respect to the deformation fabric. M2 overprint-related rocks are preserved on the islands of e.g. Naxos, Serifos, Syros, Sifnos and Tinos.

Figure 2. Map illustrating the location of the Cycladic Islands within the greater tectonic regime and highlighting the major geological units in Greece. The area of the Aegean Sea has been thinned during Miocene Aegean extension, probably due to slab-retreat at the Hellenic trench system (Fig. 1). The ongoing widening in the Gulf of Corinth can be seen as continuation of this process. Along with subduction and back-arc basin evolution, this happened during ongoing convergence and collision between Eurasia and Africa/Arabia. To the northeast, the right lateral North Anatolian Fault system (NATF) continues into the North Aegean Sea. Turning to the geological units in Greece; as part of the Central Hellenides, encompassing the Cyclades, the Attic-Cycladic massif finds its continuation in the Menderes Massif. This major element is framed by the nappes of the Internal Hellenides (composed of the Ionian, Gavrovo-Tripolitza, Pindos and Plattenkalk zones) to the east and the External Hellenides (including the Sub-Pelagonian, Pelagonian, and Vardar zones in Greece and the Ankara-Izmir and Sakarya zones in Turkey) to the west. Going further north towards Bulgaria are the Rhodopes, where the Paleozoic foreland continues. Map modified after Barr et al. 1999; Ring et al. 1999; Schmid et al. 2008 and Lenauer 2009.
Within the overall context of the extensional regime in the Cyclades, recent studies give evidence for bi-directional movement. Compared to the top-to-NNE/NE directed kinematics which characterise the Eastern Cyclades (>50 references, see Edwards & Grasemann 2008 for a comprehensive review), Project ACCEL’s new results place Kea, along with Kythnos and Serifos (Grasemann & Petrakakis 2007; Müller et al. 2007; Schneider et al. 2007; Iglseder et al. 2008; Lenauser et al. 2008; Mörtl et al. 2008; Voit 2008), in a suite of islands having top-to-SW/SSW shearing in the Western Cyclades.

Lithospheric extension during the Miocene is well documented in the Aegean (Jolivet et al. 2004, 2005). Within the Eastern, Central and Western Cyclades, extension has been documented in detail by the formation of metamorphic core complexes (e.g. Lister 1984; Jolivet 2004) and movement along low-angle normal faults (LANF’s).

Acting in an extensional setting with displacement and exhumation along low-angle normal faults (Lee & Lister 1992; Lister et al. 1984) during which low-grade metamorphic rocks were placed over higher-grade metamorphic rocks leading to the evolution of metamorphic core complexes, the island of the Eastern Cyclades like Andros, Tinos, Naxos etc. show NNE/NE movement direction (see Fig. 3).

Focusing on a hitherto unrecognised main low-angled fault geometry outcropping on northern Kea, this work presents pervasive evidence of top-to-south kinematics (see Fig. 3).

2.2 The Attic-Cycladic Crystalline Complex

As part of the Alpine orogen in the eastern Mediterranean, the Attic Cycladic Crystalline Complex (ACC) (Dürr 1986) extends (broadly speaking) over the area between the Greek mainland and Anatolia (see Fig. 2 & 3) and dominates the Aegean micro-plate.

Based on tectono-stratigraphic and -metamorphic (but not lithologically) criteria, numerous authors (e.g. Renz 1949; Jacobshagen et al. 1986) divide the ACC into three major units (see Fig. 2 caption).

The Central Hellenides include the Attic-Cycladic Crystalline Complex - further divided into a Basal-, Intermediate- and Upper Unit - and other areas, for example the tectonic windows at Olympos and a continuation in the Menderes Massif.

The ACC is then framed by two main units, the Internal Hellenides to the east and the External Hellenides to the west.

The internal Hellenides comprise the Sub-Pelagonian and Pelagonian Zone in the west, adjacent at it the Varda Zone, Serbo Macedonia and outermost east the Rhodope Crystalline.

Spanning over the area to the NW of the Aegean, the External Hellenides encompass the Pre-Apulian Zone, the Ionian Zone and finally the Pindos Zone along the boarder to the internal Hellenides.

Lithologically divided the Attic-Cycladic Crystalline Complex consists of metasediments, orthogneisses and marbles (Basal Unit), again marbles, metapelites and –basites (Intermediate Unit) and non-metamorphosed sediments, ophiolites and granitoids (Altherr 1982).
Figure 3. Stratigraphic map of the major units and geotectonic overview of the Cyclades with the geographical location of Kea in the Western Cyclades, showing main proposed detachment-type tectonic contacts and LANF’s with respective senses of shear. These are found on islands with lithologies associated with the Attic Cylcadic (ACC) Upper Unit though the majority of islands show metamorphic rocks associated with the Intermediate Unit. As marked by red arrows, movement on the Northern and the Eastern Cyclades is NNE/NE-directed. The Otzias Bay Detachment, revealing a SSW-directed extensional system, is localised on the northwest-part of the island of Kea, requiring a bi-directional symmetry of kinematics displacement directions across the Aegean. Modified after Forster & Lister 1999; Iglseder et al. 2008 and after Lenauer 2009.
2.3 A tectonic model – MCC’s, LANF’s

The term Metamorphic Core Complexes (MCC’s), models on this described by e.g. Davis et al. (1979), Davis (1983); Lister et al. (1984 & 1986), is used in association with lithospheric/crustal-scale high strain zone extension and the M2 metamorphic event (see chapter 3) involving the formation of extensional low-angled normal fault type mylonitic high strain zones (commonly termed detachments), medium to high grade metamorphic mid-crustal rocks overlain by low to non metamorphosed rocks. These are furthermore often synmagmatic and domed (e.g. Serifos, Iglseder 2005 amongst others) and associated by ductile to brittle deformation patterns like mylonites and cataclasites.

Low-angle normal faults (LANF’s) are commonly documented and mapped throughout areas of both crustal extensional and constrictional (e.g. Smith et al. 2007) settings and are often associated with Tertiary/Cenozoic metamorphic tectonics (e.g. Collettini et al. 2006) but not yet fully understood in their development and structure as the formation of brittle faults with low initial dips cannot be mechanically explained by current fault-mechanical theories (Axen 2004, 2007 and references cited therein). The mechanism leading to the exhumation along a low-angled normal fault is consequently in high debate.

2.3.1 The governing structure of Kea

Investigations on Kea reveal a subsequently antiformally domed, low-angle normal fault system (Müller et al. 2007; Rice et al. in press; and other ACCEL abstracts) within a high strain shear zone present across the whole island formed during greenschist-facies metamorphic conditions. These settings were probably established during Miocene extension and thinning of the continental crust.

Based upon the geometrical relationship of the domal long axis to the principal stretching lineation and lower crust material presence/absence, Jolivet et al. (2004) proposed an A and B dome mechanistic classification scheme by using M2 fabrics for the entire Cycladic metamorphic domes. While this scheme is largely descriptively accurate and at the same time provides an otherwise intriguing explanation of the variable 3D tectonomorphic architecture throughout the Cycladic islands, it is in the first instance inconsistent with our finding from Kea and overall with those of Project ACCEL in the Western Cyclades.

The formation of these domes proposed is associated with extension related to crustal collapse during slab retreat and the formation of crustal-scale boudinage structures involving progressive deformation leading to strain localisation and high fluid influx.

Some domes of the B-type are characterised as elongated perpendicular to the main N-S extension direction with along N-dipping detachments exhumed mid-crustal material (e.g. Tinos, Jolivet 2004).

A-type domes are described as having long axis parallel to the extension direction.

Although the island of Kea comprises a dome-type, low-angle normal fault system dominantly present in the NW (as presented in this study) and additionally unveiled during ongoing studies in the southern areas (Iglseder 2008) of the island, it can not be positively assigned to neither the A nor B dome scheme at the present state of research.
This is, for it does not entirely fit into the proposed picture of the classification scheme of A and B dome structures within the Cyclades as the evident SSW-directed sense of shear (though of an opposite extension direction arguing for a B-type dome) stays in contrast to the elongation which would rather argue for an A-type dome.

Figure 4. A- and B- dome structure and characteristics, after Jolivet 2004.

3. The island of Kea

The Island of Kea (also known as Tzia or Keos) belongs to the westernmost chain of the Cycladic Islands respectively is the northernmost island of the Western Cyclades at about 60 km southeast of Athens and an extent to around 20 km from north to south to 10 km east to west with an area of around 128 km².

The capitol Ioulis lies at an altitude of ca. 380 m osl., separated from the highest point at Profitis Elias by about 180 m. In general the island shows fairly steep and almost mountainous terrain with a gentle slope in the northwest. Several bays along the coast made up ports for shipping with a focus on Korrissia, Voukari and Otzias Bay. These were used as ports since the early times of settlement in the period of the late Neolithic (see chapter 5.1).

Back then the geology and accordingly deposits of ore already made Kea attractive to settlers as for production and trade of e.g. metal and pottery. Remnants of these activities and settlements over time could be found at Kephala, Aghios Irini, Kastriani, Spathi, Orchos, Agios Simios and Nikoleri to name a few (Fig. 83).

It forms part of the Attic-Cycladic Crystalline Complex (Dürr 1986) as described in chapter 2.2.

Forming the main rock sequence, Kea is dominated by calcitic chlorite-mica schists with occasional lenses of metabasitic rocks. Intercalated in the schists are calcitic bands of marbles and quartzites located in the footwall. Localised occurrences of phyllitic schists and, bound to the fault-rock zone, serpentinites have been mapped.
The fault-rock zone itself hosts abundant dolomitic cataclasites. From stratum to top it compiles calcitic ultra-mylonitic marble, a horizon of re-mobilised cataclasite and "hanging-wall"-cataclasite (hw-cataclasite) followed by cataclastic and brecciated dolomite and finally ankeritic dolomite.

A strong greenschist-facies (M2) metamorphic overprint during the Oligocene/Miocene (Bröcker & Franz 2006), which might have been enhanced by strain localisation and therefore high fluid infiltration along brittle features, led to a lack of relics preserved from a high-pressure metamorphism of a former regional Eocene blueschist to eclogite facies (M1) metamorphic event.

Affected by an overall strong ductile, brittle-ductile and brittle overprint of the island it offers intensely deformed rocks with spectacular superimposed folding patterns, shear and cataclastic structural feature.

Kea is interpreted to be affected by at least 3 (up to 4) deformation events. Deformation within the rocks gives evidence for two ductile events, high grade D_{n-1} and medium grade D_n, preserved in progressive fold geometries and a change in the stretching lineation to a top-to-SSW sense of shear geometry.

These events are followed by a phase of brittle faulting which may be split into a brittle-ductile (D_{n+1}) and brittle stage (D_{n+2}) dominated by young high-angle normal faults.

It is to be taken into account that a continuum from ductile to brittle behaviour of rocks present together with a high-fluid infiltration governed deformation might cover distinct ‘boundaries’ of the various ductile to brittle deformation stages.

### 3.1 Research history, previous works – our work

Kea was geologically the subject of only relatively few published articles so far.

There was some lineation data published in a thesis and a publication by Walcott (1998) and Walcott & White (1998), some (hydro-geological) mapping by the Greek Institute of Geology & Mining Exploration (IGME), but the main information source hitherto was the 1:50.000 geological map of Kea (Davis 1972, 1982, see Fig. 5).

During her studies she petrographically characterised the main lithologies, describing non-metamorphic Triassic to Jurassic micritic limestone klippen on top of greenschist-facies metamorphosed lithologies separated by a sub-horizontal basal contact, interpreted as thrust horizon (Davis 1982), of an intensely weathered surface of probably Cretaceous age, outcropping only in the northern parts of the Kea.

In the southern and western parts of the island Davis mapped a unit consisting of marble overlying the greenschist-facies gneiss/schist unit.

During remapping the ‘klippen’ turned out to be discordant 10’s m thick ultra-mylonitic marble as well as dolomitic breccia, both of which part of a brittle-ductile shear zone.
Figure 5. Geological map in the scale of 1:50,000 and lithostratigraphic column after Davis 1972. The ‘klippen’ are labelled in green, brittle overprint marked by black lines.

Concomitant to this work, my colleague K. Voit remapped the north-eastern part of Kea (see Fig. 6) modifying and reinterpreting the map and lithostratigraphy of Davis.

Figure 6. Lithostratigraphy of the north-eastern part of Kea, after Voit 2008.
As members of Project ACCEL C. Iglseder and A.H.N. Rice started their remapping in 2005 respectively in 2007. As a result of which a new tectonostratigraphic map of the area has been compiled and is, in cooperation with the Greek Institute of Geology & Mining Exploration (IGME, founded in 1952), going to be published in the collection of geological maps of Greece.

Additionally to the low-angle normal fault system outcropping in the northern areas of Kea, the ongoing studies unveiled a ductile to brittle low-angle normal fault in the southern areas of the island (Iglseder 2008).

3.2 The geological map of Kea - mapping area of this study

As part of Project ACCEL (Aegean Core Complexes along an Extending Lithosphere) and based on Quickbird imaging, high-precision GPS, kinematic, lithological and tectonostratigraphic data, a detailed (1:5.000) geological/structural map of the north-western part of Kea has been compiled.

As part of this master's (Diploma) thesis I mapped and sampled the main lithologies including structural characteristics and undertook further research on the basis of data collected.

The area of study I focus on is located on the outermost north-western tip of the island. This was seen to be interesting in order to investigate what Davis showed as main units of her klippen in this area.

Mapping started in summer 2005 with a two week stay, and continued in the following year with a more intense field season of almost five weeks. My colleague and I were joined by international members of Team ACCEL, all of whom undertook separate investigations on various topics and aspects of geology.

Initially, in the field the very broad tectonic concept of detachment was employed, the term being a general descriptor of an extensional fault(ing) system with low-angle geometry(ies). For reasons of inter-compatibility amongst the ACCEL colleagues the term is retained in this thesis for naming specific features, areas and elements identified in the field (e.g. Otzias Bay Detachment, see chapter 3.4.1.5). The term detachment is however not preferred for interpretative and model considerations.

In the course of our detailed research and mapping a low-angle fault geometry as well as extensional movement was identified, indicated by a pervasive sub-horizontal foliation and fold axial-surfaces.

Team ACCEL therefore divides Kea structurally into footwall rocks and fault-zone rocks (see Fig. 7).
Figure 7. New detailed geological map of NW-Kea, location as indicated by the red ellipse on the islands' outline inlet in the upper left corner of the map. Location of prehistoric sites with metalworking modified after Gale 1998. Coordinates are given in UTM Northings and Eastings.
3.3 Tectono-/Lithostratigraphy

ACCEL has identified two major tectonostratigraphic units on Kea – an autochthonous footwall, formed under greenschist metamorphic grade, and an overlying fault-rock zone formed during top-to SSW extension (Fig. 8). This portion of the thesis describes the appearance (including deformation) of the mapped units. Deformation overall (and the emerging structural interpretations for the area) are addressed in chapter 3.4.

