

Tectonic Studies Group

Field Excursion to the
Carboneras Fault, SE Spain

September 7 – 11, 2014

Leaders: E. Rutter and L. Valetti

University of Manchester



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Field Guide

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Safety

The principal hazard in the region is the sun. Even though we will be there in September, it is still quite hot and unprotected skin will burn quickly. You must protect yourself from the sun. A hat is essential - locally a wide brimmed straw hat can be purchased for about 3 euros. If you must start the day in shorts and short sleeves, carry some long trousers and a long sleeved shirt so you can change if need be. I always advise that fieldwork be carried out in long trousers, otherwise you will be inhibited from going into places with thorny scrub. A stumble on gravel is less painful in long trousers. You **will** need high protection factor sun oil/cream. I find the best is P20, which will allow you to stay out all day without burning if it is correctly applied. For other sunscreens, start off with at least factor 30. Do not underestimate the damage that can be done if you get burned; it can knock you out for a week. The symptoms of heatstroke are dizziness, inability to concentrate or walk more than 100 metres, a desperate feeling of need to lie down under shade, recognition that no matter how much you drink it has no effect. It is essential to get into shade and rest so you can cool off.

In the field, boots are the best footwear, but they need not be good quality boots. They will get knocked about by sharp rocks quite a bit. Although some people use only trainers, I think they are a bit too light and easily worn out, and your ankles get knocked. I find an expanding ski-style telescopic stick to be indispensable in the field.

We will aim to be out in the field by about 8 a.m. each morning to take advantage of the coolness. Daytime shade temperatures are not usually more than 28 to 30°C but it will feel hotter in the sun. Carry plenty of water with you each day, e.g. 1.5 litres. None of the areas to be visited are very hilly, but slopes are often gravelly underfoot and it is easy to slip. Don't go rock climbing, and when scrambling up a slope be careful not to send debris down onto the person

behind you. Obey the rules about hammering and protection of the eyes. Never hit one hammer with another nor hammer near another person. The number of occasions when a hammer might be used will be few.

The main vegetation is a low spiky scrub. Some of the local plants may give some people allergic skin reactions, although this is a very rare occurrence. I am not aware of any seriously hazardous local animal life. Wild pigs leave a lot of evidence of their passing because they vigorously dig for roots but I have never encountered one. There are snakes but these are very fast to get out of your way and are rarely seen. Spiders can be big but I am not aware of any that are hazardous. In a few places there are sets of beehives housing African bees, which can be quite aggressive. They are positioned by their owners to be out of the way of most people, but not necessarily geologists. Try to avoid beehives. Sometimes there is a sign saying 'Cuidado, Abejas'.

If you go swimming bear in mind that jumping into deep cold water when you are hot can cause a panic attack that will prevent your lungs from inflating. Watch out for the possibility of stepping on a sea urchin. The results are very unpleasant because the spines break off, leaving spicules embedded in your foot.

Sometimes we will be examining rocks by the side of highways. You **must** wear a high visibility yellow jacket on these occasions. Watch out for approaching vehicles on behalf of yourself and others. Our vehicles must be pulled right off the highway and must not cross continuous white lines in the centre of the road. When walking alongside a highway you must not stray onto the tarmac. A hard hat should be worn when examining rocks at the bottom of cliffs.

The emergency phone number is 112. There is quite good mobile phone coverage except in the bottoms of gullies. There is a large health centre (Urgencias) in Carboneras, in the south-west corner of town, well signposted on the main 'ring' road.

Accommodation

Hotel Felipe, Calle Sorbas, Carboneras

Outline of Schedule

Each morning it will get light about 7 a.m. so we will aim for breakfast at that time (in Bar Felipe) with the intention to get away at 8 a.m. or shortly thereafter. This will be before the supermarkets open, so we will shop the afternoon before for lunch things. You can still get fresh bread early in the morning, and cold water bottles from the bar. The first day (Monday) separate arrangements have been made for lunch.

Monday 8th

We will spend the day examining the rocks of the Betic zone and its sedimentary cover to the north of the Carboneras fault zone (CFZ) to help establish its tectonic setting.

Tuesday 9th

The CFZ is exposed, not buried beneath Pliocene deposits, in the 15 km or so north-eastern end of its onshore segment. We will spend the day examining the CFZ in the most north-eastern part of its outcrop, where it meets the sea.

Wednesday 10th

We will examine the CFZ in the south-western tract where it cuts basement and Neogene cover rocks.

