KINEMATIC ANALYSIS IN THE LIGURIAN UNIT OF EASTERN ELBA ISLAND (ITALY)

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ABSTRACT

Collision between the Adriatic and Corso-Sardinian microcontinents occurred in the Late Oligocene to Early Miocene. During this event oceanic crust and pelagic sediments of the Ligurian Ocean (Ligurian Unit) were overthrust onto the western margin of the Adriatic Plate (Tuscan Unit). In this study the fault systems and kinematics in the Ligurian Unit of the eastern Elba Island were studied in order to reconstruct its structural evolution. Fault systems were recognized by detailed mapping between the Volterraio ruin in the south and the Cala dell'Inferno in the north. The geometry and kinematics of the fault and fold systems show that the Ligurian Unit was thrust from the southwest in several imbricated tectonic slices onto the Tuscan Unit. Three tectonic phases were separated. The first one was compressional and related to nappe thrusting. The trajectories of the main compression axes show a trend from WSW-ENE in the western part of the study area to SSW-NNE in the northern part. The second event was linked to post-collisional extension as a gravitational response to nappe stacking. The third event, Pliocenic in age, created extensional as well as compressional features and was triggered by the intrusion and uplift of the eastern Elba pluton. Due to doming above the pluton, northwestward gliding away from the intrusive centre generated an extensional regime at the trailing edge in the eastern part and a compressional regime at the front of the gliding mass in the western part of the study area.

INTRODUCTION

The Elba Island with its great variety of rocks and its ore deposits has been a subject of interest for geologists and mineralogists for many centuries. Since the last century many authors studied the island and several theories on the geological evolution of Elba Island have been proposed. In the 1970's the structure of Elba Island was seen for the first time in the context of plate tectonics. Here we present the results of a kinematic analysis of brittle deformation in the Ligurian Unit of eastern Elba, based on fault plane and fold analysis, in order to reconstruct the different tectonic phases.

GENERAL GEOLOGICAL SETTING

The present geological structure of Elba Island is a consequence of the Apenninic collisional phase that started in the Late Oligocene according to Kligfield (1979), Boccaletti et al. (1980), Keller and Pialli (1990) and Keller et al. (1994) or between the latest Eocene and Oligocene according to Principi and Treves (1984) and Abbate et al. (1986). With the closure of the Ligurian Ocean the Ligurian Unit was thrust from an easterly direction onto the margin of the Adriatic Plate and its platform sediments (Tuscan Unit). As a consequence, the sediments of the Tuscan Unit experienced weak metamorphism up to greenschist facies. After a late orogenic extensional phase, which started in the early Tortonian (Keller and Pialli, 1990; Keller et al., 1994), two magmatic bodies (Serri et al., 1991) intruded into Elba Island.

After Trevisan's classic work (1950) the east-vergent stack of nappes in central and eastern Elba Island is subdivided into 5 complexes, separated by thrust faults (Fig. 1): Complexes I to III belong to the Tuscan Unit. This unit consists of late Paleozoic to Triassic continental sediments and volcanics passing into a Triassic-Jurassic sequence deposited on a subsiding shelf. Complexes IV and V belong to the Ligurian Unit. Complex IV consists of a Jurassic-Cretaceous ophiolitic sequence with serpentinite, gabbro, basalt, Monte Alpe Chert, Calpionella Limestone (including the Nisportino Formation on its base) and Palombini Shales. Complex V is detached from its base and consists of Cretaceous (Subcomplex Vb, structurally higher) and Eocene (Subcomplex Va, structurally lower) flysch sediments.

Western Elba, in contrast, is dominated by one of the above mentioned magmatic intrusions (Fig. 1). The Monte Capanne pluton is of granodioritic composition. It was dated by the U/Pb method on zircon at 6.2±0.2 Ma (Jutreau et al., 1984). The Eastern Elba pluton or Porto Azzurro monzogranite, mainly still buried at shallow depth, is dated by the K/Ar method at 5.9±0.5 Ma and by the Rb/Sr method at 5.1 Ma (Saupé et al., 1982). A number of dykes cutting through the Tuscan and Ligurian units accompany the intrusions.

STRUCTURES

The structure of the N-S striking nappe stack of eastern Elba is characterized by westward dipping thrusts which separate the above mentioned complexes. This nappe stack is the result of accretion and collision during westward dipping subduction and closure of the Ligurian Ocean from the Late Cretaceous through Early Neogene. In the late orogenic extensional stage normal faults disserted the nappe stack. A large low-angle detachment fault, the Zuccale Detachment Fault (Keller and Pialli, 1990; Keller et al., 1994), displaces the higher parts of the units for about 6 km towards the east.