The Island of Kea is mainly made up of and widely dominated by greenschist-facies chloritic schists with lithologically lensoidal variations of quartz, carbonate, epidote, actinolite, biotite and also some talc as well as, locally, dolomite boudins. Furthermore marbles of whitish, greyish to bluish colour, mostly monomineralic and thinly laminated, intercalated by quartzitic layers and accommodating ductile deformation structures such as re-/sheath folds.

Except near the extensional low-angle normal fault, strains within the footwall are relatively homogenous (lithology dependant), with multi-stage deformation, showing a variation from ductile to brittle deformation.

Overall lineation and shear-criteria show a consistent top-to-SSW movement.

At the top of the footwall close to the fault-rock zone, phyllonitic schists are common, probably indicating higher strain.

The fault-rock zone itself is built up, from substratum to top, by calcitic ultra-mylonitic marble, a unit that ACCEL terms the rmc (re-mobilised cataclasite, mylonitic) and the hw-cataclasite (dolomitic, ultra-cataclastic schist), cataclastic brecciated dolomites and finally on top ankeritic dolomites.

A conspicuous horizon is the serpentinite which, additionally to the footwall, is present as lenses within the hw-cataclasite.
3.3.1 Tectono-/Lithostratigraphy of the Footwall

The lithologies of the footwall are mainly comprised of, and dominated by rocks added to the Intermediate Unit of the Attic-Cycladic Crystalline.

In general these comprise a sequence of greenschist-facies metabasitic and felsic as well as carbonate schists which are represented by a typical mineral assemblages of albite + chlorite + muscovite + quartz + epidote/zoisite + actinolite + biotite + K-feldspar + tourmaline + apatite (after Iglseder 2008) with varying amounts of calcite.

These schists are intercalated with pure and also impure blue-grey, hosting a broad range of ductile to brittle structural feature, to locally white calcitic marble and with dm to cm thin, folded quartz layers; in some areas intensely folded and boudinaged, on both small- and large-scales, and often (ultra-) mylonitic, as well as rare quartzites.

The often mylonitic calcitic marble has a pronounced stretching lineation, which shows a maximum dipping gently towards NNE parallel to the brittle kinematics. Upright, non-cylindrical folding with fold axes parallel to the stretching lineation is common in the impure blue-grey marble and in the mylonites.

Figure 8. Schematic tectono-/lithostratigraphic column of the footwall and fault-rock zone giving examples of structural features and sense of movement observed within the various rocks.
3.3.1.1 Quartzite

Within the overall footwall tectono-/lithostratigraphy, a rare but recurrent clearly identifiable rock is the quartzite. These are often mylonitic and show, in micro-scale, healed quartz textures, dynamically recrystallised grains with subgrain rotation and grain boundary migration and also static crystallised carbonatic dolomite. The brittle overprint mainly is present as quartzitic veins.
shape-preferred orientation, defining a continuous foliation with parallel distinct aligned fine mica-rich layers in between. Note that in some areas of the thin section, quartz-quartz grain boundaries meet quartz-(white)mica boundaries at right angles as highlighted by the red arrows, which leads to slightly elongated, rectangular shapes of some of these quartz grains (e.g. Vernon 2004).

3.3.1.2 Blue-grey calcitic marble

The blue-grey calcitic marbles are bluish to grey to locally white in colour, mostly 30 cm to a couple of metres thick beds, a few mm to cm thin laminated, medium to very finely crystalline and often mylonitic. This silicate-rich impure marble is mostly monomineralic but locally with a few feldspar clasts involved and shows static recrystallisation of grains. They are intercalated with the schists of the footwall (see Fig. 11).

They are boudinaged and strongly folded, showing a wide range of various stages of isoclinal folding, tight folding, refolds (Fig. 37) and also sheath folds as shown further down (Fig. 41), indicating high strain. They have a pronounced stretching lineation which has a strikingly consistent SSW-NNE orientation and show almost isoclinal recurvature. Shear criteria show that it formed during top-to-south sense of movement.

The brittle (including a wide range of brittle-ductile structural features, see Fig. 14) overprint shows a pre-dominating NNE-SSW, WNW-ESE striking high-angle fault pattern formed/acting during the LANF formation.

Figure 11. Typical outcrop view of intercalated blue-grey calcitic marble and schist. Tight-folding and distinct preferentially weathered foliation within the impure blue-grey marble. GPS waypoint coordinates in UTM 35 (throughout). E 265117, N 4172686 (left); 265213, N 4173029 (right).
Figure 12. Equal area projection of the lower hemisphere showing foliation poles (note a general but not distinct trend towards the SW) and a main lineation trending NE-SW (left) and fold data with poles to axial planes and gently to steeply plunging fold axes and axial plains dipping towards the SE, ENE and NNE (right). Data for plots gathered from blue-grey calcitic marble of the entire mapping area.

At some locations the blue-grey calcitic marble forms strikingly distinct dark and light striped layers, a few mm to cm in scale and very finely crystalline.

Those areas host a massive variety of textbook-like example deformation structures such as (neck) boudinage and rotated boudins, mushroom-type and snail-type folds, brittle overprint of ductilely folded marble bookshelf style etc., some not yet fully understood (see Fig. 13 & 14).

A suggestion for the accumulation of structural features within the blue-grey calcitic marble might be the association with the phyllonitic schists and therefore the higher strain rate adjacent to these areas.
Figure 13. Field photographs of selected examples for the variation in ductile deformation amongst the blue-grey calcitic marble. E 265251, N 4173980.

A) Boudinaged layer of the same competence (but surrounded by a thin schist layer accommodating the strain) within the fine-grained layered impure marble forming rotated fractured boudinage. During extension and rotation the segments get separated by fractured necks (depicted by dotted line) with a concentration of quartz filling the gaps between (e.g. Twiss & Moors 1992). Perturbation strain above the fractured necks is accommodated by ductile flow of the surrounding rock (highlighted by dashed line). Note the fine dark layer (depicted by finer dashed line) within the boudin segments (viewed normal to the boudin line), acting as marker horizon for the amount of rotation in respect to the unaffected layers.

B) Extension within layered blue-grey to white impure marble forms a v-shape foliation boudinage due to competence interference. The boudin-necks (highlighted in picture by thin black lines) propagate from the upper interface of the more pure marbles to a calc-schist towards the centre of the boudinaged marble layer causing the opening of a v-shaped neck, filled with a wedge of calcitic schists. Perturbation strain below the neck is accommodated by ductile flow leading to a type of ‘upwelling’ within the marbles right beneath the neck of the boudinaged layer.

C) Mushroom-shaped pattern as a result of interference folds. Two generations of folding along different fold axis causing mushroom-like shapes (fold classification after Ramsey & Huber 1978).

D) Outcrop-pattern forming of a snail-type fold which might result only by erosion and section interference.
Figure 14. Field photographs of selected examples for the variation in brittle deformation amongst the blue-grey calcitic marble. E 265231, N 4173944.

A) Small scale brittle faulting within fine-grained distinct dark and light layered impure marbles. Extension initiates the propagation of quartz filled faults causing rotation of different amounts along a sharp defined set-off of former, at higher strains, ductile folded marbles. Note the increasing number of faults towards the neck of the fold where a cross-cutting relationship between older and a younger fault which drags layers into movement direction can be observed.

B) Brittle overprint and rotation along the faults of ductilely folded layered impure marble forming 3D bookshelf faulting and quite an offset of the marble layers. Note the earlier tight fold at lower right within the almost broken off part of the rock. Pre-defined weakening and strain accommodation along/hosted by a thin layer of schist (stretching lineation on exposed surface) causing the delamination with increasing strain.

C) Intensely faulted piece of blue-grey calcitic marble with internally differing layers (lighter and darker) showing competence contrasts. This has led to local stretching fault-type behaviour (variable displacement along discrete transecting breaks in fabric) with differing amounts of, and angles in rotation resulting in “boudinage” initiation and general flanking structure evolution (Passchier et al. 2005; Gascombe & Passchier 2003).

D) See caption for field photograph C) for further explanation.
Figure 15. Great circle lower hemisphere plot and full/quarter rose diagram (circular histogram plot displaying differing types of directional data together with the frequency of each class) for the brittle overprint of the blue-grey calcitic marble, giving the orientation and number of observed faults and veins/joints (showing a distinct WNW/NW-ESE/SE and a minor NNW-SSE striking orientation of brittle features, further more a lesser developed NNE-SSE striking direction can be observed - left, dip directions vary in direction towards SSW and NE/NNE, almost all features show a steep to vertical dip - right) of the brittle fault pattern within the blue-grey marble.

Figure 16. Optical micrograph of calcitic, silicat-rich impure marble (i.e. the grey portion of the marble) showing deformation twins of grains (sample M/K 101a). Viewed in normal polarised Nicols’ at a five-fold magnification.

3.3.1.3 Schist and metabasitic schist

The schist and metabasitic schist are ubiquitous and often intercalated with calcitic blue-grey marble (see Fig. 11). Located close to the coastline weathering forms of honeycomb structure are widely present (see Fig. 17).

Lithologically they are locally fine laminated with quartz layers in between. In general the schists comprise sigmoidal shaped variations in chlorite, +/- actinolite, +/- epidote group, +/- biotite, +/- white mica, +/- quartz, +/- carbonate. Feldspar porphyroclast are present and a blastesis increasing towards the LANF can be observed. Cross-cutting relationship requires that it is older than sense of shear.
In macro- as well as in micro-scale asymmetry SC-fabric is present and porphyroclasts indicate top-to-the south sense of shear. In micro-scale (see Fig. 20) folded and broken up clasts of calcitic rock and plagioclase can be observed.

The brittle overprint shows a pre-dominating NNE-SSW, WNW-ESE striking high-angle fault pattern.

Figure 17. Outcrop of schist showing weathering forms, Tafoni or honeycomb structure, (left) and SC-fabric picked out by dashed lines, red arrows indicate sense of shear (right). E 265973, N 4174313 (left); E 266121, N 4173313 (right).

Figure 18. Equal area projection of the lower hemisphere showing foliation poles (with best fit great circle – note general trend towards the SW) and a main lineation trending NE-SW (left) and fold data with poles to axial planes and gently to steeply plunging fold axes oriented WSW (right) and gently NE-dipping axial planes. Data from the quartzite, schist and phyllitic schist (footwall rocks) of the entire mapping area.
Figure 19. Optical micrograph of poor preserved quartz-albite-epidote-white mica-actinolite-schist (sample MK/32), viewed in crossed polarised light at a five-fold magnification.

Figure 20. Optical micrograph of chlorite-white mica-actinolite-zoisite/feldspar-albite-quartz-schist (sample M/K 27) with folded and broken up clasts of calcitic rock and plagioclase, asymmetry of porphyroclasts indicate top-to-the south sense of shear. Thin section perpendicular to the main high strain foliation and parallel to the mineral stretching lineation (crossed polarised Nicols' in five-fold magnification).
Figure 21. Optical micrograph of plagioclase-quartz-muscovite-biotite-epidote/piemontite-haematite+-apatite-gneiss (sample M/K 122) of a manganese-rich type of rock viewed in crossed polarised light at a scale-up five-fold magnification. Note microboudinage of pre-tectonic epidote-piemontite crystal in the centre (right) and boudinage in the elongated piemontite and a patchy pattern of quartz.

3.3.1.4 Serpentinite

In the mapping area the serpentinite forms lenses. In outcrop view rock show fractured clasts from cm up to 40 cm in size and small scale horizon bounded faults with no preferred orientation recognisable. Locally +/- talc can be observed.

In micro-scale those rocks show a nice SC-fabric and are hosting broken-up clasts.

There is no evidence for clinopyroxene pseudomorphs after serpentinite. The stratigraphic position of this serpentinite body is not fully constrained at the moment.

3.3.1.5 Phyllitic schist and cataclastic schist

Within the overall footwall tectono-/lithostratigraphy these represent the uppermost part of the footwall of Kea and can be characterised as silver shiny white-mica rich schists hosting +/-talc and brown weathered sericite, chlorite, muscovite as well as carbonate.

They are mainly observed around and at the base of the fault-rock zone and around marble (mega-) boudins (50 cm to 5 m), representing higher strain zones within the greenschist unit footwall rocks.

In micro-scale (see Fig. 22) the white mica minerals often act as major distinct mineral forming the foliation planes rather than just occurring randomly within the rock (see chapter discussion on cooling vs. deformation age in chapter 3.4.3.1).
3.3.2 Fault-rock zone

The fault-rock zone is a locally more than 30 m thick, complex zone of varying, essentially calcitic to dolomitic lithologies at varying strain intensities and with a brittle overprint.

Broadly this comprises numerous generations of cataclasites ranging from foliated proto-cataclasites with brittle-ductile overprint, incohesive coarse grained fault breccias to partly graphitic fine grained fault gouges.

The fault-rock zone lithologies comprise a lower zone of calcitic ultra-mylonitic marble (altered) (see Fig. 23 & 24) with occasional boudins of dolomitic marble, overlain by a zone of remobilised (mylonitic) cataclasite (see Fig. 29), termed rmc (up to 1.5 m thick), brown to rusty brown stained brecciated schist “dolostone” derived from the footwall and pale brown to rusty brown to faintly reddish cohesive dolomitic hw-cataclasite hosting ca. 2 m of serpentinite boudins associated with talc within this zone, and thence overlain by a cataclastic brecciated dolomite. The overlying ca. 7 m thick layer of dark brown to rusty brown weathering massive ankeritic dolomitic breccia (see Fig. 31) is apparently low-strained, although no sedimentary features are preserved.

3.3.2.1 Calcitic ultra-mylonitic marble (altered)

Within the fault-rock zone calcitic ultra-mylonitic marble (altered) is present. It comprises up to 4 metres (in contrast to other parts of Kea where it reaches a dimension up to 30 metres). White calcareous ultra-mylonitic marble with occasional boudins of dolomitic marble (often brecciated) and quartz boudins represent a conspicuous horizon of the fault-rock zone.
In macro-scale the calcitic ultra-mylonitic marble shows examples of fold interference patterns by hosting fold generations (see Fig. 24) In micro-scale static recrystallisation of grains and an optic preferred orientation indicating sinistral sense of shear (see Fig. 26 to 28) can be observed.

The brittle overprint shows a predominating NNE-SSW, WNW-ESE striking high-angle fault pattern formed/acting during the LANF formation.