Geological summary

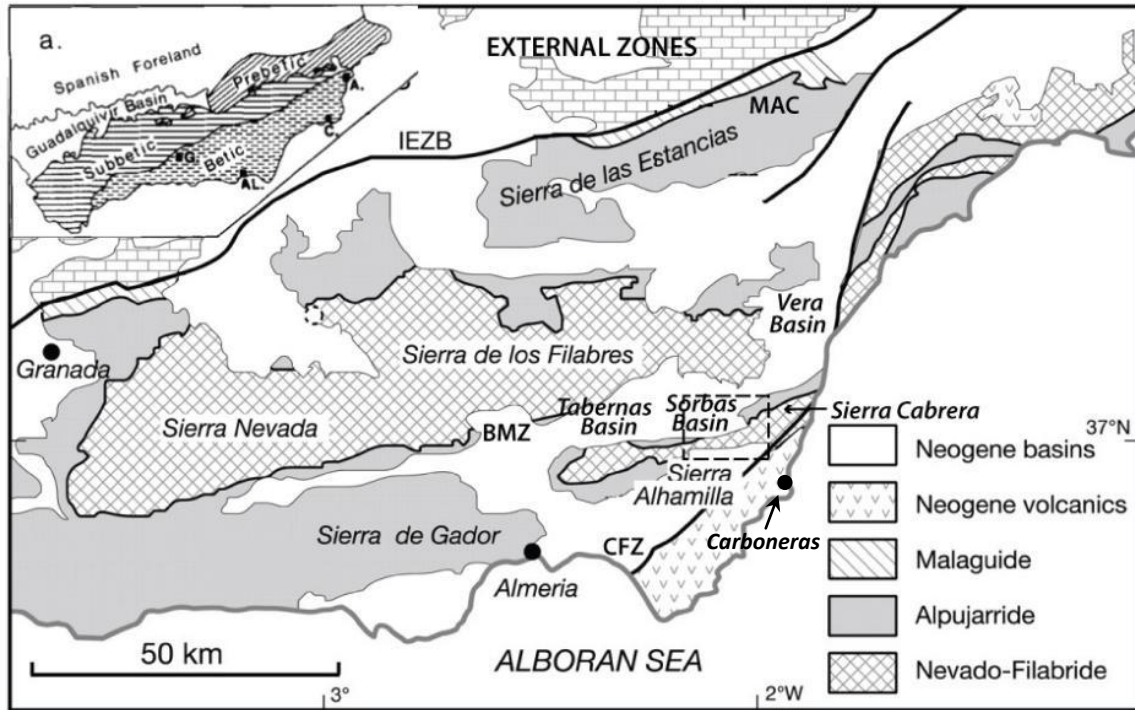


Fig. 1 – From Platt *et al.*, (2005), modified, showing the internal (Betic) zone of the Alpine orogenic belt of S Spain.. IEZB: Internal-External Zone Boundary; MAC: Malaguide-Alpujarride contact; BMZ: Betic Movement Zone; CFZ: Carboneras Fault Zone.

The Carboneras Fault Zone (CFZ) of S.E. Spain separates the Miocene Gabo de Gata volcanic terrain to the south-east from metamorphic basement rocks and post-orogenic sedimentary rocks of the internal zone of the Betic Cordilleras (Fig. 1), an Alpine orogenic belt in which tectonometamorphic activity peaked during early Miocene time (25 – 18 Ma, Alonso-Chaves *et al.* 2004; Vissers 2012). The CFZ is only exposed cutting metamorphic basement rocks in a 15 km long tract near the town of Carboneras. Elsewhere on the Spanish mainland it is largely covered by upper Miocene through Recent sedimentary rocks. The CFZ forms part of a segmented system of left-lateral strike-slip faults that extends 150 km N.E. towards Alicante, as the Palomares and Alhama de Murcia fault systems (Fig. 2). To the S.W. the Carboneras fault extends continuously 100 km into the Alborán sea (Moreno Mota 2010), beyond which it may continue as a soft-linked network to include the Nekor and Jebha faults in Morocco. The concept of the Trans-Alborán shear zone (LeBlanc & Olivier 1984; de Larouzière *et al.* 1988; Gracia *et al.* 2006) can usefully be extended to include the whole of this system of left-lateral strike slip faults.

To the north-west of the CFZ it is well established that NE-SW directed extensional faulting of upper Miocene age has affected crystalline basement rocks (García-Dueñas *et al.* 1992; Johnson *et al.* 1997; Augier *et al.* 2005; Martínez-Martínez *et al.* 2006; Meijninger & Vissers 2006; Giaconia *et al.* 2011; Vissers 2012; Sanz de Galdeano *et al.* 2012) and allowed them to become exposed as metamorphic core complexes (Sierra Nevada, Sierra de Los Filabres, Sierra Alhamilla and Sierra Cabrera) producing

accommodation space for the accumulation of post-orogenic sediments, and suggesting that the faults of the Trans-Alborán shear zone act as lateral walls or ramps to allow the extensional faulting to occur (Fig. 4). At the same time, there is evidence for widespread coeval NW-SE directed shortening causing deformation within the internal Betic zone and folding and thrusting in the external zones (Galindo-Zaldívar *et al.* 2003; Vissers 2012), making the CFZ a transpressional fault. Basement blocks uplifted during late Miocene time typically take the form of large-scale antiformal structures with a box-fold geometry, often bounded by NE-SW trending high angle reverse faults, and form the mountain ranges of the Betic Cordilleras. They testify to upper Miocene through Recent convergence of N Africa with Iberia.