The study area is in the Ligurian Unit (Complex IV), located on the western coast of the northeastern peninsula of Elba between the Volterraio ruin in the south and Cala dell'Inferno in the north (Fig. 1). Two different tectonic subunits were recognized in this area by detailed mapping (Fig. 2). These subunits were already defined by Bortolotti et al. (1997) and are part of their more detailed subdivision of Complex IV. The structurally lower Monte Serra Subunit with the Monte Peritondo slice (*nomen novum*) is exposed in the northeastern part of the study area. It is dominated by Calpionella Limestone and contains WSW-ENE and NW-SE striking sets of faults (lateral, oblique and frontal ramps). It displays a complex geologic situation at Monte Serra. The structurally higher Volterraio Subunit in the main part of the study area is dominated by the Monte Alpe radiolarian chert. The internal structure of this subunit is less complex

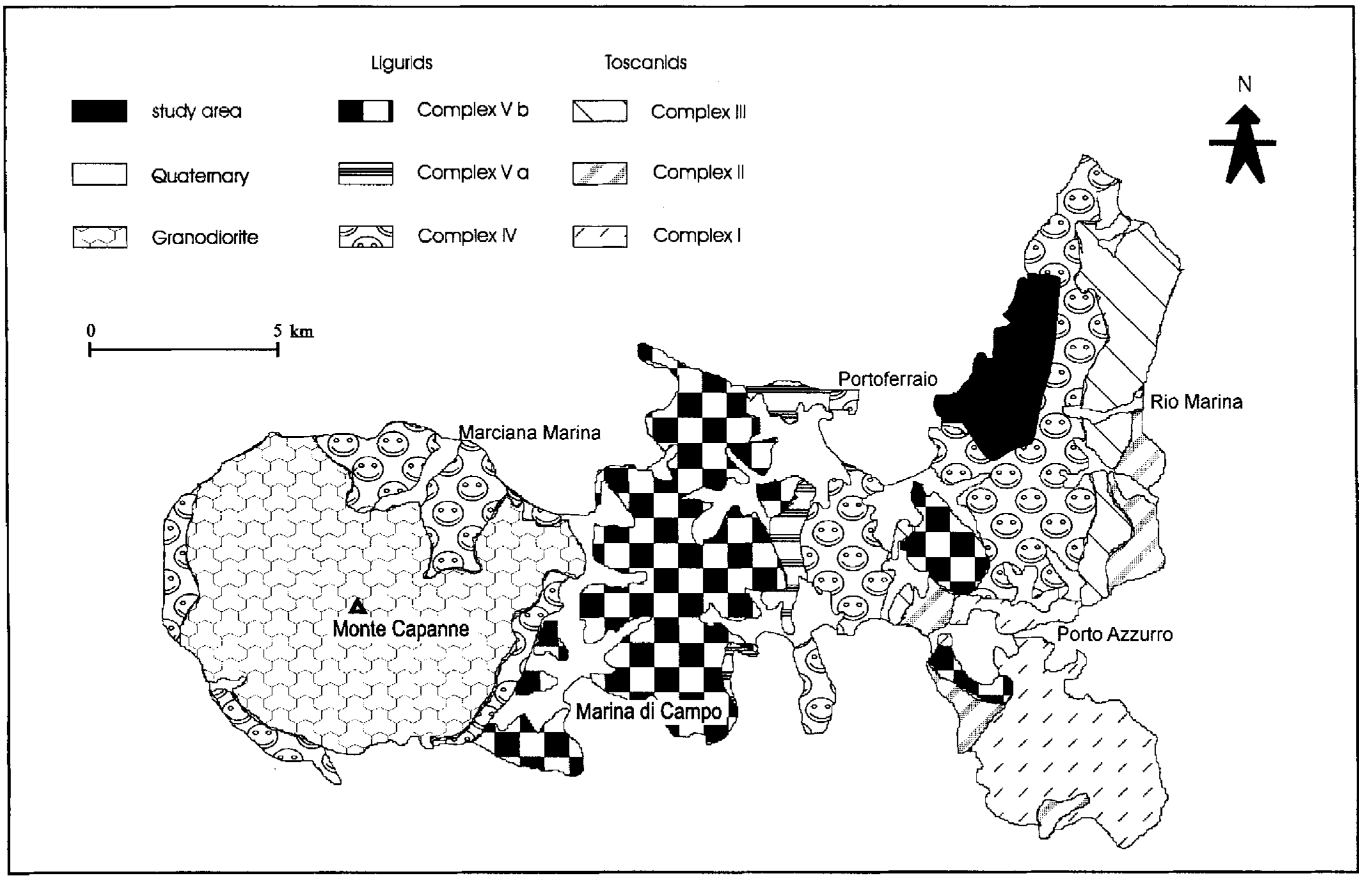

Fig. 1 - Geological sketch showing Trevisan's complexes and the study area.

than that of the Mt. Serra Subunit. Apart from a large east-vergent tight fold east of Bagnaia and a number of mesoscale folds in the chert, stata generally dip to the NW at about 30°. The shallowly SW dipping Cala dell'Inferno thrust separates the two subunits (Fig. 2). Basalt and serpentinite occurrences south and east of Monte Peritondo are interpreted as isolated relics of the Volterraio Subunit, which formerly extended furhter east.