Figure 23. Outcrop view of the calcitic ultra-mylonitic marble forming mega-boudins (traced by dashed lines) within the schists and often surrounded by phyllonitic schist representing higher strain zones. Largest boudin in centre right of photo is ca. 1.5 to 2 metres thick. E 265292, N 4173911.

Figure 24. Characteristic appearance of the calcitic ultra-mylonitic marble in the field featuring folds associated with $D_{n-1}$ and $D_n$. E 265292, N 4173911.
Figure 25. Equal area projection of the lower hemisphere showing foliation poles (with best fit great circle – note moderately equal trend of steeply dipping foliation planes towards the NE and SW) and a main lineation trending N-S with a second rather distinct lineation developed trending NE-SW with variations toward NNE-SSW and ENE (left). Fold data with poles to axial planes and gently to moderate to steeply plunging fold axes oriented WNW-ESE, NE-SW and slightly poorer developed ENE-WSW (right) and distinct NE-dipping axial planes. Data recorded from the calcitic ultra-mylonitic marble of the entire mapping area.

Figure 26. Photomicrographs of a calcitic vein sitting in the quartzite (sample M/K 77). Elongated and deformed quartz grains form a well-developed shape-preferred orientation, crossed polars (left) and an optic preferred orientation on the right (gypsum plate). Note the "undeformed" area of the later vein of calcitic grains in the lower part of the photos. Thin section perpendicular to the main high strain foliation and parallel to the mineral stretching lineation.
Figure 27. Calcite-sillimanite-rich ultra-mylonitic marble (sample M/K 11). Cataclastic mylonitic microdomains of white mica (muscovite, impure) and calcitic. Dispersed quartz crystals form clasts that are cataclastically broken up to form sigma geometry clasts in an SC-fabric, both within a calcitic matrix. Note microdomains are more distinctly developed in the centre of the photo (bottom left to top right) and black impurities form discrete boundaries to the sigmoidal regions suggesting much higher displacement in some portions. Photo of thin section in crossed polarised Nicols’ in a five-fold magnification. Thin section perpendicular to the main high strain foliation and parallel to the mineral stretching lineation.

Figure 28. Fibrous strain fringe of quartz developed alongside an opaque pyrite grain. Note diffuse quartz at the top of the left fringe. Individual fibres at the right are undeformed but show bends which are interpreted as result from changes in the orientation of the instantaneous stretching axis (ISA) with respect to the fabric in the wall rock. He, Fs and carbonate-rich fluids are present. Note the SC-fabric at the right bottom end of grain. Scale-up 2.5 (sample M/K 34a). Thin section perpendicular to the main high strain foliation and parallel to the mineral stretching lineation.
3.3.2.2 hw-cataclasite and rmc

Another striking feature within the fault-rock zone is a package of cataclasites and mylonites that can be divided into two discrete units based upon the deformation conditions and lithology; the hanging-wall cataclasite (hw-cataclasite) and the re-mobilised cataclasite (rmc).

The hw-cataclasite is hosting clasts made up of fragments of the footwall rocks and also some derived from the overlying cataclastic and brecciated schists as well as the ankeritic dolomite. It shows a cataclastic foliation and a pervasive overprint by carbonate rich-fluid.

The rmc lies immediately structurally below the hw-cataclasite shows brecciated pieces and clasts of the original hosting mylonite (see Fig. 29, right photo). The entire package is not cross-cut by any of the major (quartz or calcite) vein systems that are widespread in the main mylonites. However, it is upright folded on m to 10’s m wavelengths (Müller et al. 2007).

Figure 29. Left photo: outcrop view of the hw-cataclasite with a well developed cataclastic foliation containing shear criteria indicating top-to-south displacement. Clasts are predominantly quartz, and ankeritic dolomite, less commonly dolostone. Note mustard-colour weathering finely foliated layers in lower right of this image dipping gently to NNE - this is transition to rmc. E 266239, N 4174067.

Right photo: the rmc has typical appearance of hosted mylonitic clasts of various sizes and with a range of shapes, from angular to sub-rounded. These show an old stretching lineation with a variable orientation. The clasts are embedded in the high-T and new (mylonitic) foliation with a NNE-SSE oriented new lineation. E 266238, N 4174062.

The outcrop images above are typical and importantly, evidence the absence of the suite of fractures, extension gashes, joints (vein filled or absent) that are ubiquitous in the footwall juxtaposed immediately below the re-mobilised cataclasite (see 3.4.2.2).
Figure 30. Thin section of the dark (graphite en-riched?) basal portion of the hw-cataclasite, where fabric generated by flow such as "mylonitic fabric" and foliation-parallel faults/discontinuities outweigh the cataclastic fabric. Here sample M/K 20a shows microstructural evidence for brittle deformation. Broken-up components form angular fragments of various sizes and dark zones of very fine-grained material of intense micro-fracturing, as almost to a fault gouge. Some fragments act as clasts and become rounded components, in some parts they are even enveloped in a rim of fine-grained phyllosilicate (clay minerals), sometimes stylolites can be observed. Ultra-cataclastic bands and areas of sc fabric host well rounded clasts whereas other areas show still angular clasts. Viewed in normal plane-polarised light in a 2.5-fold magnification. Thin section perpendicular to the main high strain foliation and parallel to the mineral stretching lineation.

3.3.2.3 Cataclastic and brecciated dolomite

The unit mapped as klippen of unmetamorphosed rocks are the cataclastic and brecciated dolomites and the overlying ankeritic dolomitic breccia are present as klippen, like 10's to 100's m long/wide lenses pale brown to taupe in colour (see Fig. 31).

The brittle overprint is well developed in some areas. Although they are broken not fractured, coherent regular internal structure is absent. A large fault breccia fragment size distribution (0.1 – 10's cm) interlayered with few cm-thick ultra fine-grained clay-rich gouge are present.

These gouges typically form low-angle horizons that occasionally converge/branch over several metres and thereby compartmentalise the coarse fragment cataclasites into lenses.

3.3.2.4 Ankeritic dolomitic breccia

Dark brown to rusty brown to faintly reddish ankeritised dolomitic breccia (see Fig. 31) with, in parts, minimal microstructural evidence of deformation, overlies the cataclastic and brecciated dolomite
The brittle overprint shows a similar fault pattern to that of the other fault-rock lithologies.

Ankeritisation is seen as a late static process transforming Ca-carbonate into Fe-rich carbonate which implicates a big enough reservoir of iron-rich fluids.

![Figure 31](image.png)

Figure 31. Stratum made up of dolomitic cataclasite and clayey gouge with a former fault plain (highlighted by red dotted line) of broken up dolomite at the fault surface (marked by red dashed line) adjacent to the overlying zone of brown weathered ankeritic dolomitic breccia. E 266168, N 4173595.

3.4 Deformation and kinematics, selected examples – interpretation of field data

This portion of the thesis describes the overall deformation and the structural interpretations for the overall area. This is presented in an order of features that very approximately correspond to “ductile” to “brittle”, such as foliation and lineation, folding, rheology and boudinage and also shear-sense indicators of various types.

3.4.1 Ductile, brittle-ductile deformation

In this chapter data plots and photos of representative selected examples (outcrop view) are given and some models going along with structures observed are presented.
3.4.1.1 Foliation and lineation

Primary foliation within the footwall rocks is dipping to the southeast and the main direction of lineation, amongst others (E-W, NNE-SSW), is NE-SW (see Fig. 32).

Figure 32. Equal area projection of the lower hemisphere of the footwall rocks altogether showing foliation planes (S, with best fit great circle – note general trend towards the SW) and a main lineation (L) unravelling a major trend to the NE-SW.

The foliation within fault-rock zone is steeper dipping and wider spread (see Fig. 33). Outcrop views as well as an equal area projection of the lineation reveals two (to three) generations of lineation of all types (stretching and crenulation lineation) strike in an older N-S and a younger NE/NNE-SW/SSW direction. The cataclastic lineation is more directed to the north.

Figure 33. Equal area projection of the lower hemisphere of the fault-zone rocks showing foliation planes (S, pole to best fit great circle) consistently dipping to the south. Note weak but evident grouping of two lineation (L) suites of all types (stretching and crenulation lineation) sub horizontal plunging north and NE-SW. This is the result of variable identifiable lineation trends seen in the field. Plots compile all structural data from throughout the fault-rock zone.
3.4.1.2 Folding

At least two different stages/dominant directions of folding are observed on northern Kea, represented by folding event $F_1$ with E-W fold axis, $F_2$ NE-SW and finally $F_3$ associated with fold axis NNE-SSW.

Examples for various types and stages of folding are present all over the mapping area, with a special focus on the blue-grey calcitic marble if the footwall and the calcitic ultra-mylonitic marble of the fault-rock zone.

A range of examples therefore (e.g. isoclinal folds, tight folding, refold structures, sheath folds) and data accompanying plots and models by e.g. Fusseis & Grasemann (2002) and Alsop (2006) for structures observed are given here.
Figure 35. Isoclinal folding associated with F₁ with fold axis within the schists intercalated with the blue-grey calcitic marble. Folds are moderately inclined horizontal. E 266192, N 4174448.

Figure 36. Two principal folding directions as seen in the Schmidt’s equal area projection of the lower hemisphere (footwall and fault-rock zone rocks) show main fold axis parallel to the overall stretching lineation NNE-SSW (F₃) and a minor fold axis orientation NE-SW (left). Contour plot of fold axis of observed refold structures at the Otzias Bay Detachment with fold axis parallel to the stretching direction (right).

Due to high-strain shearing in an extensional regime accompanied by perpendicular shortening and upright folding, axes of non-cylindrical folds in the mylonites have rotated into the finite stretching direction, generating and preserving various stages within the evolution of ductile refolds.
The structural features are differentiated by their two-dimensional interference patterns. Established from these Type 0-3 interference patterns four end-members of refold structures (3D) are distinguished. These are described and classified by Ramsey (1960, 1962), Ramsey & Huber (1987), Thiessen et al. (1980), Thiessen (1986) and updated by Fusseis & Grasemann (2002). They show that not four, as assumed, but six end-members of three-dimensional refold structures can be distinguished by means of coordinate transformation (see Fig. 38).

The most striking structural observation is the upright non-cylindrical folding of the mylonites whose fold axes parallel the stretching lineation (see Fig 37).

Shearing of these folds into tubular/sheath folds (e.g. Cobbold & Quinquis 1980; Skjernaa 1989; van der Pluijm & Marshak 2004, see Fig. 44; Alsop & Holdsworth 2006, see Fig. 39) suggests that folding occurred during shearing as a result of shortening perpendicular to the stretching lineation (see Fig. 40 & 41). Interestingly, the E-W shortening component that accompanied the ductile deformation further persisted into brittle-ductile and even into brittle conditions. The mylonites have a pronounced stretching lineation towards the NNE parallel to the brittle kinematics extension direction. In one area distinctive lineations and nearly isoclinal recurvature are present. This portion of the Kea shear zone records folds which have been sheared sub-parallel to the fold axes, subsequently ultimately developing into apparent
sheath folds, which resemble Type 0₁ refold structures (Skjernaa 1989; Grasemann et al. 2002 & 2004, see Fig. 42).

Figure 38. Model of refold evolution of the six end-member refold structures in 3D (Fusseis & Grasemann 2002; Grasemann et al. 2004). Marker lines on type O₁ to 0₃ refold structures reveal the various finite deformation recorded. On NW-Kea sheath fold observed resemble Type 0₁ refold structures.

Figure 39. Schematic sketch illustrating the x, y and z axes of a sheath fold together with the inter-limb angle (α) and apical angle (β) of the curvilinear fold hinge-line, after Alsop 2006. Y to z orientated cross sections across the length of the sheath fold result in eye-fold geometries. The x-axis is parallel to the finite stretching direction and should be broadly parallel to the mineral elongation direction (Alsop 2006).
Figure 40. Nearly isoclinal recurrvature (black dotted line) and superposition of folds within the mylonites. Overall stretching lineation marked by black dashed line. E 266060, N 4174379 (upper); E 266225, N 417446 (bottom).
Figure 41. Various stages of refold and sheath fold evolution within the blue-grey marble can be determined. Red arrows indicate top-to-SSW movement direction, black line highlights the (re)curvature. Overall stretching lineation marked by black dashed line. E 265311, N 4173919 (upper); E 266222, N 4174445 (bottom).
3.4.1.3 Rheology and boudinage

Structural features like boudins as well as pinch and swell structures are found in the schists and also in the blue-grey marble.

Within the schists competent layers of quartz are imbedded. As they are orientated parallel to the axis of maximum stretch (NNE-SSW) they accommodate the lengthening by, depending on the contrast in competence between the layer and the matrix, forming necked boudins, pinch and swell structures before finally segmenting into boudins.

As a consequence of different competence boundary conditions these quartz and feldspar-rich layers (see picture on the right of Fig. 43), almost start to act as broken-up clasts within the (mica?)-rich schists and behave like rotating components within a ductile flow.
Figure 43. Ductile structures illustrating that rheological inhomogeneities may be an efficient localizing factor of ductile simple shear deformation. These have a polyphase structural history, all of which indicate a top-to-south shear sense. The schists often host almost ductilely less- to undeformed quartz layers and others, as shown here, which record an earlier ductile stretching into a pinch-and-swell type boudinage suggesting deformation at higher metamorphic conditions (E 266041, N 4173516, left) albeit the initial geometry (e.g. planar, wavy, other) of the syn-straining, intruding quartz vein is unknown (E 264091, N 4172749, right).

3.4.1.4 Shear-sense indicators

Within both the footwall schists and in the overlying fault rock, ductile shear-sense criteria consistently show a top-to-SSW movement. Indicators recorded include delta and sigma clasts, flanking structures, asymmetric boudinage, stable porphyroclasts with monoclinic symmetry, as well as rotated and boudinaged veins.

Brittle shear-sense indicators, in particular scaly fabrics and Riedel geometries of secondary fractures, are consistent with this shearing direction.

Some examples in the hw-cataclasite and rmc that indicate the co-existence of fabrics generated at brittle as well as creep conditions are fabrics showing a range of creep-type fabrics, mm to metre scale breccia tails, smeared out matrix layers and discrete slip planes that define geometries of SC-planes, flanking structures and asymmetric porphyroclasts all indicate a top-to-south sense of shear.