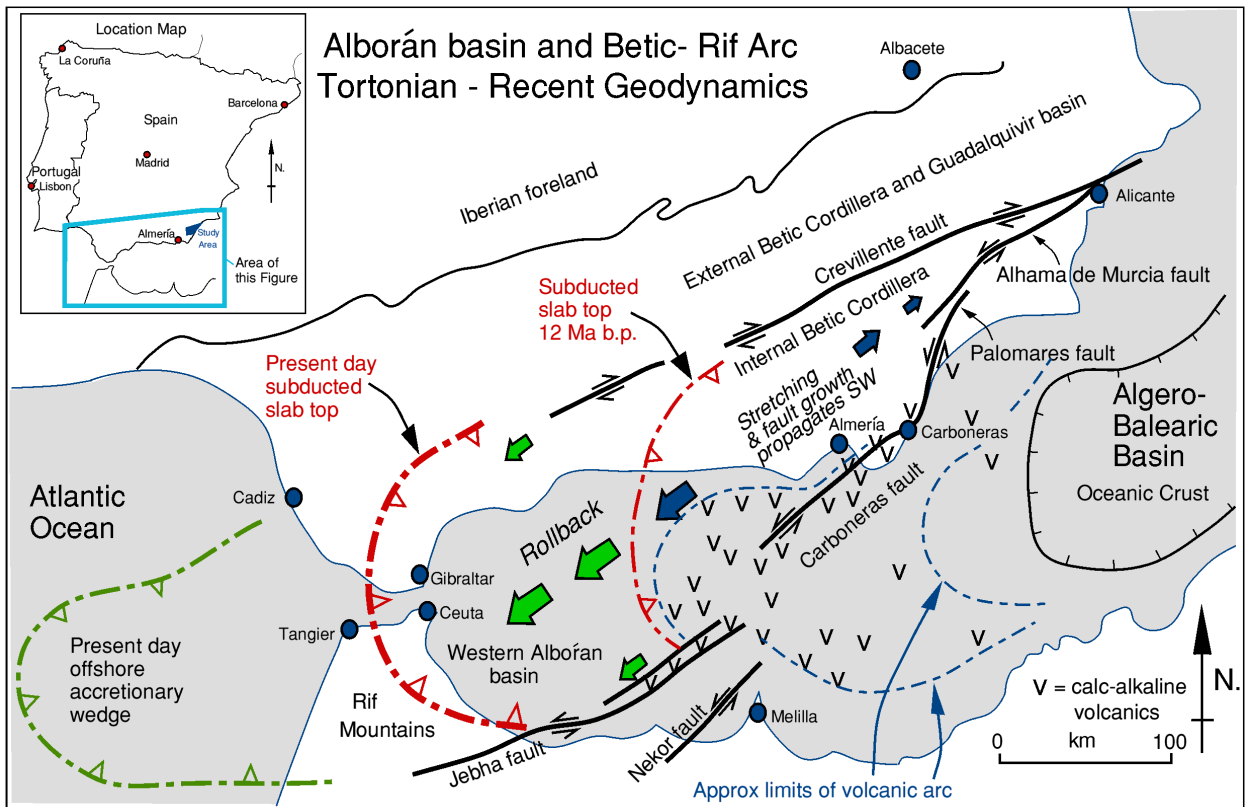


Fig. 2.

Map of S.E. Spain and N.W. Africa, separated by the Alborán sea basin, showing the geodynamic scheme (based on Lonergan & White 1997, Gutscher *et al.* 2002 and Gutscher 2012) for the Serravallian through Recent evolution. Slab rollback is accommodated by stretching within the Betic-Alborán wedge that is bounded by right-lateral and left-lateral wrench fault systems, and displacing part of the pre-Serravallian volcanic arc south-westwards, with Tortonian igneous rocks being injected into the active Carboneras fault segment. Offshore distributions of Neogene calc-alkaline rocks based on Comas *et al.* (1999) and Booth-Rea *et al.* (2007) shown offset by the Trans-Alborán shear zone, with intrusions into the fault zones as displacements occur.