KINEMATIC ANALYSIS

Methods

For the kinematic analysis fault planes with a lineation, either striae or fibre crystals (Fig. 3), were measured. Fibres, breakouts and Riedel shears were taken as indicators for the sense of movement. The exposed size of the fault planes normally ranged from square decimeters to square meters.

Before calculating the directions of the principal axes of stress, the measured data were checked with the computer program "CHECK" (Sperner et al., 1993) to assure that lineation and plane fit together; minor corrections were made where necessary. The computer program "NDA" (Sperner and Ratschbacher, 1994) was used for calculating the principal stress axes by a numeric-dynamic analysis based on the method of Spang (1972). The empiric value of 30° was assumed for the angle between compression axes and fault planes. In Figures 4 to 6 the fault planes, striae and principal paleostress axes are plotted in the stereonet (lower hemisphere), using the computer program "F-S" (Sperner et al., 1993). In these plots fault planes appear as great circles, striae as dots on the fault plane great circle with an arrow showing the direction of the movement of the hangingwall block, and the quality of the shear sense determination by the character of the arrowhead (see legend in Fig. 4). The principal stress axes are plotted as numbers, where 1 refers to the s_1-axis and 3 to the s_3-axis (Fig. 4). Bold arrows outside the individual diagrams indicate either the orientation of the main compression axis (compressional regime) or the main extension axis (extensional regime).

Results

From the calculated paleostress tensors, several tectonic events could be separated by overprinting criteria (Fig. 3) and general geological considerations. Local variations in the directions of the principal stress axes were recognized for each single tectonic event. The diagrams shown in Figures 4 to 6 display the data collected in larger, homogeneous areas in the northern, central, southeastern, and western parts of the study area.

A first tectonic event shows a compressional regime and can be related to thrusting. The main compressional axis systematically changes its orientation from WSW-ENE in the southwestern part of the study area to SSW-NNE in the northern part (Fig. 4). This change is shown by the curve s_1-trajectories in Fig. 4.

A second tectonic event shows an extensional regime with steep s_1-axes (Fig. 5). The s_3-axes again show a systematic variation of orientation across the study area. The curved s_3 trajectories are oriented similarly as the s_1 trajec-