The overall consistent kinematic indicators show pervasive evidence for top-to-south extension /displacement direction. This non-coaxial 'hanging-wall' displacement is consistent with displacement indicators recorded in other island in the Western Cyclades like Serifos and Kithnos (e.g. Grasemann 2007; Iglseder 2008; Laner 2009; Lenauer 2009). These are all in contrast to the north-directed shear-sense indicators in the Eastern Cyclades like Andros, Tinos, Mykonos, Paros, Naxos and Ios (e.g. Lister 1984; Bröcker 2006; Jolivet 2004; Famin 2004; Brichaut 2008)
Figure 44. The calcitic ultra-mylonitic marble/rmc at the Otzias Bay Detachment shows a clear mylonitic fabric, a distinctive stretching lineation and a great variety of kinematic shear sense indicators with consistent top-to-SSW movement (classified after Ramsey & Huber 1983, Lister & Snoke 1984), indicating non-coaxial deformation. E 266271, N 4174017.

Upper picture: close-up of a top-to-SSW sheared clast, about 5 cm in diameter. Note the foliation (dashed bright line) which appears to get "dragged" into the locally rotating (brittly broken-up, original mylonite protolith) clast.

Bottom picture: rotated clast within the re-mobilised cataclasite. Small red arrows indicate constriction direction, bigger red arrows indicate the sense of shear.
Figure 45. Outcrop picture (upper) and thin section image (bottom) of kinematic data for D deformation in re-mobilised cataclasite at the Otzias Bay Detachment. Red arrows indicate the consistent top-to-SSW displacement direction. E 266271, N 4174017.

Upper picture: Note consistent sense of shear also in the macro scale micrograph as shown by a porphyroclast (delta-type) with ‘wings’ of fine-grained mica within a matrix.

Bottom picture: thin section image of calcite-sillimanite-rich ultra-mylonitic marble (sample M/K 10) is orientated perpendicular to the main high strain foliation and parallel to the mineral stretching lineation and was taken at ten-fold magnification and under the use of the gypsum plate.
Figure 46. Top-to-SSW movement (indicated by red arrows) observed in phyllonitic rock exhibiting SC'-fabric (line drawing in the right bottom corner of the upper photo) and also in the schists and intercalated thin quartz layers, which show an offset caused by shear band formation. E 264829, N 4173934 (upper); E 263989, N 4172484 (bottom).

3.4.1.5 The Otzias Bay Detachment – a high strain shear zone

Within the overall fault system of Kea, the Otzias Bay Detachment is part of a higher strain shear-zone with consistent SSW-displacement direction. As mentioned earlier in the text (see chapter 2.4) the island comprises a domed, low-angle normal fault system forming a
mid-upper crustal high-strain shear zone within the Western Cyclades. Thin section analysis suggests that it formed during low to (very-)low grade metamorphism.

At the peninsula of Akrotiri and along the west coast of Otzias Bay (located in the NE-part of the mapping area, see Fig. 7), the fault zone crops out nicely, giving a view of protocataclastic brecciated dolomite (locally strongly ankeritised), serpentinite lenses associated with talc schists, a cataclastic schistous zone bounded by the low-angle normal fault and, representing the footwall, calcitic marbles with thin quartz layers and chloritic as well as quarzitic schists.

A several metre thick brittle cohesive cataclasite with large calcitic breccia fragments with a broad grain-size distribution, interlayered with a few fine-grained gouge layers, several cm thick, separates (i) minimal deformation-related microstructures as well as ankeritised dolomite in the hanging wall from (ii) brittle-ductile to ductile folded calcitic (ultra-) mylonitic marbles with thin quartz layers and carbonate-derived cataclasite, greenschist facies chloritic and quarzitic schists in the footwall. The faults dip at low angles towards the NNW.

The mylonites have a pronounced stretching lineation and has maximum plunge of ca. 20°-40° towards the NNE, parallel to the overall brittle kinematics extension direction.

Gentle folding of the Otzias Bay Detachment and the structurally upper cataclastic zones about essentially NNE-SSW orientated axes, upright close folds plunging to the north, suggests that a WNW-ESE (and E-W) shortening component during extension (as documented elsewhere in the Cyclades, e.g. Naxos, Lister 1984; Jolivet 2004) accompanied deformation from ductile, through brittle-ductile to brittle conditions. Wavelengths of folds vary from a few centimetres to several tens of metres.

The low-angle normal fault geometry is distinguished by subhorizontal foliation and fold-axial planes.

Figure 47. Schmidt’s equal area projection of the lower hemisphere of foliation (S), stretching lineation (L) and fold axis of the Otzias Bay Detachment, computed eigenvector 017/10 (left). Mylonitic foliation and stretching lineation (L) refolded around a fold axis of 043/23 at the area of the Otzias Bay Detachment (right).

Figure 48 see next page. Line drawing illustrating the fault-rock zone rock distribution at the Otzias Bay Detachment, view SSW. Colour code of lithologies highlighted according to geological legend of Figure 7. Dashed red line represents the sharp contact of the low-angle normal fault, folded on an intermediate-scale by upright, E/ESE-W/WWNW oriented folds (see Fig. 47 left for data plot). Middle left: close-up of a typical outcrop view of the major knife sharp LANF which separates brittle cohesive cataclasite of the fault-rock zone from brittle-ductile to ductile marbles in the footwall, (person
for scale). Small inlet in the bottom right corner of the line drawing marks the location of the Otzias Bay Detachment within the over low-angle normal fault geometries on Kea by a red line and arrow for the displacement direction. E 266271, N 4174017.
3.4.1.6 Field evidence for brittle-ductile transition?

There are multiple deformation features mapped in the scope of this thesis that clearly evidence brittle-ductile behaviour. Examples like the re-mobilised cataclasite seem to record a switching between the two behaviours.

See figure 49 and 50 for further illustration.

3.4.1.6.1 Low grade ductile - high grade ductile - brittle

Within the overall fault system of Kea, the Otzias Bay Detachment is part of a higher strain shear-zone.

The detachment dips at low angles towards the NNW. The calcitic blue-grey marbles (mylonitic) of the footwall have a pronounced stretching lineation (see Fig. 49, blue line) which has a strikingly constant SSW-NNE orientation that shear criteria show formed during top-to-south movement.

The varying orientations of faults and veins indicate different generations and multiple reactivation periods (see chapter 3.4.7.1 & 3.4.7.2).

Axes (see yellow dashed line in Fig. 49) of non-cylindrical folds in the marbles have rotated into the finite stretching direction, generating various stages of ductile sheath-/refolds (see chapter 3.4.2 for figures and further discussion).

Gentle folding of the Otzias Bay Detachment and the structurally upper cataclastic zones about NNE-SSW orientated axis (see Fig. 49, dashed yellow line), suggests that a WNW-ENE shortening component accompanied deformation from ductile, through brittle-ductile to brittle conditions.

Late brittle cross-cutting steep faults are cross-cutting the footwall and fault-rock zone rocks throughout the examined area (at the Otzias Bay Detachment marked by grey dashed line, see Fig. 49).

Various stages of transition from ductile, brittle-ductile to brittle can be observed, representing the exhumation history of the low-angle normal fault system during Miocene extension.

Figure 49 see next page. Top big photo of the main deformation features at the Otzias Bay Detachment. Note the displacement along a late high-angle fault in the centre left traced by a grey dotted line. Arrows indicate shear sense. E 266271, N 4174017.

Upper left picture: post-mylonitic brittle-ductile folding of calcitic ultra-mylonitic marble (and rmc), with kink bands, a type flanking fault, fault drag and later brittle joint displacement (mint green square and dotted line, see next figure for details). This units form large-scale folds and due to different generation and a change in fold orientation it finally develops into dome and basin structures in the detachment footwall.

Upper right picture (greyish frame) highlights a late brittle steep fault marked by a blue dotted line.

Bottom left picture: light green dotted line in the upper left corner (yellow frame) traces fault planes within the hw-cataclasite parallel the Otzias Bay Detachment plane. Blue line represents the overall stretching direction lineation; yellow dashed line the fold axis.

Bottom right picture: refold structure, note the fold axis parallel to the lineation (same colour code).
Figure 50. Photograph and line drawing of the assumed brittle-ductile transition zone within the calcitic
ultra-mylonitic marble reflecting the deformation history in parts. Various stages and cross-cutting
relationships of late brittle overprint of ductile large-scale folded footwall rocks can be observed. Post-
mylonitic brittle-ductile folding of mylonite, with kink bands, fault drag, A-type flanking fault and joint
displacement can be viewed. E 266238, N 4174083.

Brittle faults marked by brown dashed line represent WSW-ENE and E-W orientation corresponding to
$D_n$ and (?) $D_{n+1}$. These faults might originally have been directed equally but due to a later brittle
overprint, orientations now seem to have changed or, to provoke discussion, have already represented
two different orientations in the first place, then overprinted by late brittle steep faults of $D_{n+2}$. (see
table 1 in chapter 3.4.8 for further discussion).

Photo and line drawing corresponding to mint green frame in figure 49.
3.4.1.6.2 The Niemeijer and Spears Model

Typical microstructures from rock analogue experiments using halite-muscovite mixture deformed with different sliding velocities (Niemeijer & Spiers 2006, 2007) suggest two major different deformation mechanisms:

In the velocity strengthening regime (i.e. low sliding velocities), the samples record a mylonitic fabric with a continuous, anastomosing foliation resembling SCC'-type foliation formed by slip along the mica flakes and diffusive mass transfer processes.

In contrast, the microstructures in the velocity-weakening regime (high sliding velocities) resemble a cataclasite with no foliation and a large variation in grain size and a chaotic fabric. The deformation mechanism involves pervasive granular flow with grinding and rounding of grains associated with dilation and compaction solution transfer processes (Fig. 51).

As part of this thesis movement and deformation mechanisms along the low-angle normal fault system on NW-Kea were looked at into detail, for mesoscopic structural features, like intensely developed SCC'-type foliation next to well-rounded clasts of sorts, suggested brittle-ductile dominated deformation.

For gathering further evidence samples along a profile across the Otzias Bay Detachment within the hw-cataclasite were taken. Thin sections revealed that these record strikingly similar structures with a variety of transitions between the mylonitic and cataclastic end-members (Fig. 52 & 53).

Interestingly, both transitions from mylonitic to cataclastic fabrics but also cataclastic fabrics overprinted by mylonitic SCC'-foliations can be observed. All deformation mechanisms are associated with the formation of different generations of extension gashes suggesting the general presence of diffusive mass transfer mechanisms.

Some veins generations are ductilely rotated and folded with fold axes perpendicular to the stretching lineation. Other vein generations are cataclastically deformed together with its host rocks (Fig. 54).

Cross cutting relationship of frictional dominated and viscous dominated deformation mechanism suggests that the switch between both regimes occurred several times.

This work therefore suggests that the Otzias Bay Detachment operated as a subhorizontal extensional fault within the brittle-ductile transition zone and that the dominant deformation mechanisms were controlled by non-constant sliding velocities switching between the velocity strengthening and the velocity weakening regime (Müller et al. 2009).
Figure 51. Optical micrographs taken in the course of rock analogue experiments of the constant sliding velocity test as shown in Niemeijer & Spiers 2005 illustrate the microstructural development with increasing sliding velocity in samples deformed wet at various velocities (from 0.03 in A to 13 μm/s in B). Muscovite content is 20 wt% and normal stress around 5 MPa. γ represents the total amount of (wet) shear strain.

Note the progression from a mylonitic structure (A) at low velocity to a cataclastic structure (B) at high velocity. The frictional resistance versus deformation rate plot illustrates the (cyclic-) curve and style of rock deformation during increasing deformation. Stress in the rock builds up as frictional resistance during velocity strengthening before finally reaching a certain peak. There a change in deformation (from brittle-ductile pressure solution to ductile rolling of grains) then leads to a momentary (remittent?) drop in stress. Modified after Niemeijer & Spiers (2005) and Grasemann (2007).

Multi-stage cataclastic faults and viscous deformation mechanism features like SC-fabric developed in the cataclasites (evidence of strain-rate dependency, stable sliding during periods of velocity strengthening) next to mylonitic structures (initiated at a stress drop during periods of velocity weakening) indicate a several reactivation periods (creep and dynamic rupture) of the Otzias Bay Detachment low-angle normal fault system, small and also large-scale.
Figure 52. Thin section perpendicular to the main high strain foliation and parallel to the mineral stretching lineation, five-fold magnification (sample M/K 10, cataclasite, mylonitic bands) Optical micrographs showing microstructural development as in the constant sliding velocity test (Fig. 51) by Niemeijer & Spiers (2005) in samples taken at the base of the Otzas Bay Detachment hw-cataclasite and rmc.

Increasing sliding velocity in samples A to B results in a progression from mylonitic structure at low velocity (A) to a cataclastic structure at high velocity (B). Shear sense as indicated. We therefore suggest several reactivation periods (creep and dynamic rupture events) along the LANF on Kea.
Figure 53. Shear criteria right at the Otzias Bay Detachment rmc and hw-cataclasite in macro (E 266239; N 4174067) as well as micro scale (sample M/K 10).

Upper photo (previous page): outcrop view of the ultra-mylonitic marble, rmc and hw-cataclasite. Black dashed lines mark SC-fabric, red dashed line indicates the fault plane, brown and white dashed lines represent fault pattern, blue line highlights the stretching lineation.

Bottom photo: thin section image. Strain seems to focus on bands hosting rounded components within the cataclastic matrix due to a variation in frictional behaviour (A- and B-zone after Niemeijer & Spiers 2005, see Fig. 51 for comparison). Thin section perpendicular to the main high strain foliation and parallel to the mineral stretching lineation.

Figure 54. Thin section image of components of cataclasite with ultra-mylonitic bands. Components made up of former mylonites. Vein generations represent former vein vibres next to nearly rounded clasts indicating stages of break-up within the cataclasite. These older veins become cataclastically deformed together with its host rocks. (sample M/K 20b). Thin section viewed in analysator light at five-fold magnification, unorientated sample.
3.4.2 Brittle Deformation

The varying orientations of veins and faults indicate different generations and multiple reactivation periods. An superposition of ductilely deformed footwall rocks by various stages of late brittle overprint, like e.g. mode 2 cracks (Irwin 1957, see Fig. 58) alternately being refilled by ore-rich fluids, quartz and calcite, can be observed throughout the area.

In some places minor faults bearing angular-breccia of host rock are filled with travertine and calcite (see Fig. 63). Those faults cross-cut older sets of veins and joints and continue into the cataclastic domains of the fault-rock zone. Suspended nature (“frozen-in” status) and restorable geometry of broken fragments puts dynamic rupture accompanied by high fluid pressure into debate.

Furthermore evidence for a cataclastic injection (see Fig. 64) into a calcitic ultra-mylonitic marble indicates high fluid pressure syn- to (immediately) postdating the emplacement of the cataclasite.

The absence of evidence for (co-seismic) pseudotachylite, however, abundant in the steep faults throughout the examined area was observed.