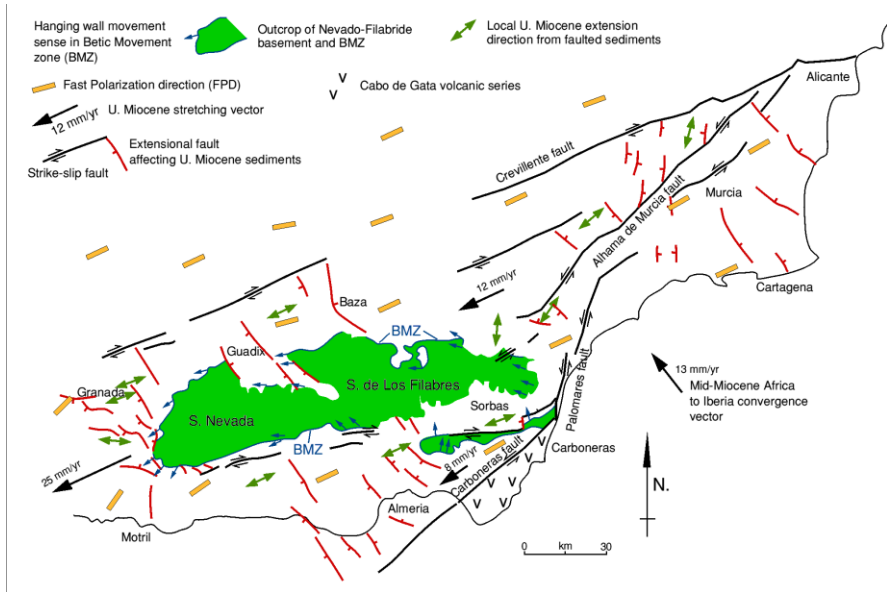


Fig. 3. Tortonian NE-SW directed stretching in the back-arc wedge that now comprises the Betic internal zone. Pre-Tortonian stretching is revealed by the displacements on the Betic Movement Zone (BMZ), separating the Alpujarride nappe from the underlying Nevado-Filabride metamorphic rocks (after Vissers 2012). Traces of generally NW-SE trending extensional faults that

generate the Tortonian extensional basins and cut Tortonian sedimentary rocks are linked by the network of SW-NE trending strike-slip faults (compiled from Martínez-Díaz & Hernández-Enrile 2004; Martínez-Martínez et al. 2006; Meijninger & Vissers 2006). Stretching velocities shown based on Gutscher (2012). Mid-Miocene Africa-Iberia convergence rate after Vissers (2012). Upper mantle S-wave fast polarization directions from Diaz et al. (2010).

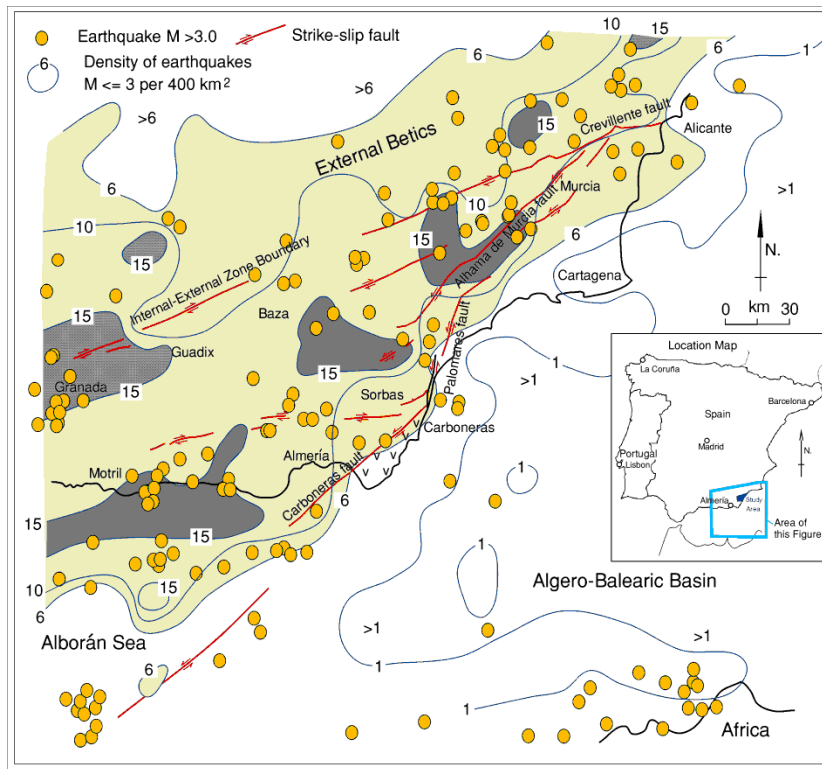


Fig. 4. Location of the Carboneras Fault Zone (CFZ) in SE Spain, and the linked Palomares and Alhama de Murcia faults, comprising the NE end of the Trans-Alborán shear zone. Seismic activity between year 2000 and 2010, based on Martínez-Díaz et al. (2012). Discrete events of M > 3 shown as filled circles, activity of M < 3 is density contoured. The Betic internal zone is wedge shaped, between the left-lateral Trans-Alborán system and the right-lateral Internal-External Zone Boundary - Crevillente fault system. The wedge is most active, with a marked seismic activity decrease to the SE across the trend of the Trans-Alborán shear zone, which is interpreted to be an upper mantle flow velocity discontinuity.