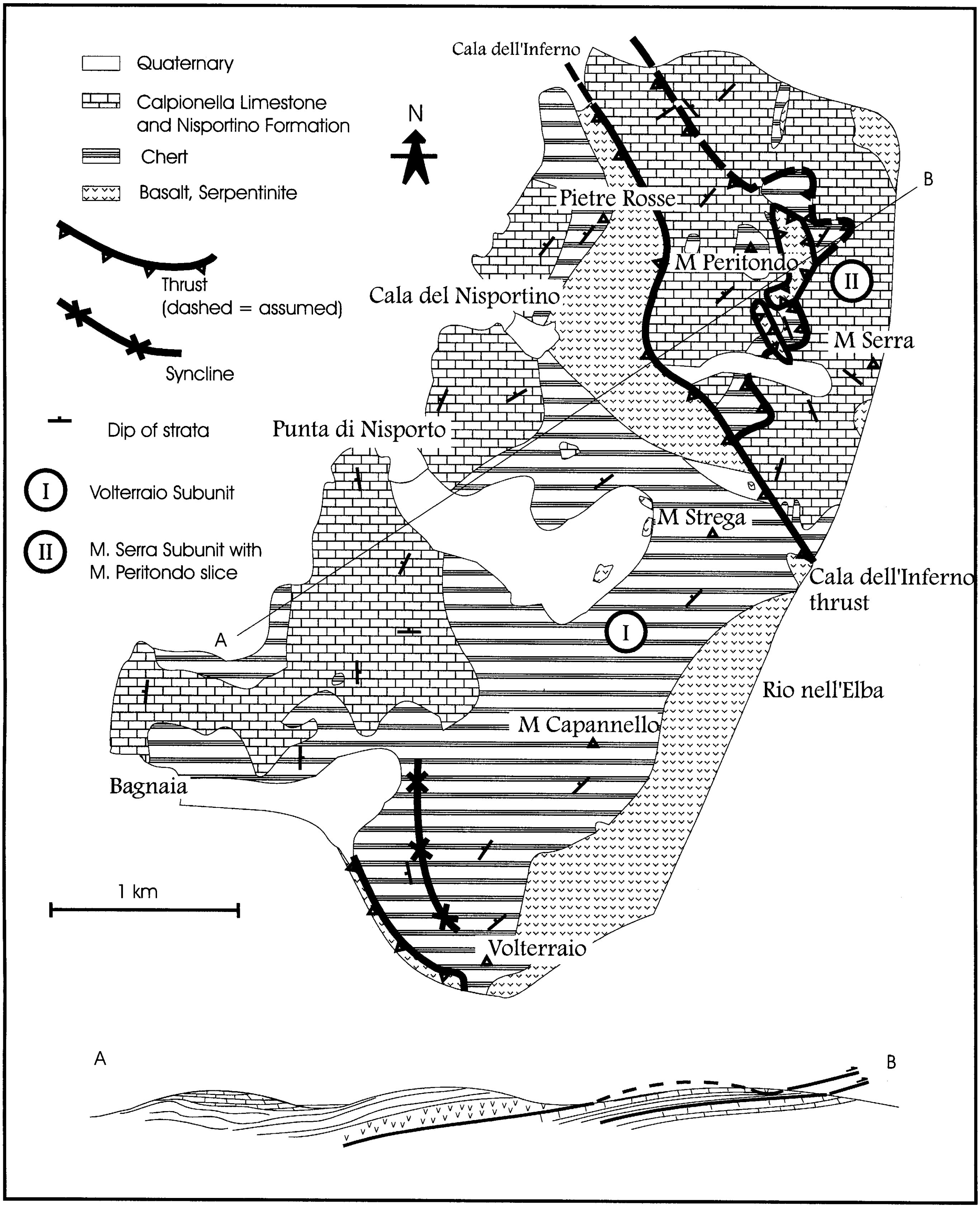

Fig. 2 - Simplified geological map of the investigated area with major tectonic structures and SW-NE cross-section with SW-dipping thrusts.

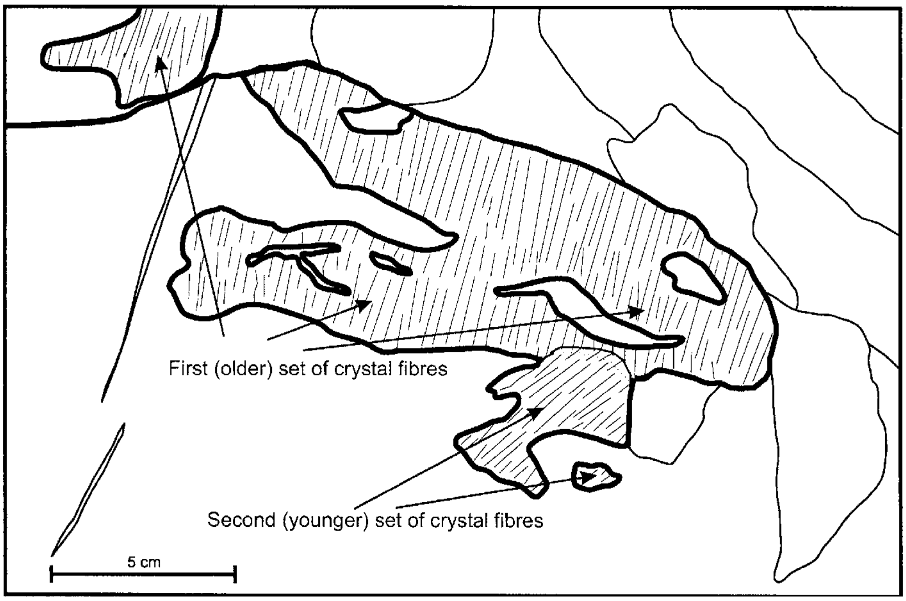

Fig. 3 - Photo (a) and sketch (b) of a fault plane in the Calpionella Limestone on the road from Bagnaia to Nisporto. Two sets of calcite fibres indicate two distinct movement phases. Overprinting criteria allows to recognize between older and younger fibre set. Motion of removed hanging-wall block is to the upper right as shown by tears on the upper fibre ends, indicating a reverse fault mechanism.

tories during the first event.

A third event, which is the youngest, as shown by overprinting criteria (Fig. 3), is complex and is characterized by an extensional tectonic regime in the eastern part of the study area and a compressional regime in its western part (Fig. 6). In the eastern part the axes of principal extension are oriented NNE-SSW to NW-SE. Due to reactivation of the fault planes, calculations for the stress directions here may be not too reliable. In the western part the main compression axis calculated from a fault population is oriented WNW-ESE. This is supported by fold orientations exposed in a locality southwest of the study area (Fig. 6). The folds are tight and display flat-lying axial planes. N-S trending fold axes in combination with mainly NW-dipping axial planes are in line with roughly WNW-directed movement.

A very limited number of fault planes could not be associated to any of these events, but did not form a separate population. Local complications or rotations during younger events are considered to be responsible for these deviations.