A very late stage of brittle overprint (associated with $D_{n+2}$) is represented by major cross-cutting steep faults.

![Figure 55. Lower hemisphere plot and full/quarter rose diagram (circular histogram plot displaying differing types of directional data together with the frequency of each class) of the brittle overprint, giving the orientation and number of observed faults and veins/joints (in a way conjugated set of brittle features, moderately to steeply dipping, major trend NNE/SSW, NNW-SSE with a subsidiary trend almost NE-SW and a minor developed set of WNW-ESE and WSW-ENE trending faults - left, right –](image-url)
joints orientated NNE/NE-SSW/SW and NW-SE, a distinct dip direction towards the SSW spreading SW and S as well as a minor direction to the NE is given here) of the brittle fault pattern within the footwall rocks and the fault-rock zone.

Pi-plot of the brittle fault planes shows a major NNE/NE-SSW/SW fault orientation and a minor developed WSW-ENE and NNW-SSE directed orientation (left).

Pi-plot of the brittle joints shows a NNE/NE-SSW/SW orientation and a NNW-SSE as well as a NE-SE directed orientation (right).

### 3.4.2.1 Faults

A multi-stage late brittle fault system consists of widely spaced high-angle faults as well as steeply dipping to subvertical (hydro-)fractured veins – alternately filled by ore-rich fluids, quartz and calcite. Brittle faults are associated with hydrothermal activity – high fluid infiltration by hydrothermal fluids, ground fluids - leading to iron ore deposition (see also chapter 5, Fig. 87 & 88).

Disseminated brittle fault-zone networks associated with \( D_{n+1} \) and \( D_{n+2} \), post-date the cataclastic flow (see chapter 3.4.1.6.2 for deformation history).

Overall geometry of the fault network in the mapped area is quite complex as various generations of faults can be observed. The pattern of shallow and predominantly steep dipping faults can be seen in both, the footwall and the fault-rock zone rocks, with a difference in E-W striking of faults and a variation in dip directions, note a greater variance in dip within the footwall rocks compared to fault dip in the fault-rock zone (see Fig. 59 & 62 for comparison).

Examples and data for faults within the footwall rocks:

Figure 56. Left photo: several sets of en-echelon array quartz filled tension gashes (feather veins) are developed in ultra-mylonitic marble and re-mobilised cataclasite of the semi-brittle sinistral strike slip shear zone (see Fig. 57 for data plot). Fractures used to be perpendicular to the minimum compressive stress but the central portion of the fracture started to rotate during ductile shearing which ended up with the sigmoidal shape visible. The tips of these gashes are still perpendicular to the minimum compressive stress (e.g. Twiss & Moore 1992). Red arrows indicate sense of shear. E 266274, N 4174200.

Right photo: tension gashes (framed by black line) in en-echelon arrangement in the schist near the shear zone. The sense of curvature of tension gashes and foliation is similar (see Fig. 57 for data plot). E 265927, N 4174256.
Figure 57. Schmidt’s equal area projection of the lower hemisphere of foliation (great circles), stretching lineation (L) and tension gashes (planes, S) at the Otzias Bay Detachment. Note the NNE/NE-SSW/SW extension direction parallel the stretching lineation.

Figure 58. Mode two strike slip fault breaking up and dislocating a clast within the re-mobilised cataclasite, causing an offset of about a cm. Red arrows indicate direction of movement along the fault plane (mode 2, Irwin 1957). Note zoned mineralisation of the fault. Sketch to the left redrawn after Voit 2008. E 266274, N 4174200.
Figure 59. Lower hemisphere plot and full/quarter rose diagram (circular histogram plot displaying differing types of directional data together with the frequency of each class) of the brittle overprint of the footwall rocks, giving the orientation and number of observed faults and veins/joints. Main features are striking NW-SE with a minor developed WNW-ESE and NNW-SSE direction as well as a kind of conjugated set striking WSW-ENE and NE-SW - left, main dip direction towards the SSW/SW but also NNE/NE and, minor developed NW-SE, most structural features are dipping steeply to intermediate - right) of the brittle fault pattern.

Pi-plot of the brittle fault planes shows a major NNE/NE-SSW/SW fault orientation and a minor developed WSW-ENE and NNW-SSE directed orientation (left). Pi-plot of the brittle joints shows a NNE/NE-SSW/SW orientation and a NNW-SSE directed orientation (right).
Slickensides are not very common in the area but still a few could be mapped and measured in the schists of the footwall.

Figure 60. Slickensides developed as fibrous crystals of quartz on a stepped brittle fault plane within the footwall schist show a movement direction down, line drawing in the upper right corner of the photo represents the movement direction of the actual fault plane visible. E 263648, N 4172670.

Figure 61. Angelier lower hemisphere equal-area plot of brittle fault planes and associated slickensides occurring within the footwall schist. Conjugate shallow-dipping brittle fault planes indicating NE–SW extension direction. A set of high-angle fault planes has been identified as well.
Examples and data for faults within the rocks of the fault-rock zone:

Figure 62. Great circle lower hemisphere plot and full/quarter rose diagram (circular histogram plot displaying differing types of directional data together with the frequency of each class) giving the orientation and number of observed faults and veins/joints (3 directions are identifiable here, the main striking towards NW/WNW-SE/ESE, the second minor distinct direction is forming an interesting set striking WNW-SSE and perpendicular NNE-SSW. Further directions are WSW-ENE and a well developed E-W orientation – left, mainly dipping at a high angle toward the S/SSE/SW and some NE -right) of the brittle fault pattern within the fault-rock zone.

Pi-plot of the brittle fault planes shows a major NNE/NE-SSW/SW fault orientation and a minor developed NW-SE and NNW-SSE directed orientation (left).

Pi-plot of the brittle joints shows a NNE-SSW orientation and a NNW-SSE directed orientation (right).

3.4.2.2 Joints and veins - the role(s) of fluids

Joints and veins in cross-cutting relationship to the finite stretching lineation at the Otzias Bay Detachment show at least three different orientations measured, present right in the low-angle normal fault adjacent area: J₁ 358 (white carbonate infill material), J₂ 028 (white carbonate infill material) and a young J₃ of 015 (brown infill material).

Healed up joints of cataclasitic broken angled fragments suggests the formation within an event of high pressure fluid break-up as well as highly fluidised cataclastic injection vein, both present at the Otzias Bay Detachment. Similar hydrofracturing events were observed by e.g. Collettini & Holdsworth (2004) (see Fig 63 & 64 & chapter 3.4.6.2 for similar examples of observations on Kea).
Figure 63. Left photo: only a hand-full healed up joints of angular breccia of the youngest generation (probably associated with either $D_{n+1}$ or $D_{n+2}$), filled with travertine and calcite, cross-cut older sets of veins and joints along the Otzias Bay Detachment as well as the cataclastic schist and re-mobilised cataclasite (person for scale). E 266274, N 4174200.

Right photo: suspended (‘frozen-in’) nature and restorable geometry of cataclasitic broken angled fragments suggests the formation within an event of high pressure fluid break-up (Müller et al. 2006). Due to (fluid?) overpressure within the rock it starts to fail and finally breaks apart to stress can drop. Weak planes of faults hereby act as conduits for calcitic fluids. E 266274, N 4174200.

Figure 64. Left photo: (in-?)cohesive highly fluidised cataclastic injection vein (brown stuff) with broken-up components of various sizes of the surrounding rocks filling hydraulic injection apophysis along a fault into an ultra-mylonitic marble indicating high pressure.

Right photo: close up. E 266366, N 4174450.
3.4.3 Deformation mechanisms and history

After detailed data analysis and interpretation of lithological/structural field observations (see Fig. 65) a deformation history based upon preliminary results suggests the following division (implicating transitions between the like):

\( D_{n-1} \) - high grade ductile dominated deformation (associated with M1)

Probable formation of clasts, development of folds along an E-W axis in the schists and blue-grey marbles as well as an E-W oriented lineation is associated with this event.

\( D_n \) - medium grade ductile dominated deformation (associated with M2)

This is assumed to be the main deformation phase. Ductile deformation and mylonitisation of rocks dominates this event. The deformation stage is associated with a lineation that parallels the stretching direction NE-SW/NNE-SSW, fold axis are now developed along a NE-SW direction. Progressive formation of sheath folds.

\( D_{n+1} \) brittle-ductile dominated deformation

Likely associated with the cataclastic overprint are two lineation directions observed at the Otzias Bay Detachment. Moderate to steeply dipping faults are developed in the footwall rocks, slightly differing from the pattern within the fault-rock zone. Fault planes are oriented E-W. Velocity weakening/strengthening processes within the hw-cataclasite are taking place.

\( D_{n+2} \) - brittle dominated deformation

A late stage of steeply dipping faults cross-cuts both, the footwall rocks and the fault-rock zone. Probably related to this, and/or the previous event are late healed up joints of angular breccia and also highly fluidised cataclastic injection veins.

In general in the examined area, the mean foliation and fold axial surfaces are sub-parallel and dip shallowly northwards. Folds are observed in all scales and show small to long wavelengths. These are close to tight, rarely isoclinal and in some areas interference fold patterns and even sheath folds, indicating higher strains, can be observed. Minor folds in the NW are variably orientated. Shear criteria like SC-fabric, \( \delta \) and \( \sigma \) clasts as well as a consistent and well-developed stretching lineation, indicate top-to-SSW sense of movement.

Generations of brittle fault overprint and in-filled veins are widespread with a cumulation towards the fault-rock zone at the area of the low-angle normal fault.

<table>
<thead>
<tr>
<th>( D_{n-1} )</th>
<th>deformation</th>
<th>fold axis</th>
<th>FA</th>
<th>lineation</th>
<th>Lin</th>
<th>fault plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>high grade ductile (M1)</td>
<td>E-W</td>
<td>270</td>
<td>E-W</td>
<td>080</td>
<td></td>
<td>pre-mylonitisation</td>
</tr>
<tr>
<td>medium grade ductile (M2)</td>
<td>NE-SW</td>
<td>225</td>
<td>NE-SW</td>
<td>045</td>
<td>ENE-WSW</td>
<td>main mylonitisation</td>
</tr>
<tr>
<td>brittle-ductile</td>
<td>NNE-SSW</td>
<td>190</td>
<td>NNE-SSW</td>
<td>010</td>
<td>E-W</td>
<td>myl. &amp; ultra-cataclasis</td>
</tr>
<tr>
<td>brittle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>post-myl. &amp; cataclasis, faults</td>
</tr>
</tbody>
</table>

Table 1. Overview of the (preliminary) deformation stages based on the observations and implications in the course of investigating the study area on the NW-part of the island of Kea.
Figure 65. Schematic synoptic diagram of the footwall and fault-rock zone at the Otzias Bay Detachment Shear zone on NW-Kea and summarizing the main tectono-lithostratigraphic units of the footwall and the fault-rock zone and furthermore highlighting the features of the various deformation events. Arrows indicating the two main (red) and minor (yellow) SSW-displacement direction planes. As the latest brittle overprint, high-angled faults and small fill veins have been identified.
3.4.3.1 Timing of deformation phases on Kea relative to metamorphism (greenschist facies) – geochronology on white mica

In the course of the second field season (followed by more sampling in the years after) samples for $^{40}$Ar/$^{39}$Ar thermochronometry on white mica were taken in cooperation with D.A. Schneider, University of Ottawa (Canada), in various parts of the Island of Kea, including the northwest. White mica was separated from micaceous schists (samples M/K 1b, M/K 94, M/K 101) and analysed using conventional incremental heating techniques at New Mexico Tech Geochronology Laboratory.

Overall on Kea $^{40}$Ar/$^{39}$Ar plateau ages generally constrain mid-crustal cooling to between 20-15 Ma (Schneider et al. 2007), whereas ages vary from 14.81 ± 0.07 Ma for M/K 1b, a phyllonite located close to the Otzias Bay Detachment, and 18.50 ± 0.53 Ma for a schist sample (M/K 101). Mineral splits of the same separates were also analyzed at New Mexico Tech Electron Microprobe Laboratory for elemental abundances to confirm mica chemistry and homogeneity of mineral composition. All of the mineral separates were characterized by 45-50 wt% SiO$_2$, 0.35-0.65 wt% Na$_2$O, 10-11 wt% K$_2$O and Fe/(Fe+Mg) ratios of 0.50-0.70, confirming a phengite mineralogy (Vogel 2009). Some samples, mostly those with disturbed age spectra (e.g. M/K 94), contain intergrown chlorite within the white mica crystal host.

The white mica-chlorite relationship likely explains the low-temperature stair-step shape of the $^{40}$Ar/$^{39}$Ar release spectra, but we are confident that the ages are nonetheless a fairly good representation of the bulk sample’s cooling through 350°C.

Still further investigation and detailed in situ laser thermochronology needs to be carried out to reveal whether these mica ages constrain "cooling" or "deformation / recrystallisation". However, looking at thin sections of these samples (M/K 1b, M/K 101) one can assume the white mica minerals as major distinct mineral forming the foliation planes rather than just occurring randomly within the rock. Therefore it is likely that these ages constrain the timing of mica recrystallisation and thus, deformation on Kea.

Nevertheless, implications on the deformation history of the area might be taken with care but it might give us a frame after all as it shows here a younger deformation fitting into the picture of the Miocene extension age within the Cyclades.

![Figure 66. $^{40}$Ar/$^{39}$Ar spectra for sample M/K 1b (phyllonite) and sample M/K 101 (schist), (after Schneider et al. 2007).](image-url)
4. Strain analysis

In attempt to quantify the kinematic flow for the area adjacent to/of the higher strain zone structural data was gathered in the field. Therefore a domain of gneissic schists hosting trains of elongated boudins was further investigated (see chapter 4.1.3).

In this portion of the work the Mohr circle of the Second Kind is used to quantify the kinematic flow (De Paor & Means 1984). This illustrates the amount and nature of the finite shear strain in this particular area.

Non-rotated, discordant quartz filled veins, spread over the examined area, represent those indicators present before the finite strain was imposed while suitably orientated stretched (boudined) veins are those indicators used to constrain finite strain.

As a realistic scenario, one interpretation shows a high non-coaxial component and a vorticity number near to 1 as well as a delta near to 135° thereby indicating simple shear. The undeformed- to deformed-area contrast provides an exciting view of a volume-increase associated with the input of vein-fill material (assuming plane strain and predominantly simple shear) (Müller et al. 2007).