Rutter *et al.* (2012; 2013) suggested that the Trans-Alborán fault system has acted as a stretching fault (Means 1989), accommodating a velocity discontinuity (Odé 1960) in the upper mantle flow regime (Fig. 3). The fast polarization directions from observations of teleseismic shear wave splitting throughout the region show a consistent NE-SW trend, that has been interpreted as indicating the contemporary and/or Neogene upper mantle principal extension direction (Díaz *et al.* 2010), and this is consistent with the orientation and movement picture of extensional faults in upper Miocene rocks that partially cover the internal Betic zone (Fig. 4) on *both* sides of the Trans-Alborán shear zone (Dabrio & Polo 1991). Following Martínez-Díaz *et al.* (2012), Fig. 4 also shows the distribution of earthquakes in the region since year 2000. The Trans-Alborán shear zone appears to delimit the largely onshore tract of more frequent earthquakes to the NW from the lower frequency of tremors to the SE. This probably implies a greater degree of active deformation in the region to the NW and supports the notion of the shear zone acting as a velocity discontinuity.

Rocks of the Cabo de Gata calc-alkaline volcanic terrain cover much of the onshore area to the south-east of the CFZ, between Cabo de Gata and a few km north from Carboneras, and include a number of individual eruptive volcanic centres (e.g. Rodalquilar, Majada Redondo, Los Frailes). The ages of these rocks are dominantly Serravallian through Messinian (Serrano & Gonzáles Donoso 1989; Comas *et al.* 1999; Turner *et al.* 1999). In the Carboneras area, rather older volcanics also occur (Scotney *et al.* 2000). The age of the oldest in-situ volcanoclastics at the exposed stratigraphic base of the sequence is 18 Ma, but evidence of older volcanic activity extending to 21 Ma is found as amphibole crystals in water-lain sediments. Hardly any volcanic rocks of the Cabo de Gata suite outcrop to the north and west of the CFZ, suggesting that displacements on the fault zone have been sufficient to remove volcanic rocks originally lying to the north-west. The fault zone hosts a swarm of vertical intrusive andesitic dykes that have apparently used the fault zone to reach the surface (Rutter *et al.* 2012), testifying to a link between faulting and volcanic activity, and also suggesting that the CFZ cuts right through the continental crust and into the upper mantle. Stratigraphic relationships between the Cabo de Gata volcanic rocks and the CFZ are of particular importance to dating movements on the CFZ, and the volcanic rocks are particularly well suited to radiometric dating. The main aim of this summary is to illustrate these relative and absolute age relationships, as well as to stimulate discussion on the need for constraining the movement history and the implications for the geodynamic evolution of the region.

Summary of the geology of the CFZ near Carboneras

Only near Carboneras town is the CFZ extensively exposed cutting basement rocks over a distance of 9 km and juxtaposing them against volcanic rocks of the Cabo de Gata complex. Further SW the fault zone disappears beneath uppermost Miocene and Pliocene rocks of the NE corner of the Nijar basin. Fig. 5 shows that the geology of the area may be considered as a group of lithotectonic units bounded by unconformities and/or major faults (Rutter *et al.* 2012: you are provided with a copy).

Metamorphic basement rocks of the Nevado-Filabride and Alpujárride groups outcrop extensively to the NW of the CFZ and form fault-bounded blocks within it (Fig. 5). To the SE of the CFZ near Carboneras only Maláguide and Alpujárride (Visser 2012) basement rocks are found at the current level of exposure, and these are overlain

unconformably by Burdigalian through Serravallian post-orogenic volcanic rocks of the Cabo de Gata complex that are tilted to the vertical against the fault zone, hence indicating that they are older than the time of onset of the faulting.