INTERPRETATION

Structures of the Monte Serra and Volterraio subunits are mainly determined by their roughly northeastward transport direction, but structures overprinted during younger events become locally dominant. In large parts of the Volterraio Unit stress was transformed into folding, because of the material properties of the Monte Alpe Chert. This chert formation, very variable in thickness, consists of thin chert layers (± 10 cm thick) separated by extremely thin clay veneers. These veneers facilitate displacement along the bedding planes. Although chert is a very rigid material under non-metamorphic conditions, the thin individual layers and the clay veneers favour folding. The chert generally shows mesoscale folds.

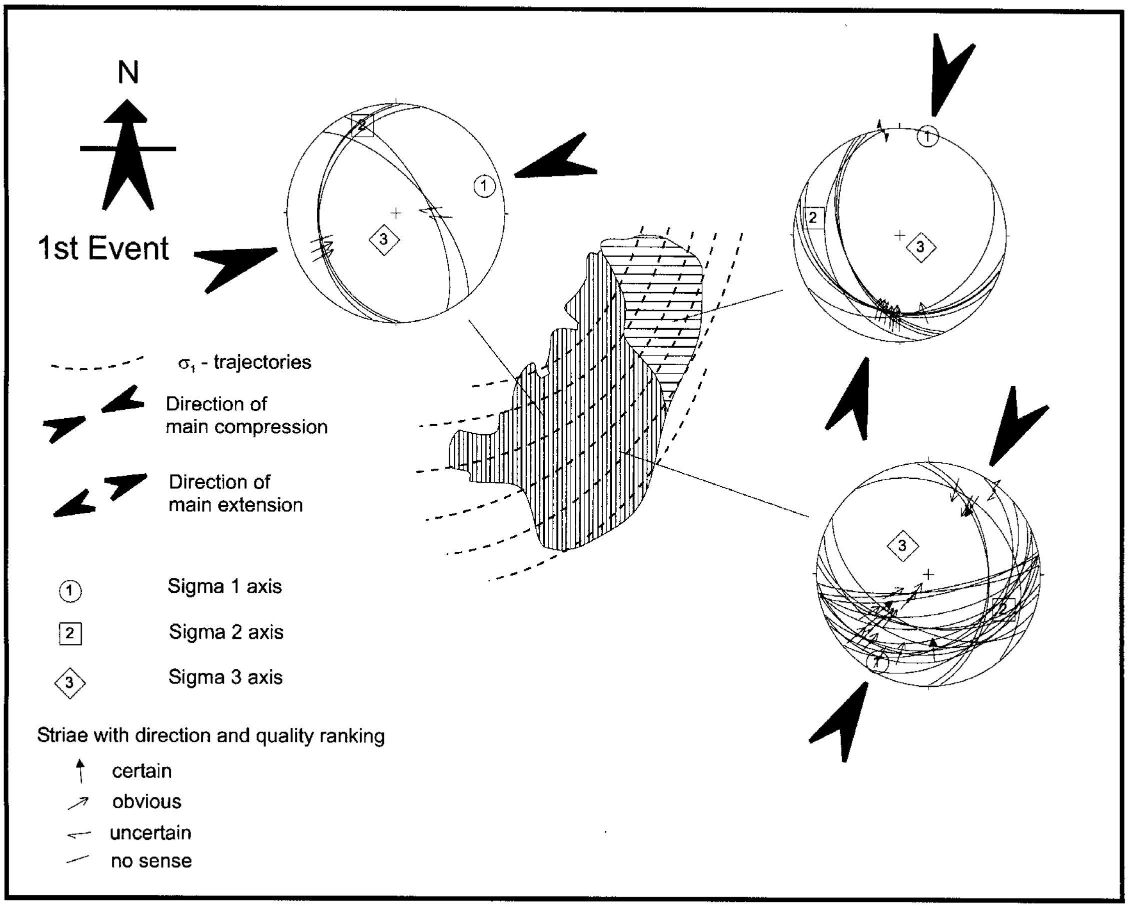

Fig. 4 - Fault planes and principal stress directions in the first tectonic event (thrusting).