Furthermore, using a dilatancy term, we modify the velocity gradient tensor dependent on the stretching rate factor, kinematic dilatancy and vorticity number, to illustrate the change in the volume increase with changing amount of shear strain and at various (e.g. increasingly greater) pure shear components (Ramsey & Huber 1983; after Grasemann et al. 1999; Ebner & Grasemann 2006; Grasemann et al. 2006).
4.1. Quantitative kinematic flow analysis using Mohr circle of the 2\textsuperscript{nd} kind

![Mohr circle diagram](image)

Figure 68. Mohr circle of the general velocity gradient tensor $L$ (for area increase). Shown are relationships between instantaneous stretching axes – $ISA_{1,2}$; eigenvectors of flow – $a_{1,2}$; differential stretching rate – $S$; vorticity – $W$; and angles $\alpha$ and $\beta$ whose cosine give kinematic vorticity ($W_k$) and kinematic dilatancy ($A_k$), respectively. Note $\epsilon$ is the axis where the stretching rate is plotting, $\omega$ is the axis for the angular velocity.

4.1.1 Field data

Structural data gathered in the field for the attempt to quantify kinematic flow utilised domains of gneissic schists hosting trains of elongated boudins.

Several generations of extension gashes filled with calcite, quartz and actinolite are widespread throughout the mylonitic rocks, schists and gneisses. Locally situated in these schists, some extension gashes with associated flanking folds are rotated into the shearing direction developing trains of elongated boudins over a few meters.

To estimate the stretch within these trains of elongated boudins measurement for calculating $L$ (the length of the boudin train) and $L_0$ (initial length of the boudinaged vein before deformation) were taken.

Furthermore measurements of the angle between the boudin train and the fabric attractor, here represented by the foliation, and also the assumed non-rotated orientation of the boudinaged veins, represented by discordant cross-cutting veins acting as indicators before our finite strain constraints, were taken.

Photographs in figure 69 correspond to the line drawing in figure 71 of boudin trains and perpendicular quartz filled veins, present over several meters, in the examined rocks. Equal
area plots of the lower hemisphere of figure 70 show foliation orientations on the left and represents a consistent vein orientation in the plot to the right.

Figure 69. Extension gashes with associated flanking folds (Gascombe & Passchier 2003) within the schist are rotated in shearing direction and have developed trains of elongated boudins. Cropping out over several metres the boudin train shows progressive stages of rotation due to shearing to-the-SSW as indicated by red arrows. Small red arrows show the extension direction. E 265275, N 4173902.

Figure 70. Great circle plot/equal area projection of the lower hemisphere shows plane orientation (S) and lineation (L) on the left and consistent dip to the SW of extension gashes (joints, Sj) on the right.
Figure 71. Quartz boudinage in schist with veins, partly cross-cutting regularly-spaced single boudins. Non-rotated, discordant veins represent the indicators before our finite strain constraints. In places, some veins are sheared and have started to rotate. Line drawing (enhanced, not to scale) represents the quartz boudins cross-cut by younger veins. E 265275, N 4173902.

Various studies of quantitative kinematic flow studies on naturally sheared rocks suggest that shear zones record a layer-normal thinning and at the same layer-parallel stretching component (e.g. Lister & Williams 1983; Passchier 1987; Simpson & De Paor 1997; Law et al. 2004).

In the examined rocks of the study area the initial opening of the veins likely is slightly oblique to the foliation which suggests an opening normal to the ISA$_1$ (maximum instantaneous axis, Ramsey & Huber 1983). The older veins are assumed to then have rotated during shear deformation while still new ones developed in the direction of ISA$_2$ (minimum instantaneous stretching axes, Passchier & Trouw 1996).

4.1.2 Physical space – Mohr space

The physical space comprises measurements of angles and orientations taken in the field (see Fig. 70 & 71) as described in chapter 4.1.3. Measured angles then are conveyed into a numerical model of the physical space (see Fig. 73 A).

To draw a Mohr circle these need to be transferred into the Mohr space.
4.1.3 Quantification of area/volume increase

In an attempt to quantify the kinematics a Mohr circle of the Second Kind was constructed. Using field data as well as modelling different scenarios this illustrates the amount and nature of the finite shear strain as well as a massive area-increase.

From suitably orientated and stretched (boudined) as well as non-rotated veins, we obtain key constraints of before and after finite strain (e.g. the instantaneous stretching axes, fabric attractor, finite stretch). Moreover, the undeformed- to deformed area contrast provides an exciting view of a area/volume-increase associated with the input of vein-fill material (assuming plane strain and simple shear).

This is further quantifiable with the new area-increase (e.g. volume-increase) deformation tensor of Grasemann et al. (2006) used by him for modelling melt-input influenced slab extrusion for orogenic wedges.

This part of the thesis shows examples of finite deformation of a unit square for the matching finite deformation tensor $D_{ij}$ after a time increment 1 and corresponding Mohr circle construction illustrating the deformation gradient tensor $D$ as derived from the examined shear zone, having constant stretching factors $S = 2$ and $S = 1.33$ used in physical space.

Examples are shown for kinematic vorticity numbers (a measure of the rotational quality of a flow type) of a) $W_k = 0.86$ b) $W_k = 0.64$ c) $W_k = 0.34$. $\beta$ is the angle between eigenvectors of flow, $\delta$ is the angle between ISA$_2$ and the shear zone boundary. Dots on the Mohr circle represent the orientations of the ISA$_1$ and ISA$_2$ before deformation.
Note that, for flow with area change, the Mohr circle in figure 73 on the right side indicates area/volume increase.

In (A) of figure 73 and 74 Physical space and geometrical orientation of the Instantaneous stretching axes (ISA₁ and ISA₂) and eigenvectors (a₁, acting as fabric attractor and a₂) of flow are given. The vein m₂ which is parallel to the ISA₂, rotated during deformation to an orientation m₁ (boudinage represents finite stretch) by an angle of ψ (amount of shear strain). In this example, the angle between the boudin train and foliation is assumed to be 25°. Other scenarios, represented by changes in this angle, are shown in table 3.

In (B) of figure 73 and 74 Mohr circle construction of the position of the Lagrangian position gradient tensor (Dᵢⱼ, polar coordinates of points on the Mohr circle representing the rotation and stretching of material lines in real space, Means 1982) for the flow that rotated m to m₁, with Wᵦ (kinematic vorticity number) equal to the cosine of β. A value of Wᵦ near to 1 as well as a δ near 135° indicates simple shear. As the most realistic scenario, a) shows a high non-coaxial component although finite strains are moderate.

Two further Mohr circles b) and c), constructed for two further datasets, illustrate the change in volume increase with a changing amount of shear strain and a higher pure shear component.

This actually is a good starting point to think about a 3 by 3 matrix for an accurate and mathematically correctly estimated/calculated amount of volume-increase as this needs to be done in a XYZ-coordinate system.

Further investigations into the mechanical behaviour of the boudined veins as well as chemical rock and vein-fill material analyses not covered within this work, would help quantify the most realistic scenario for volume-increase for our model.

However, this study has been a highly simplified first attempt.
Figure 73. Physical space (A) and Mohr space (B) for simple shear dominated zones, medium values general shear and pure shear dominated areas.
Figure 74. To cover the range of and a possible error in orientation of m1 (boudins) and ISA2 (cross-cutting veins, primary orientation before the elongation and rotation) to a1 (foliation, fabric attractor) we show various Mohr circle construction for medium values general shear extension and pure shear dominated extension illustrate the change in area increase with a changing amount of shear strain to a higher pure shear dominated component.

(A) Physical space, numerical model

\[ W_s = \cos \beta = 0.64 \]

\[ \alpha = 20^\circ, \quad \beta = 50^\circ, \quad \delta = 110^\circ, \quad \gamma = 85^\circ \]

(B) Physical space, Mohr space

**Medial values general shear extension**

\[ D_{g} = \begin{pmatrix} 5.648 & 3.985 \\ 0 & 0.899 \end{pmatrix} \]

\[ D_{g} = \begin{pmatrix} 3.765 & 2.656 \\ 0 & 0.599 \end{pmatrix} \]

**Pure shear dominated extension**

\[ D_{p} = \begin{pmatrix} 11.474 & 3.864 \\ 0 & 0.858 \end{pmatrix} \]

\[ D_{p} = \begin{pmatrix} 7.649 & 2.576 \\ 0 & 0.572 \end{pmatrix} \]

\[ l_s = 75 \text{ cm} \]
\[ l = 100 \text{ cm} \]
\[ l_i = 1.33 \]
\[ l_0 = 50 \text{ cm} \]
\[ S = 2 \]

\[ (k,0) \quad (r,1/k) \]

---

\[ l_s = 75 \text{ cm} \]
\[ l = 100 \text{ cm} \]
\[ l_i = 1.33 \]
\[ l_0 = 50 \text{ cm} \]
\[ S = 2 \]

\[ (k,0) \quad (r,1/k) \]

\[ \text{ISA / vein} \]
Figure 75. Examples of finite deformation of a unit square (dark grey) for various flow types, including finite area-increase (light grey). $\beta$ is the angle between eigenvectors of flow, $\delta$ is the angle between ISA$_2$ and the shear zone boundary. The stretching eigenvectors are fixed to the $x$-direction, assuming constant value stretch ($S = 2$). The labels a, b and c are referring to the examples of Mohr space further illustrated in Fig. 73 & 74.

Using the software Mathematica (Wolfram 1999) and basic trigonometry, we developed a simple code to calculate various finite deformation parameters to cover a great range of different possible scenarios and to better estimate an area change for the area.
Table 2 Excel sheet based on calculations done by the use of the software Mathematica examines the amount of area-increase $D$ for a stretch of $S = 2$ with changing $W_k$ for various angles, assuming $25^\circ$ between fabric attractor and the boudinage-train $m_1$. This has been done for a variety of other angles as well (see table 3) so to better get a mean error and to cover a broad range of possible scenarios.

<table>
<thead>
<tr>
<th>alpha</th>
<th>beta</th>
<th>gamma</th>
<th>delta</th>
<th>Wk</th>
<th>$D (S = 2.00)$</th>
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</thead>
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<td>65</td>
<td>90</td>
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</tr>
<tr>
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<td>1881,000</td>
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<tr>
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<td>90</td>
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<tr>
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</table>

Plot 1 illustrates various angles of stretch $S$ and $W_k$ (vorticity number) for a wide range of possible scenarios according to numbers calculated in table 3. The simple shear-dominated cases show only minor area-increase (in this case area-increase) compared with the pure shear-dominated cases which, surprisingly, have a significant higher area-increase.

Table 3. Excel sheet based on calculations done by the use of the software Mathematica gives results for area-increase $D$ inventing a variation in the angle between fabric attractor and the boundinage-train $m_1$, and the stretch $S$.  

<table>
<thead>
<tr>
<th>alpha</th>
<th>beta</th>
<th>gamma</th>
<th>delta</th>
<th>Wk</th>
<th>angle of $D (S = 2,587)$</th>
<th>angle of $D (S = 2,587)$</th>
</tr>
</thead>
<tbody>
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<td>65</td>
<td>90</td>
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<td>15°</td>
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<td>110</td>
<td>135</td>
<td>1</td>
<td>239.14</td>
<td>89.69</td>
</tr>
</tbody>
</table>

Plot 1 illustrates various angles of stretch $S$ and $W_k$ (vorticity number) for a wide range of possible scenarios according to numbers calculated in table 3. The simple shear-dominated cases show only minor area-increase (in this case area-increase) compared with the pure shear-dominated cases which, surprisingly, have a significant higher area-increase.
Figure 76. As an attempt, line drawing illustrating the approximate strain regime inferred for the examined area. The ellipsoid represents vein orientation before (dark-grey ellipsoid), and the boudins after finite deformation (light-grey ellipsoid). Thin black half-arrows on the right show the sense of shear movement direction in the examined area. A W-E compression component is inferred from NNE-trending folds that formed synchronously with the regional vertical shortening and massive N-S stretch (part of the Miocene Aegean extension). E 265587, N 4174115.
5. Evidence for mineral deposits, their historical mining and use in metallurgy on Kea (with a focus on the NW)

As part of this work insights into the historical aspects of Kea in terms of mineral deposits, early settlement accompanied by mining and metalworking (as well as ancient trade in relation to other Cycladic Islands and the mainland) are given in this chapter. Furthermore results on XRD analysis on iron oxide-rich vein fill material are presented.

The Island of Kea is known for abandoned places of mining, metalworking and settlement and what can be interpreted by ‘human remains’, not e.g. bodies found in a cemetery on Kephala so much as the remnants of slag, kilns, shards, stone and metal tools etc. found all over the area.

For a chronological sequence of the periods and phases of Early Cycladic Culture and their presence on the various islands see the timetable in Doumas 2000.

5.1 Final Neolithic Period habitation

Excavations at Kephala (see Fig. 7 & 83 for location) revealed a Late Neolithic settlement which is the only open settlement that fully represents the Final Neolithic Period (4500 - 3200 BC) of the Cyclades (http://www.fhw.gr/chronos/01/en/nl/tn/kefalafr.html).

The similarity of cultural elements at Kephala with its counterparts from settlements in Attica and Aegina led investigators to classify a part of the long Final Neolithic Period in southern Greece with the term Attica-Kephala culture (after). Fine pottery showing a back burned surface and decorated with linear patterns in whitish and red are finds indicating this culture.

It is estimated that the Neolithic community settling at Kephala numbered 45 to 80 inhabitants and had a farming/stock-rearing character but, was also involved into the manufacturing of Melian obsidian tools as well as needles and tools like chisels made out of copper which is assumed to originate from Lavrion in eastern Attica. Artefacts found at the spite give evidence for early settlers’ in situ practice of metalworking as testified by fragments and crucibles.

Also known from the last phases of the Neolithic is the melting of metals in open, shallow clay crucibles at controlled temperatures. Finds of remains of slag (a shapeless mass of burnt metal) have also been recorded from Kephala.

Besides metal finds, excavations also revealed marble vases, shards of pottery (Fig. 80) and remnants of basketry in the form of imprints on vase bases. A conical beaker with a pointed or flat base that is known from Kephala was allocated to the Late Neolithic Period and can be seen as the ancestor of beakers of later periods (Doumas 2000). From Dalmatia there are similar scoops resembling vessels like the ones (probably used for burial rituals) encountered in the cemeteries on Kephala (http://www.fhw.gr/chronos/01/en/nl/tn/fn_potfr.html) (see Fig. 77 & 78).

The cemetery discovered during excavations on Kephala is situated lower that the settlement and encompasses two terraces (see Fig. 78) containing 40 circular or rectangular graves with walls built of stone and their open side sealed with slate slats. It is estimated that during the 60 to 150 years of active use, over 65 dead, infant to aged, were buried.