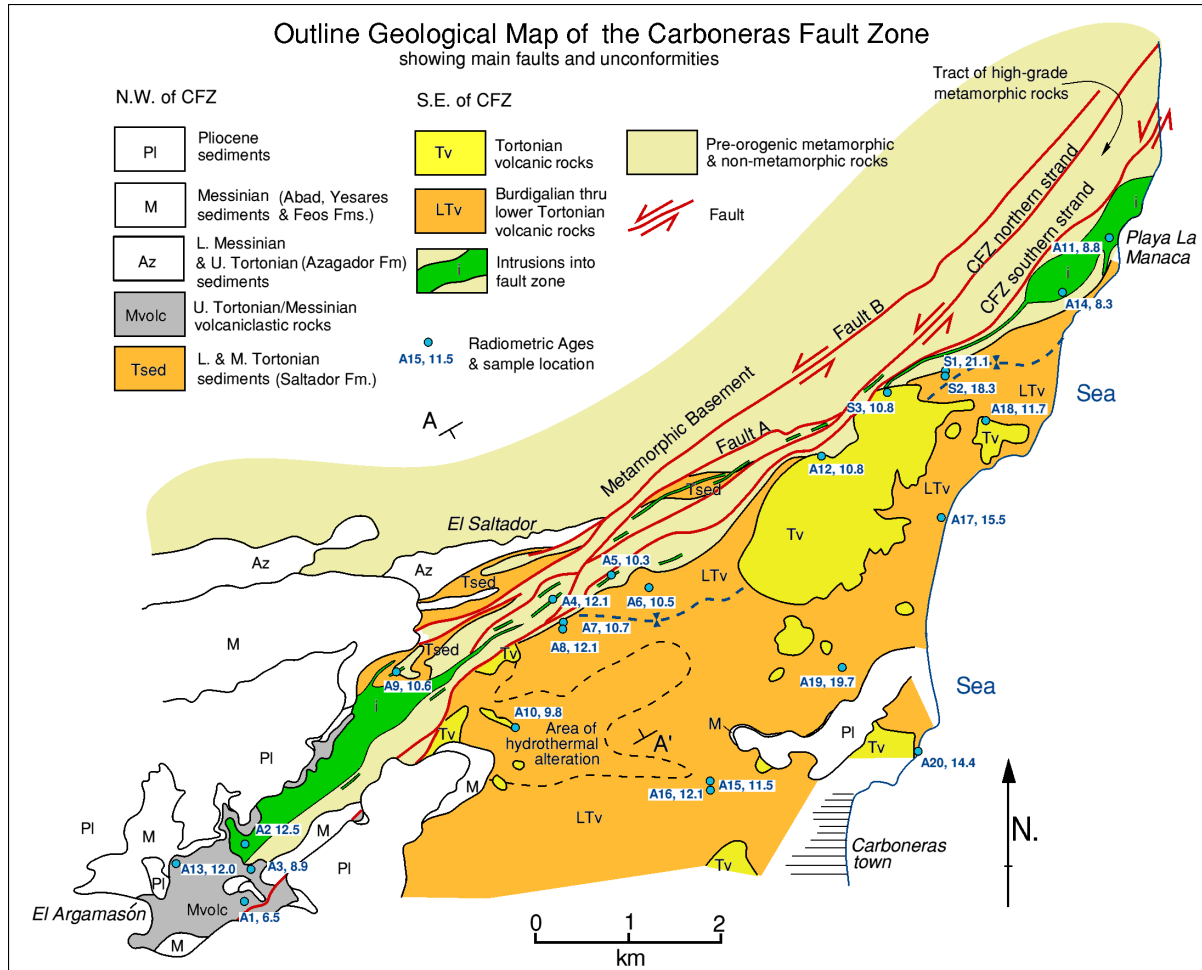


Fig. 5.
Geological outline of the Carboneras Fault Zone near Carboneras town, where the fault system can be seen cutting metamorphic basement rocks. Outlines of the succession of main unconformities affecting the postorogenic sedimentary and volcanic rocks are shown, together with andesitic dykes and minor intrusions into the fault zone. The outcrop area of basement rocks is shown not divided into lithotectonic units. The intrusive rocks cut only basement rocks and L. Tortonian sediments. Locations of dated volcanic rocks are shown, together with mean ages in Ma. Uncertainties ($\pm 2\sigma$) on the mean ages are shown in Table 1. A-A' marks the position of the line of geological cross section in Fig. 4, which is close to the trend of the valley of the Saltador river.

Tortonian volcanoclastic rocks lie unconformably above the older volcanics and overstep their base northwards, only to become truncated against the CFZ (Fig. 4). Messinian volcanoclastic rocks overlie these, and overstep northwards the CFZ but are slightly

affected by the later fault movements (Fig. 5). Intrusive andesitic dykes outcrop in the CFZ, including two that are some 500 m wide.

To the NW of the CFZ the oldest post-orogenic rocks are Serravallian/Tortonian marine marls and sands of the Saltador Formation (Fig. 5). These are preserved from erosion in tight synformal inliers in the basement rocks. In the CFZ they are cut and offset by the faults and often are intruded by andesitic dykes. They are equivalent to the Chozas formation of the Sorbas basin, which is strongly affected by NE-SW directed extensional faulting at its eastern margin with uplifted basement rocks of the S. Cabrera (Giaconia *et al.* 2011).

The rocks of the Saltador Fm are overlain unconformably (Figs. 5) by the less strongly folded rocks (beach sands and marls) of the Azagador Fm (U. Tortonian/L. Messinian, Van der Poel 1992; Fortuin *et al.* 2003), and these are not cut by igneous dykes. This unit is in turn overlain unconformably by the three Messinian formations (Abad Fm (marls), Yesares Fm (selenitic and alabastrine gypsum), Feos Fm, (marls), (Fortuin *et al.* 2003), and in turn unconformably by Pliocene formations. Pliocene formations are gently arched over the trace of the CFZ, are only minimally affected by fault movements and testify to continued transpression or to localized uplift of the rocks of the CFZ. They are also tilted gently against the southern side of the S. Cabrera and each of the progressively older units are tilted at a steeper angle against the basement block, testifying to continued progressive uplift of the S. Cabrera from Tortonian through Quaternary time. This succession of basement uplifts is responsible for the overall shape of the geological units in the CFZ area.