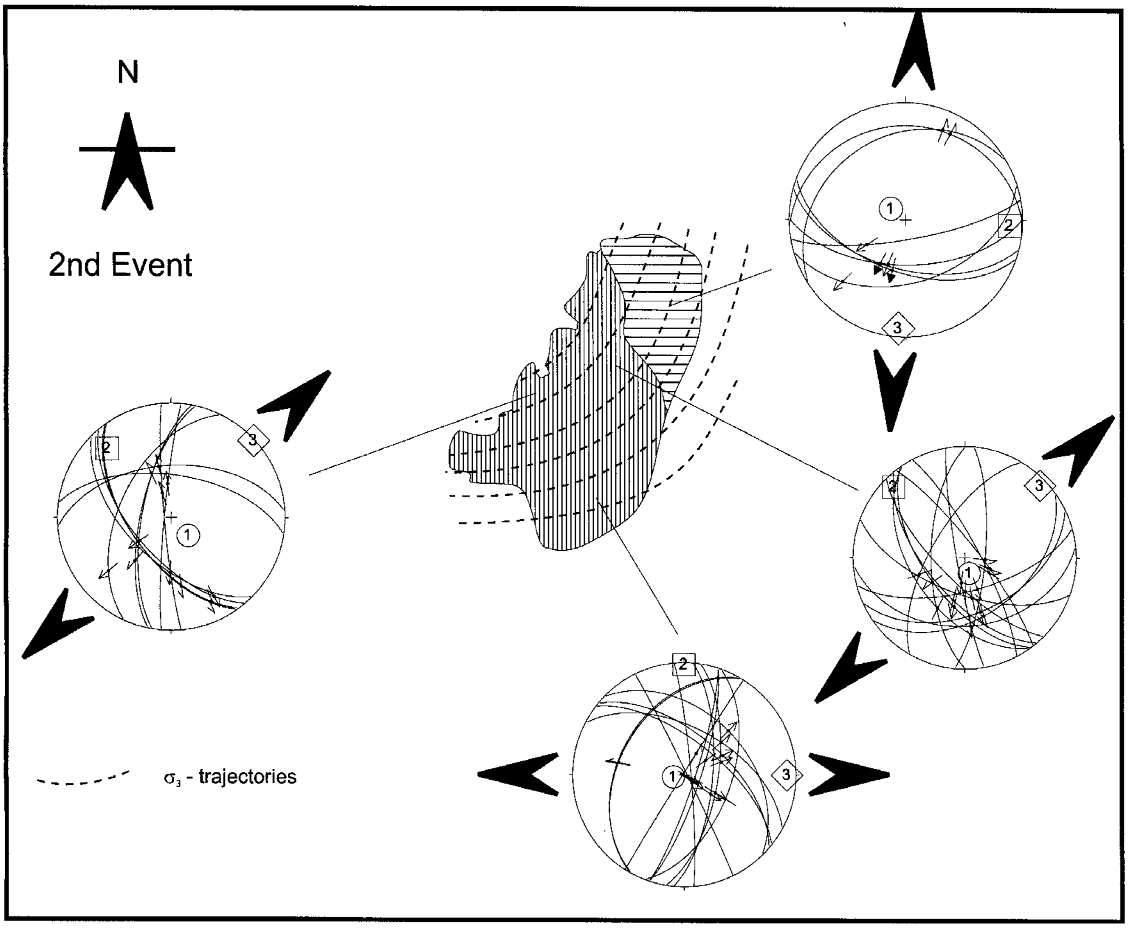

Fig. 5 - Fault planes and principal stress directions in the second tectonic event (reversal of thrust/extensional response). For legend see Fig. 4.