Interesting to note is that the cemetery on Kephala (unlike other cemeteries e.g. in the Dodecanese) reflects a kind of social differentiation from simple to multiple in the burials.
during which dead were buried in a foetal position. Also offerings like e.g. the conical beaker mentioned before or sometimes figurines, were included. (http://www.fhw.gr/chronos/01/en/nl/society/fn_burialfr.html).

At the end of the excavation, the cemetery was covered with earth so only a slight disturbance in the surface appearance can be seen today.

The reason for settlers to actually give up the settlement at the bay/peninsula of Kephala can only be assumed but it is likely that the community moved to the site of Paoura on Kea.

Figure 77. View of Kephala with the location of the area of the Neolithic graveyard marked with an ellipse. Excavations during which also stone walls and small rectangular stone buildings of a settlement were discovered (to the left of the photo), took place in 1960-66 and 1973. E 264512, N 4173710.

Figure 78. Plan of the Final Neolithic cemetery (4500-3200 BC) on Kephala stretching over two different terraces (Coleman 1977). Source: http://www.fhw.gr/chronos/01/en/gallery/nl/kefala/kef1.html.
5.2 Trade in the Aegean from the Bronze Age to the beginning of the Antiquity

The Early Bronze Age in the Cyclades is known as the Early Cycladic (3200 - 2000 BC), subdivided into Early Cycladic I (3200 – 2800 BC), Early Cycladic II (2800 – 2300 BC) and Early Cycladic III (2300 – 2000 BC) (Doumas 2000). These three periods are based on the development of settlement and technical achievements. Their chronological sequence was confirmed by the stratigraphy at the settlements of Ayia Irini on Kea and Phylakopi on Melos.

The history of trade in the Aegean does not have a definite point of origin, its roots are rather lost in the depths of centuries of the history of mankind. However, to set a rough timeframe the earliest metal artefacts known at present from the Cyclades date to the Final Neolithic (FN 3200 - 4500 BC, timetable of periods after Doumas 2000, p. 20) with examples from Naxos, Mykonos and Andros. From the same period come the earliest finds of slag and metallurgical ceramics associated with copper production from the settlement of Kephala on Kea (Coleman 1977, see chapter 5.1).

In the ensuing Early Bronze Age (EBA) both the metal artefacts and the metallurgical remains increase in the archaeological record and are seen as one of the prime stimulants for the important social changes observed in the Cyclades during the EBA I.

Bronze Age

In Europe, the Bronze Age comprises the period between late 4000 BC until the beginning of the 2000 BC. It was the time when metal objects were manufactured mainly from bronze, usually an alloy made of copper and about 10% tin, but additionally also alloys with antimony instead of tin are known.

In contrast to the relatively easy availability of copper ores in the Aegean and surrounding area, tin had to be imported from afar, therefore cultures of the Bronze Age had to organise a kind of metal-network, which lead to serious changes in the structure of the society. Local restricted access to the resources and control over the right of mining and trading led to the development of social differences. As a consequence of this, upper-class societies like e.g. the Minoan Palace-culture developed.

Evidence for trade

About 2000 BC, the Aegean population had developed a kind of standardised weights system. The idea of the modular unit and a system of numeration had been invented. People were using weights to control and exchange, or trade commodities. Evidence for this includes a series of approximately 55 lead disc weights found at Ayia Irini on Kea and several others from Akrotiri on Thera and Crete, all of which Petruso (1992) has accommodated within a single standard major weights system. This can be interpreted as evidence for trade relations. Moreover stone weights were used within the same standard system.

Generally usage of weights systems argues for existence of a trading network, which was mainly controlled by the Cycladic islanders during the Early Bronze Age, Minoans during MMA (Middle Minoan Age), and Mycenaeans in the Late Bronze Age. Further evidence for trade relations or at least for the import of materials and goods, is stated by the fact that the Aegeans used raw materials and commodities which did not occur naturally in this region and therefore required transportation. An example is the processing of tin, used in bronzes and as a covering for clay vases, as it does not occur in Crete, the Cyclades or mainland Greece.
Development of the Aegean trade

Early Cycladic Time

In the Early Cycladic Time the Grotta-Pelos Culture and Keros-Syros Culture were the first cultures which could be verified on a number of islands. Characteristics are a strong increase in population during the latter culture as well as dominance of similar ceramic styles among both cultures, which points to an intense exchange of technology between the islands.

Archaeological finds include idols made of marble, ceramics, marble vessels and miniature bowls made of marble green gemstone. Also metal, which was distributed widely for the first time and different kinds of grave goods were found.

Cultural relationships in those times already existed as far as the Greek mainland and Crete. Especially Ayia Irini (see Fig. 7 for location) situated at a well protected natural harbour on NW-Kea provided surprisingly abundant Minoan objects, implicating close relationships.

Middle Cycladic Time

In the Middle Cycladic Time trade in the Aegean had reached new heights. By this time, a trade route through the Cyclades, linking Crete and the Greek mainland, was established. There is mounting evidence that Crete played an important role in the Middle Cycladic Time trading relationships. For buildings and also construction of palaces, as well as for the luxury style of living, more and more products were needed to be shipped to and from the island.

Late Cycladic Time

A striking event during this phase of the Cycladic Time is the massive volcanic eruption (constrained eruption date: 1627-1600 BC, Friedrich 2006) of the Santorini volcano with a strength of 7 (Plinian Eruption, Volcanic Explosivity Index) which buried the town of Akrotiri located in the southern part of the island under masses of volcanic ash and eruptives. Due to the absence of dead bodies or valuables found in the old town, it is assumed that the population of Akrotiri was warned of the eruption, possible by earthquakes preceding the eruption (Friedrich 1994).

The main eruption itself occurred at a time when small reconstruction works on houses had started. This eruption had haunting consequences for daily life in the Aegean region (e.g. people inhabiting the Aegean and adjacent areas had to endure a volcanic winter resulting from dust and gases in the atmosphere shadowing the sun).
Origin of important trading goods

Obsidian from Milos

Navigation among and at least short visits to the islands in the Aegean in the upper Palaeolithic has been testified by the finds of tools made of Melian Obsidian (see Fig. 79) along the eastern coast of the Peloponnese at the cave of Franchthi, approximately 150 km west of Milos. Tools made of Melian obsidian were also found on Crete and Cyprus. Obsidian was a resource lying exposed on the surface and easily available for collection with little effort or skill.

It is assumed that obsidian tools were primarily manufactured on Milos. The material was used among others for various tools and as spearheads, also found on Kea (see Fig. 79).

Silver, copper and lead

By the Early Bronze Age, copper, lead and silver were produced locally in the Cyclades. Several slag heaps or scatters have been reported e.g. on Kea (e.g. Caskey et al. 1988; Papastamataki 1998; Georgakopoulos 2004 and references therein), as well as from Kythnos and Siphnos. Furthermore slag, metallurgical ceramic fragments and/or litharge has been reported from Ayia Irini on NW-Kea (Stos-Gale 1989; Wilson 1999) as well as Syros and Paros, to name a few.

Litharge is a by-product of cupellation, which is the extraction of silver from silver rich lead. Silver was the metal sought after during that period. Lead was not sought for its own sake in the Late Aegean Bronze Age. There is indication of Late Bronze Age silver production at Akrotiri on Santorini and Phylakopi on Milos (Gale 1998). Silver content and lead isotope data rules out the Bronze Age use of lead ores on Antiparos, Kythnos, Poliegos, Syros and Anaphi.
On Kea in particular there is much evidence of metallurgy in the northwest at Ayia Irini and Kephala, in the form of crucibles and tuyeres, small amounts of slag, copper ingot fragments and quite an amount of litharge was already recorded by Caskey (1988) in his excavation report of 1962. Also at Akrotiri and on Kythnos there is evidence for copper production.

The Lavrion Mines

It does seem that in the Aegean, the beginning of silver and lead production is centred in the Cyclades, for it is in Siphons that there is direct C\textsuperscript{14} dating evidence that mining of lead-silver ores was in progress in Early Cycladic Times (EC 2300 – 3200 BC, for detailed timetable see Doumas 2000), whilst most EC lead and silver has been shown by lead isotope analysis to have been made from Siphnian ores (Gale 1998). As for other metal in the Early Cycladic times, there is evidence for smelting of copper on the island of Kythnos copper.

As mining, smelting and cupellation seem to have originated in the Cyclades, it is assumed that, in slightly later times, this expertise was used to discover and exploit the ores in Lavrion. Once discovered, the Lavrion mines had not only the advantage of much larger resources of lead and silver ores than Siphons, but also reserves of copper much larger than available elsewhere in the Cyclades.

Ceramics

The ceramics manufacturers at the settlement of Phylakopi (late EBA to MBA) on Milos produced ware which was found from Crete to the Peloponnese, in the whole Aegean region and the neighbouring mainland. In the village, imported ceramic import goods from the Greek mainland were also found.

Figure 80. Finds of shards on the Island of Kea (after http://www.arts.cornell.edu/cgi-bin/halaiscripts/Archive/mkimgpg.pl?Category=t).
Metallurgical extraction of miltos and the role of Kea in the Antiquity

“Miltos”, or “ruddle”, a red pigment minium consisting basically of iron-oxide, was mined and made (from galena brought from Lavrion) on Kea. Further non-natural litharge and yellow lead oxide, found in the northern part of the town of Voukari (NW-Kea, see Fig. 7 for location), support the theory of a production based on the island (Cherry et al. and references therein).

Miltos was primarily valued for its colour as it enjoyed a considerable reputation in Antiquity and was, amongst others, used for marking plumb lines, medicine, as make-up and also as paint for ships, as well as an agent to colour pitch or way applied to the hulls of ships (Photo-Jones et al. 1997). Major use was in the vase-painting industry of Athens. Theophrastus reported that the best miltos or ruddle is that of Keos (Kea) which was proven by both Davies (1935) and Caley & Richards (1956). It was mined itself and/or as a by-product of the mining of iron ore for smelting.

Another source for the importance of the miltos pigments are Keian decrees regulating its export and granting to Athens a monopoly on its purchase. There are also decrees preserved which set out provisions limiting Karthaia, Ioulis, and Korissia from exporting miltos elsewhere than to Athens or in ships other than those designated by the Athenians. Decrees of Korissia and Ioulis on the trading of fine Keian miltos are well preserved and are document the establishment of a transport charge and payment of an import duty. Dated before 350 BC (Second Athenian Confederacy) those writings state Kea as not operating under a federal constitution (Cherry et al. 1993) and aimed at an increase of political control of Kea through the manipulation of a major export of the island. In former times miltos was
once erroneously taken to be cinnabar (a mineral of mercury, HgS), so that Burchner (1921) in writing about ancient Kea, asserts that cinnabar mined on that island was sent solely to Athens.

On the Island of Kea itself, traces of possible miltos workings have long been known but can so far not be closely dated.

Ancient galleries in part, small caves (Trypospilies) at Kalamos, where at the marble/schist contact there is a very large mineralised vein consisting of Fe-Mn oxides (Fiedler 1841), have been assumed to be abandoned miltos mines since reddish petromata and chunks of rock were found in the caves. Other ancient findings at Spathi (see Fig. 82) suggest mining for ore required as a pigment rather than for smelting due to the absence of slag. Whereas at Ayios Symeon and Orkos remains of slag, associated with black-glazed sherds and a flake of obsidian, found on a Classical site nearby, have been found (Cherry et al. 1993).

Although not all these traces were proven to be the result of mining for pigment, as opposed for smelting into iron, at least three of the four cities of Kea were involved in the export of the product. Before the rise of Ioulis and Korissia, goods were supposed to have been traded at Otzias where ancient harbour installations have been reported. It is coincidently well sited for shipment of ore from the mines at Trypospilies (Cherry et al. 1993).

To further examine the ore found at Trypospilies samples of rocks were collected (Cherry et al. 1993) and in experiments a representative example, dark brown on the surface with orangish stains, could be crushed easily and ground to powder with a simple mortar and pestle offering a buff colour with slightly orange tint. Further experiments showed evidence
for an iron ore, probably an ocher high in limonite. Small pieces were heated in a sealed cubicle with graphite powder to a maximum temperature of 900°C for an hour (Cherry et al. 1993). After this procedure they had become magnetic, indicating that some reduction to iron metal or perhaps to magnetite had occurred. The second experiment was set up different: this time powdered samples were heated in air for brief periods over a range of modest temperatures (Cherry et al. 1993). The powders changed colour to the brick red characteristic of ordinary hematite.

The colours achieved in both experiments correspond to the most highly priced mitlos (and especially of the Keian product) used anciently by the potters of Athens. Therefore it is postulated that the procedure for changing an ocher high in limonite to an ochre high in hematite through roasting was already understood in antiquity (Cherry et al. 1993).

However, the findings of chunks of rock at the caves (Trypospilies) at Kalamas together with the experiments might be interpreted in a different way. One of which suggests the dumps to be the less-desirable lumps of ore which would have been lower in percentage of hematite and thus would have required roasting to achieve its range of red colours (Cherry et al. 1993). It is reasonable that miners were following veins of hematite-rich ore (see chapter 5.3 for recent rock-sample XRD analysis), enlarging natural fissures in the bedrock (Cherry et al. 1993).

**Copper**

In collaboration with the Greek Institute of Geology & Mining Exploration (IGME) a study on isotope geochemistry was conducted on Kea in 1989. Together with earlier fieldwork in 1982, locations of metallurgical interest on Kea were examined. Chemical analyses of ores from various localities yield only vanishingly small amounts of copper so evidence is vague on copper ores occurring on Kea which could have been exploited in antiquity. Nevertheless various locations are described as follows:
- At Kephala (see Fig. 83) copper slags and metal was found.
- There was also abundant evidence for metallurgy at Ayia Irini.
- Copper slag heaps have further been described by e.g. Caskey et al. (1988) and Papastamataki (1998) at Ayia Simeon.
- Chemical analyses showed vanishingly small amounts of lead or copper (less than 50 ppm copper and less than 200 ppm lead) in the ores at the Kalamas mines (Gale 1998).

Ancient mines exploiting a strata bound iron mineralization and copper at the south side of Spathi bay (Fiedler 1841) are partly calcified. These small galleries were probably not used to work iron ore as such, but still contain pockets of red earthy material (miltos?) which was assumed to be the object of the ancient operation here (Fig. 84).

At Orkos copper slag was found since there are at least three modern (late 1930’s) iron ore mines. Older galleries at the same spot mentioned by Davies 1935 were exposed due to modern mining. Ancient stopes and adits, with iron hammers and gads, with close by black-glaze shards (Roman?) and a few pieces of slag with slight traces of copper were found (Gale 1998).

At Liparos iron ores occurring at the contact of marble and schist, contain very small amounts of chalcopyrite and secondary copper minerals but unfortunately there were no traces of mining found here (Gale 1998). By contrast a cave at Otzias leads into a large ancient gallery for iron ore mixed by barites, sitting in the marble (Gale 1998).