The Carboneras fault zone consists of four main fault strands labelled on Fig. 5 as follows:

- (a) The northern and southern strands of the CFZ. These seem to accommodate the largest displacements of the fault system. Between them lies a belt of distinctly higher metamorphic grade Nevado-Filabride basement schists (Westra 1969), including sillimanite-bearing gneisses with evidence of partial melting (e.g. at GR 597550 4099510) dated at 20 Ma BP (Platt & Whitehouse 1999).
- (b) Faults labelled A and B in Fig. 5. These lie immediately to the north of the main faults of the CFZ and collectively have an estimated strike-slip offset of almost 2 km on the basis of the displacement of the axial zone of a synform in the Saltador Fm. Fragments of the Saltador Fm are strung out along the northern strand of the CFZ over at least 6 km.

The fault cores consist of typically several metres thickness of clay-bearing fault gouge derived from graphitic mica schist. The clay minerals are produced by breakdown of mechanically granulated feldspars and micas (Rutter & White 1979; Solum & van der Pluijm 2009). The fault rocks characteristically display a foliation that is transected by Riedel shear surfaces (Rutter *et al.* 1986, 2012; Faulkner *et al.* 2003). Displacement indicators within the fault rocks and stratigraphic constraints show that the fault displacement pattern is close to pure strike-slip (Rutter *et al.* 2012). The country rocks between the fault cores are typically variably damaged by crack networks.

The depth of burial during the formation of the fault gouges now seen at the surface is not well constrained, but does not seem likely to have been much more than 1 km, according to the likely maximum thickness of the Saltador Fm (bearing in mind it is always truncated at the top by an unconformity) or of the thickness of the volcanic

deposits. Absence of a dip-slip component of faulting explains the lack of higher grade rock products of faulting. The formation of chlorite as a secondary mineral in the fault gouge may have been aided by elevation of the geothermal gradient under the influence of the igneous activity.

The Sorbas Basin

The Sorbas Basin (Figs 6 and 7) is presently being targetted for study in order to determine how NE-SW extension of the continental crust is accommodated immediately adjacent to the north side of the CFZ. As presently outcropping, the basin is deeply dissected. The upper part of the fill comprises up to about 400 m of Azagador, Abad, Yesares and Feos Fms (Messinian) rocks. These are arched into a broad, low amplitude antiform trending E-W as a result of the Messinian and Pliocene uplift of the S. Cabrera (Figs. 6 and 7). This sequence sits with marked unconformity on the underlying 1 km thick Serravallian through U Tortonian Chozas Fm (equivalent to the Saltador Fm immediately adjacent to the CFZ). This unit comprises conglomerate megabeds interlayered with turbiditic sands in the lower part, derived from the Sierra de los Filabres to the north, giving way to marls in the upper part. The lowermost units are affected by extensional faulting that propagates down into the basement, but this syn-rift sequence is sealed by an unconformable and monotonous sequence of younger turbidites that oversteps eastward onto the basement. It is not clear yet whether these younger rocks are bounded against extensional faults further east that cut basement rocks. The folding that terminates the Chozas sequence produced an E-W trending fold trough, with rocks vertical on the south side, that also folded the extensional faults. Thus initially low-angle extensional faults appear as wrench faults bounding what is now seen as the lowermost part of the basin fill in contact with the basement rocks to the south. The folding demonstrates continued NW-SE compression of Africa against Iberia at the same time as Iberian crust is being stretched NE-SW. Thus the result may be nearly plane-strain deformation in the horizontal plane.

Before the beginning of emergence of the basement massifs in late Tortonian time, the original Sorbas rift basin sediments would have been contiguous with the Saltador Fm sediments that are now truncated against the CFZ and the lower parts of the fill of the Nijar and Vera basins. These sediments can be seen resting unconformably on Alpujarride basement rocks near Turre, at Nijar and at el Saltador, with small erosional outliers near Gafares and north of El Saltador, and strung out to the NE almost to the coast along the northern strand of the Carboneras fault (Fig. 6).

The estimated position of the Gibraltar subduction 12 Ma BP is about 150 km NE of its present position, requiring an average rollback rate of about 12 mm/yr hence an extensional strain in the back-arc of about 30% to be accommodated (the strain is the same everywhere in the back arc according to the stretching transform model, but fault displacement rates must increase to the south-west). This must be accommodated by localized faulting in the brittle upper crust and flow in the lower crust and upper mantle. In the Sorbas basin area, if this were accommodated on a single low-angle detachment fault, it would require a displacement of about 5 km, or less if more faults were involved. Some evidence of such extensional faulting has been found, but intuitively there are more faults

yet to be discovered. This may prove difficult where they are sealed by unconformably overlying deposits, and it can be hard to locate them in the basement rocks.