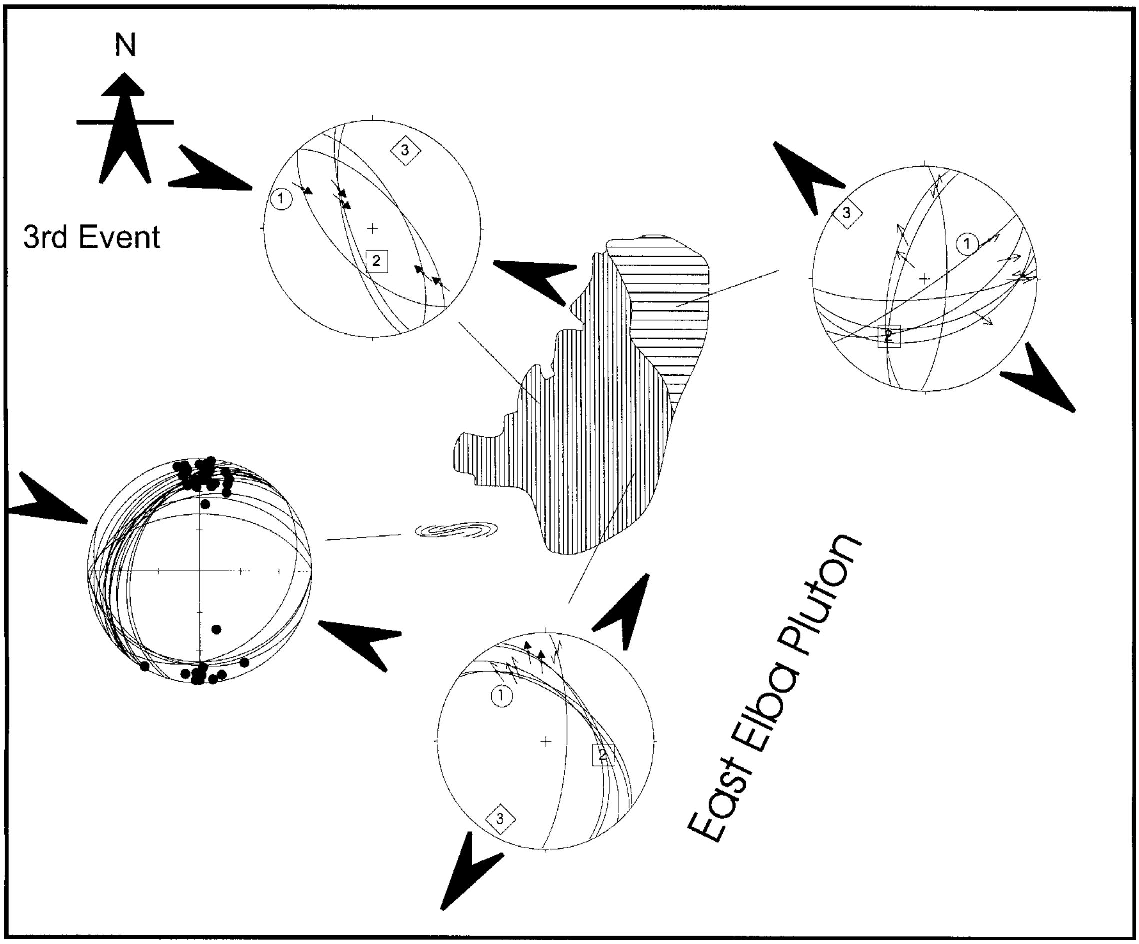

Fig. 6 - Fault planes with principal stress directions in the third tectonic event (uplift of Eastern Elba Pluton creating extension in eastern and northern parts and compression in the western part). Left diagram shows axial planes and fold axes for recumbent folds SW of study area formed during this phase. For legend see Fig. 4.

In contrast, the thick-bedded Calpionella Limestone (individual layers generally 30-100 cm thick) shows little ability to form folds. The resistance to folding and overall rigidity of the Calpionella Limestone are responsible for the preferred deformation by faulting. The thrusts ramped through this formation, whereas the highly deformable radiolarian chert and the serpentinites served as flats during thrusting. Footwall ramps cutting through the Calpionella Limestone characterize the two thrusts mapped in the study area and limiting the Monte Peritondo slice on its floor and roof (Fig. 2).

The Cala dell'Inferno thrust (Fig. 2) is a major tectonic feature within the Ligurian Unit (Complex IV). The stack including the Mt. Serra and Volterraio subunits was thrust over the Tuscan units probably in a piggy-back structure. Highly deformable serpentinite at the base of the Ligurian Unit and Jurassic shales of the Tuscan Unit served as tectonic lubricants.

The reason for the curvature of the s_1-trajectories across the study area may be a hidden structural high in the overridden units causing northward deviation of the generally ENE-directed transport of material. During this first compressional deformation event, or in a late stage of it, fault plane populations formed which reflect the tectonic regime. The overall northeastward direction of transport during thrusting is also observed in the Tuscan units, where weak metamorphism led to the formation of ductile and brittle structures. Such structures are developed, for example, in Liassic calcareous formations due east of the study area, showing top-to-NE transport by asymmetric boudins, shear bands, and other structures.

We interpret the second, extensional event as the gravitational response to nappe stacking and crustal thickening by a rough reversal of displacement. The s_3 trajectories of this extensional event take a similar course as the s_1 trajectories of the first event. We argue that gravitational forces affecting the overthickened crustal stack were about to attain crustal thinning. This Middle or Late Miocene extensional event may be part of a gravitational collapse that finally enabled the formation and ascent of granitoid melts by crustal-scale distension (Monte Capanne and Eastern Elba intrusions). The uprise of these intrusions triggered the third distensional event around the Miocene/Pliocene boundary.

We relate structures formed during the third tectonic event to the intrusion and uprise of the Eastern Elba pluton to the east and southeast of the study area. The intrusion cuased a dome-like structure, elongated in a N-S direction. We consider it responsible for the formation of a (north)westward gliding mass on the (north)western flank of the dome. The gliding masss developed extensional features (normal faults) near its trailing edge and compressional features (reverse faults and recumbent folds) near its front (Fig. 7). Compressional forces were probably induced near the front of the mass by a backstopping effect of some sort of abutment or simply caused by the retarding forces when the depression between two structural highs was reached. Another structural high to the west was the Monte Capanne dome formed by the Monte Capanne intrusion, which was emplaced about 1 Ma earlier than the Eastern Elba pluton. A similar gliding mass was triggered by the uprise of the Monte Capanne dome. This mass was displaced on the eastern flank of the Monte Capanne dome along the Zuccale Detachment Fault (ZDF) and moved towards the east (Keller and Pialli, 1990; Keller et al., 1994). According to the slightly different intrusion ages of the Monte Capanne and Eastern