At Spasmata there are, again, at least three modern galleries which exploit iron ore containing sporadic inclusions of galena, though the bulk ore is very low in both, lead, copper and silver (Gale 1998).
Silver and Lead

As mentioned above quite an amount of litharge gives evidence for metallurgy at Ayia Irini on Kea. Litharge (tetragonal lead monoxide) does not occur in nature. On archaeological sites it is a by-product of cupellation, which is the extraction of silver from silver rich lead. Litharge can be converted back to lead metal by heating it under reducing conditions which, on the basis of findings, was not done in the Bronze Age (Gale 1998).

Nevertheless lead metal itself does occur commonly e.g. used for lead disc weights found on Kea. The occurrence of Litharge can be interpreted as a waste product in the Bronze Age and therefore gives evidence of the production of silver from silver rich lead on that site. Consequently we have evidence of Late Bronze age silver production at Ayia Irini on Kea (Gale 1998).

Two separate lead mines sitting in intercalating schist and marble producing galena occur at Nikoleri but so far no traces associated with the Bronze Age could be found. Walls of galleries expose marble and traces of iron mineralization in the area. Abundant lumps of galena (weathered black on their exterior) can be found (Gale 1998).

At the southern tip of the Island (at Faros, see Fig. 83) a small deposit of galena with accessory fluorite and iron minerals in metasomatised marble is exposed. There are no signs of any mining at this site however (Gale 1998). At Faros galena also occurs in a discordant vein (2 m by 20 m) of marble which also contains pyrite, minor zincblende and cerrusite. The gangue minerals are fluorite, ankerite, limonite and calcite. Galena was collected both in situ in the trench and from the spoil heap. Again there are no indications of ancient working, though recent mining operations are known from this area (Gale 1998).

Marble

It is probable that marble was mined in the antiquity and is still mined in some areas of southern Kea. Most of the marble services the building industry.
5.3 XRD on iron-rich veins and faults

X-Ray Diffraction (XRD) is used for mineral/chemical composition analysis by comparing diffraction data against a database. The technique is based on the elastic scattering of X-rays from structures that have long range order over.

Iron-rich veins and faults throughout the investigated area are very common. Probably due to a high hydrothermal fluid infiltration along those faults, iron-minerals were deposited. In some areas these altered areas of host-rock and faults form systems of perpendicular sets of steep to horizontal cross-cutting sets (see Fig. 87).

To better understand the nature of the composition of the hydrothermal altered iron ore rich material associated with faults and veins (see Fig. 88) all over the mapping area, looking into the mineral composition of was suggested.

In cooperation with my colleague M. Bottig XRD (powder diffraction) analyses on, to a fine rock-powder (<2 µm-fraction) crushed and pressed small rock samples, were carried out at the University of Vienna to better characterise the different ore-rich bodies.

For analysing the rock-powder generated, and for semi-quantitative analysis on the whole-rock composition (after Schultz, 1964) of the samples of vein fill material taken in the course of this study, a Phillips PW 3710 X-Ray Diffractiometer (CuKα – radiance, 35mA, 45kV, step scan, step size 0.02, 1s per step) was used.

Interpretation of results was carried out after Moorwand Reynols (1997) and Brindley & Brown (1980).
Figure 87. Representative outcrop view of high hydrothermal fluid infiltration along faults within the schists causing alteration, spreading into the fault adjacent rock. Length of horizontal fault in the lower part of the shot is approximately 4 metres. White cover on the rock surface is made up of sea-salt as the outcrop is located at the coastline. E 263459, N 4172637.

Figure 88. Again, alteration from the inner portions to outer portions of the fault is affecting the contact to the surrounding host-rock (schist). E 263446, N 4172602.
Macroscopic (and mineral-composition) characterisation and mineral composition of samples analysed with XRD:

Sample M/K 41 – 501 is compiled of quartz and iron-oxide peaks would suggest manganese. Macroscopic: fine laminated, fine-grained matt black, hosting fine layers and little fragments of quartz, showing a small-scale brittle deformation overprint, sampled in a quartzite, quartz, feldspar, white mica, ore.

Sample M/K 78 – 401 quartz, goethite (enriched in water) and an iron-oxide, presumably haematite is present, macroscopic: ochre in colour, homogenous, vessel-rich, fine-grained rock showing calcite at open plains (see Fig. 89).

Sample M/K 79 – 502 goethite, quartz, macroscopic: hard and heavy, dark brown to reddish brown to ochre in colour, hosting quartz components of up to almost 1 cm and mica-rich fragments from the adjacent rocks, small vessels filled with calcite to some extend within a very fine-grained dark brown matrix, chlorite, epidote, quartz, feldspar, calcite.

Sample M/K 79 crust – 503 occurring two times in the plots, contains a high amount of quartz, goethite and not clearly identifiable chlorite and/or muscovite, macroscopic: rusty to dark brown weathered, chlorite, epidote, quartz, feldspar, calcite, ore.

Sample M/K 83 – 402 has a relatively high content of goethite (suggested) than quartz and is rich in iron-oxide as there almost all the peaks are associated with iron-oxides as shown in XRD image, macroscopic: silver shiny black glossy surface, weathered out within the chloritic-, feldspar- and quartz-rich schists.

Results of the X-Ray Diffraction (XRD) allow a distinction between quartz-rich samples and vein infill material high in iron-oxide as shown in XRD images (see Plot 2 & 3). Some of similar infill material high in iron-oxide might have been used for metalworking in ancient times.
Plot 2. XRD Image of samples from NW Kea showing labelled peaks of minerals within the rock samples as follows: M/K 79 – 502 iron-oxide (goethite), quartz; M/K 79 crust quartz, iron-oxide (goethite), illit - 503 & M/K 78 – 401 quartz, iron-oxide (goethite, haematite).

Plot 3. XRD Image of samples from NW Kea showing labelled peaks of minerals within the rock samples as follows: M/K 79 crust quartz, iron-oxide (goethite), albite, quartz; M/K 41 - 501 quartz, manganese; & M/K 79 crust – 503 quartz, iron-oxide (goethite). Note the high peak for quartz, absent only in sample M/K 83 which therefore shows a remarkably distinct peak distribution associated with iron-oxide.
6. Discussion and conclusion

Based upon detailed geological and structural mapping various stages and conditions of low-angle normal fault formation along a major shear zone in the north-western part of the island of Kea can be described.

The hitherto undescribed brittle-ductile low-angle normal fault focused on in this study – the Otzias Bay Detachment – is dominating the tectono- and lithostratigraphy of the examined area which is divided into a footwall and a fault-rock zone.

The footwall is predominantly represented by greenschist-facies chlorite-epidote bearing schists and metabasitic schists intercalated with calcitic mylonitic marbles hosting thin quartz layers and quartzitic schists/quartzites. Phyllonitic schists and cataclastic schists are observed around marble (mega-) boudins, thought to represent higher strain zones within the footwall unit.

Phyllonites associated with lenses of serpentinite and locally talc-schists, form the topmost part of the footwall, representing a transition to the fault-rock zone which comprises calcitic ultra-mylonitic marble and the hw-cataclasite associated with rmc (re-mobilised cataclasite) and strongly ankeritised dolomite in some parts of the study area.

A locally developed intervening layer of cataclastic and brecciated dolomite comprises several metre-thick layers of cohesive interlayered with ultra fine-grained, several cm thick clay-rich gouge, representing high-strain zones. The brittle cohesive dolomitic cataclasites are separated by a strikingly sharp, but gently folded, fault surface from brittle-ductile dominated mylonitic marbles in the footwall.

Structural investigations reveal a pervasive sub-horizontal foliation and fold generations with varying fold axis. Due to a superposition of fold patterns some of which developed fold axis parallel to the overall stretching lineation forming sheath folds due to shearing.

Shear sense indicators such as SC-fabrics and $\delta$ and $\sigma$ clast geometries, are consistent and give striking evidence for top-to-SSW directed movement in contrast to the opposed NNE-extension kinematics of the Western Cyclades.

Within the extensional regime of the Aegean region an early stage extension-related deformation on Kea involved ductile processes dominating within the pelitic and calcitic footwall and ductile/brittle conditions dominating within the calcite/dolomite fault-rock-zone.

Multiple, low-angle cataclastic fault zones formed within, and (sub-) parallel to, a regional mylonitic ductile foliation, and a widespread system of minor and major sets of high-angle (sub-) vertical cross-cutting steep faults act as indicators for co-genetic architecture and activity of both fault systems during the evolution of the crustal-scale low-angle brittle-ductile normal fault system on Kea.

Steeply dipping to sub-vertical hydro-fracture veins associated with hydrothermal fluid migration and ore deposition are developed predominantly in the footwall but cross-cutting the footwall and fault-rock zone lithologies these representing a late stage of brittle overprint.

Some of these ore depositions are very high in iron-oxide and might have allowed worthwhile mining and therefore encouraging early metalworking and settlement as finds/remnants of these activities in the study area unearth.
Thermochronometry ($^{40}$Ar/$^{39}$Ar plateau ages) on white mica-rich samples of miscaceous schist and phyllonite constrain mid-crustal cooling to between 20-15 Ma. Suggesting deformation age would support the Miocene extension age within the Cyclades.

Based upon preliminary results, the deformation history is divided into 4 events. Development of folds along an E-W axis is associated with $D_{n-1}$, as well as clast formation. Followed by what is suggested as the main deformation phase $D_n$, ductile dominated deformation and mylonitisation developing a NE-SW lineation and fold axis along a NE-SW direction.

Ongoing mylonitisation and the formation of cataclasites characterises $D_{n+1}$ brittle-ductile dominated event. Fold axis develop NNE, parallel to the overall stretching direction. Moderate to steeply dipping faults are present in the footwall. The latest brittle dominated deformation event, $D_{n+2}$, finds its expression in steeply dipping faults and ore-rich filled veins.

In summary, lithological and structural investigation on NW-Kea indicate that the mapped shear zone is part of an extensional SW/SSW-directed low-angle normal fault system, probably bending around the whole island forming a dome-shaped antiform and affecting the present-day geology.
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</table>
Curriculum Vitae - Monika Müller

Current address: Structural Processes Group
Department of Geodynamics & Sedimentology
University of Vienna, Austria
Althanstrasse 14/UZA 2, A-1090 Vienna
Lab.: +43 (1) 4277 53446
Email: geomail@gmx.at
Web: http://geologie.univie.ac.at/
Nationality: Austrian
D.O.B: 17. December 1978

Education and academic work experience
2002 – present Department of Geodynamics & Sedimentology, University of Vienna
Mag.rer.nat. (Magister der Naturwissenschaften) Geologie
2005 - 2009 Student assistant at the EGU General Assembly, Vienna
2001 Final exam & graduation from school, HBLA for economics, Reumannplatz, 1100 Vienna, Austria
1993 – 1998 HBLA for foreign language & economics, Straßergasse, 1190 Vienna, Austria
1985 – 1993 Elementary School, Gymnasium Sacré Coeur, Austria

Linguistic skills
German: first language
English: fluent proficient written and spoken communication
Italian: intermediate moderate written and spoken communication
Spanish: basic/beginner rudimentary written and spoken communication

Teaching / demonstrating experience
2008 Tutor, Geologische Kartierung (Geological Mapping), Prof. Dr. R. Lein
2007 Tutor, Isotopengeologie (Isotope Geology), Prof. Dr. U. Klötzli
2007 Field trip organiser, Namibia, Dr. F. Popp (Uni Vienna), Dr. D.A. Jerram (Uni Durham)
2007 Field trip leader, European S-Alps, Prof. Dr. U. Klötzli (Uni Vienna), Dr. J. Imber (Uni Durham)
2006 Tutor, Kartenkunde & Profilerstellung (Geological Methodology & Maps), Prof. Dr. B. Grasemann
2005 Tutor, Gesteins- und Bodenkunde (Petrography & Pedology), Prof. Dr. W. Richter
2004 Field trip organiser, Iceland, Prof. Dr. T. Ntaflos
2003 Tutor and field trip organiser, Islands of Lipari, Italy, Prof. Dr. W. Richter

Other training
Field experience
Geological/structural mapping & traverse planning
Petrographic, structural and sedimental /geochemical sampling
Planning of and leadership on field trips

Computer skills
Microsoft Windows operating systems
Microsoft office programmes (Word, Excel, PowerPoint, Access)
Various vector based graphics programmes (CorelDraw, ArcGis)

GPS
Navigation & data management (Garmin, Trimble)

Vehicle operation
B class driving permit
Operation of 4-wheel off-road vehicles
Operation of sailing boats

Certificate of Proficiency in the English language
FCE (First Certificate in English), British Council, Vienna, Austria

Other responsibilities
Invited speaker
2007 formative seminar day, ‘The Southern and Central Alps – an overview’, Department of Earth Sciences, University of Durham
2006 Dept. seminar, ‘Geology of Mongolia’, Department of Palaeontology, University of Vienna
Community outreach (in the course of a field trip)
2008 interview to the local press (Corangamite Extra) at Camperdown (Vic, Australia)
2006 interview to the local press (Otago Daily News) at Dunroon (S-Island, New Zealand)
### Awards / Grants

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<tr>
<td>2007</td>
<td>Poster nomination at TSG in Glasgow, 3rd best student poster presentation</td>
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<td>2008</td>
<td>Student travel bursary, The Geological Society, London (GBP 300,-)</td>
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<td>2007</td>
<td>Travel grant for invited speaker, University of Durham (€ 200,-) &amp; coverage of field trip expenses (~€ 600,-)</td>
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<td>2006</td>
<td>Research scholarship (Förderungsstipendium), University of Vienna (€ 1500,-)</td>
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<td>Research scholarship (Förderungsstipendium), University of Vienna (€ 860,-)</td>
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### Publications

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#### Conference presentations / Meeting abstracts – first / presenting author

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<th>Year</th>
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<td>2008</td>
<td>Müller, M., Grasemann, B., Edwards, M.A., &amp; Team ACCEL</td>
<td>Quantitative kinematic of a frictional viscous low-angle normal fault on Kea (Western Cyclades, Greece). International Meeting of Young Researchers in Structural Geology and Tectonics (YORSGET), abstract volume, Trabajos de Geología, Oviedo, Spain. <em>(Extended abstract)</em></td>
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<td>2007</td>
<td>Müller, M., Grasemann, B., Edwards, M.A., Voit, K.</td>
<td>Mohr circle construction for quantifying volume increase in an extensional high strain shear zone. Tectonic Studies Group (TSG) AGM, Glasgow, UK.</td>
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