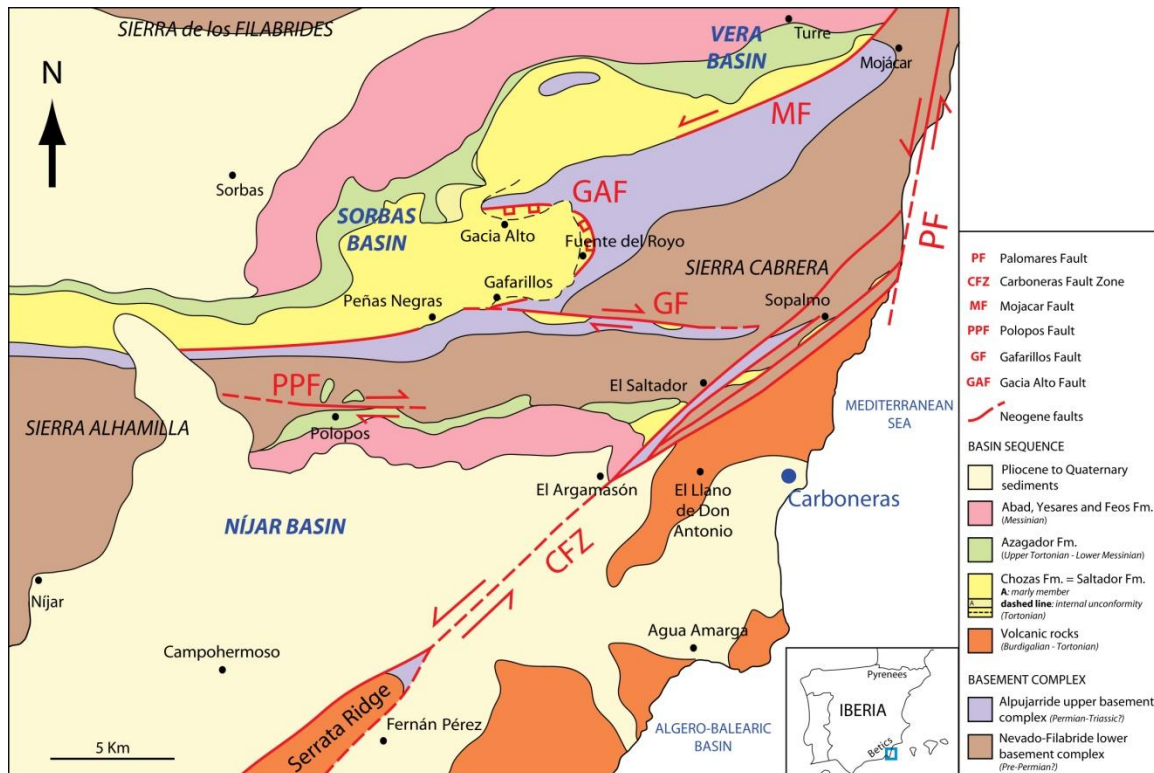


Fig. 6.
Outline map showing the main stratigraphic and tectonic elements that will be seen in the Sorbas basin and along the CFZ. The rocks of the Tortonian Chozas Fm are regarded as equivalent to the Saltador Fm. In the west L. Pliocene rocks are suspected to be U. Messinian.

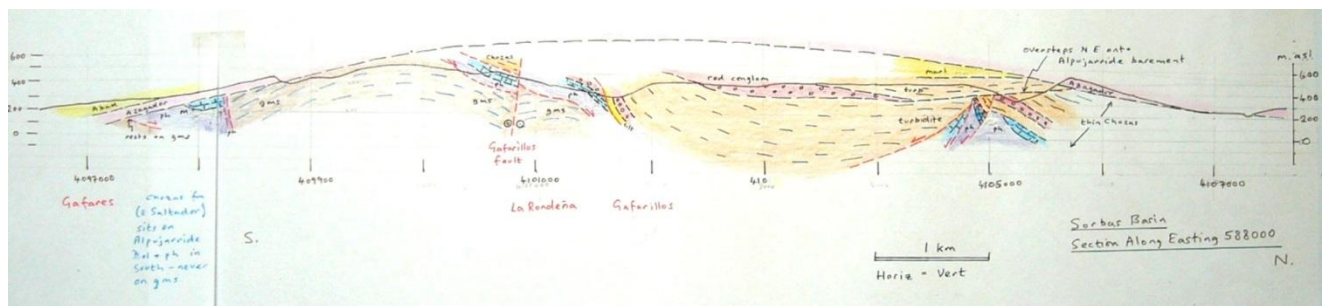


Fig. 7
N-S sketch section (looking west) across the Sorbas basin and basement rocks to the south along the centre line of the map in fig. 6. Extensional faulting affecting basement is seen at the lower part of the Chozas Fm and then sealed by unconformity. The overlying rocks overstep eastward onto the basement, but the disposition of extensional faults affecting the basement is not yet clear. The early extensional faults have been folded, together with the overlying rocks, about ENE-WSW axes as a result of continued NW-SE compression.



Fig. 8.
View SE near the village of Gacia Alto in the eastern Sorbas basin showing the extensional faulting (Fig. 7) that affects basement and L. Chozas Fm.

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