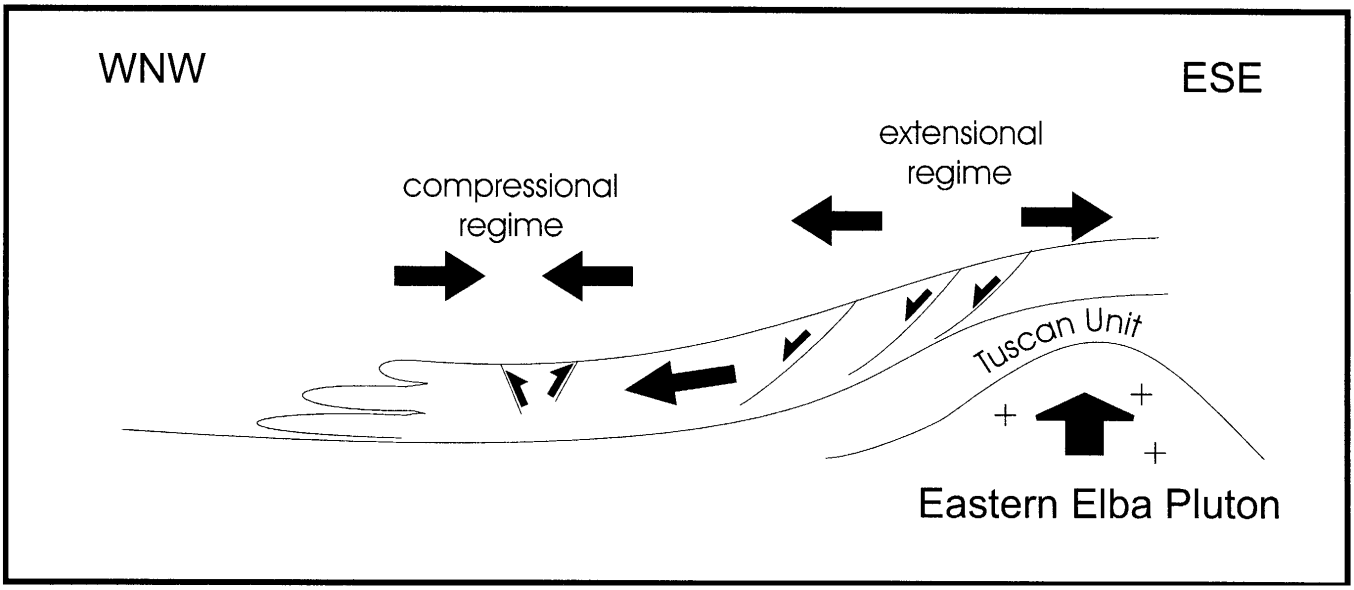

Fig. 7 - Sketch of the tectonic effect of the Eastern Elba Pluton rise (extension in eastern parts and gliding to the west).

Elba plutons (see above), the westward gliding mass in the study area is considered to be younger than the ZDF. Direct evidence for this temporal succession are overprints and a large scale undulation of the ZDF south of the study area.

DISCUSSION

Interpretations of the structure of the Ligurian Unit of eastern Elba Island were proposed by several authors (e.g. Bodechtel, 1963; Perrin, 1969; Bortolotti et al., 1994), all agreeing on the major features. Detailed mapping in the study area resulted in some modification of the local boundaries. As a new result, the occurrences of oceanic basement lithologies (basalt, serpentinite) in the northern part of the study area are interpreted in terms of klippen, i.e. erosional remnants of the structurally higher Volterraio Subunit on top of the Mt. Serra Subunit. These basalt and serpentinite occurrences were formerly considered as tectonic lenses within the Mt. Serra Subunit.

Modern structural analyses, mainly carried out in the Tuscan units, demonstrated that thrusting generally occurred in a top-to-E or -NE direction and was followed by an extensional event (Keller and Pialli, 1990; Keller et al., 1994). Little is known about internal movements in the Ligurian units. Our results show that movement directions during both nappe stacking and its gravitational response were not uniform but show systematic variations, probably due to morphologic anomalies in the thrust surfaces. Such anomalies may account for deviations from the regional movement direction and cause local disturbances of the flow pattern.

Overprinting criteria show that thrusting and gravitational extensional response were followed by a third, independent event, which is characterized by a complex but systematic pattern of extensional and compressional features. This pattern is in line with a gliding mass triggered by the uprising Eastern Elba pluton. This west-directed gliding mass is considered to be a (slightly younger) counterpart of the larger, east-directed gliding mass that slipped off from the rising Monte Capanne pluton along the Zuccale Detachment Fault (Keller et al., 1994).

Our results are in agreement with the scheme of events proposed by Bortolotti et al. (1997). These authors also emphasize two extensional events after accretion and nappe stacking, which was completed by the Early Miocene. They related the first extensional event to uplift in the Apennine orogen in Early to Middle Miocene times and stress the importance of gravity gliding during the last event as a response (around 2 Ma ago) to the emplacement and uplift of the Mt. Capanne granitoid body. According to this model, the two extensional events are clearly separated by a long period of time.

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