COMBINED PSI AND DIFFERENTIAL GPS STUDY OF ZAKYNTHOS ISLAND (W. GREECE) FOR THE PERIOD 1992-2012

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ABSTRACT

Ground deformation studies based on Differential GPS (DGPS) measurements and Permanent Scatterers InSAR (PSI) analysis using ERS and ENVISAT radar data have been conducted on the island of Zakynthos (Western Greece) covering the period 1992 to 2012. These results were compared, validated and integrated with geological, geotectonic and seismological data aiming to better understanding the pre-earthquake deformation process, as well as the behavior of the present tectonic regime, in order to lead to a more effective and standardized approach to monitor the hazard and risk in this seismically very active region of Western Greece. PSI results for Zakynthos Island indicate that a slight uplift (1-1.5 mm/yr) had occurred along the extreme western part of the island, while a moderate subsidence (about -2mm/yr) took place at its southwestern part. Ground differential motion along faulting zones was apparent in the PSI-derived velocity field, verifying the multi-fragmented character of the western part. The occurrence of the seismic outbreak that took place offshore to the south of Zakynthos during 2005-2006 may have contributed to the different deformational pattern as revealed by the ERS and ENVISAT PSI products covering the periods 1992-2000 and 2003-2010, respectively, as well as the strong opening of the southern part of the island as deduced by the DGPS measurements.

1. BRIEF GEOTECTONIC SETTING

The area of Western Greece, and in particular the central Ionian islands, plays an important role in the kinematic processes of the eastern Mediterranean, since it lies within a seismotectonically very active and complex region that is undergoing rapid and intense ground deformation. The highest seismic activity in Europe currently takes place in that region, constituting part of the Eastern Mediterranean lithosphere that is subducting beneath the Aegean lithosphere along the Hellenic Arc**.**

The subduction zone terminates against the Cephallonia Transform Fault (CTF) – a major strike-slip fault that links the subduction boundary to the continental collision between the Apulian microplate and the Hellenic foreland [1], and plays a key role in the regions geodynamic complexity [2], [3], [4].

The CTF lies offshore to the west of Cephallonia in an area with a deep bathymetric trough (water depths in excess of 3000 m) that strikes N20E. Its slip-rate varies from 7 to 30 mm/yr based on DGPS measurements [5], [6] which is consistent with seismological data [7]. The phenomena of active subduction and continental collision are responsible for earthquakes produced by compressional stress along the western coasts of Greece and Albania, as well as the convex side of the Hellenic arc.

Zakynthos Island consists of rocks of two isopic zones, the Pre-Apulian or Paxos Zone and the Ionian Zone (Fig. 1). Both of these zones lie to the west of the Pindos thrust and the boundary between them is the Ionian thrust which is generally considered to represent the most external Hellenide structure [8]. This thrust is not well exposed in Zakynthos, because the absence of Mesozoic carbonates and the occurrence of a thick Pliocene cover make the boundary between these zones difficult to define. The Pre-Apulian or Paxos zone is characterized by Upper Cretaceous to Miocene sediments (limestones, marly limestones etc.), whereas the Ionian zone, which appears in the southeastern part of the island, consists of limestones and evaporitic rocks of Triassic age. The post Alpine deposits are marls of Pliocene age and Quaternary marine and continental formations [2],[8].

Zakynthos Island is separated from mainland Greece by an extensional basin, which is referred to in the literature as the Zakynthos Valley/Canyon system and is located between the coastline of Western Peloponnesus and the island, in the vicinity where many earthquake epicenters have occurred over the past decades. This system is characterized as a structural basin trending parallel to the local tectonic zones [9]. The Zakynthos Valley/Canyon system is thought to have been formed during the middle Pleistocene – Quaternary and is controlled by salt tectonics and compressional tectonics that are associated with the subduction along the Hellenic Arc [9]. In response to these regional tectonic activities, subsidence or uplift has affected large parts of Zakynthos' coastline during historical times. Considering all the above mentioned phenomena it can be clearly concluded that the broader region of Zakynthos is geologically and seismotectonically very complex and is key for a better understanding of the processes related to the collision between the African and Eurasian plates.

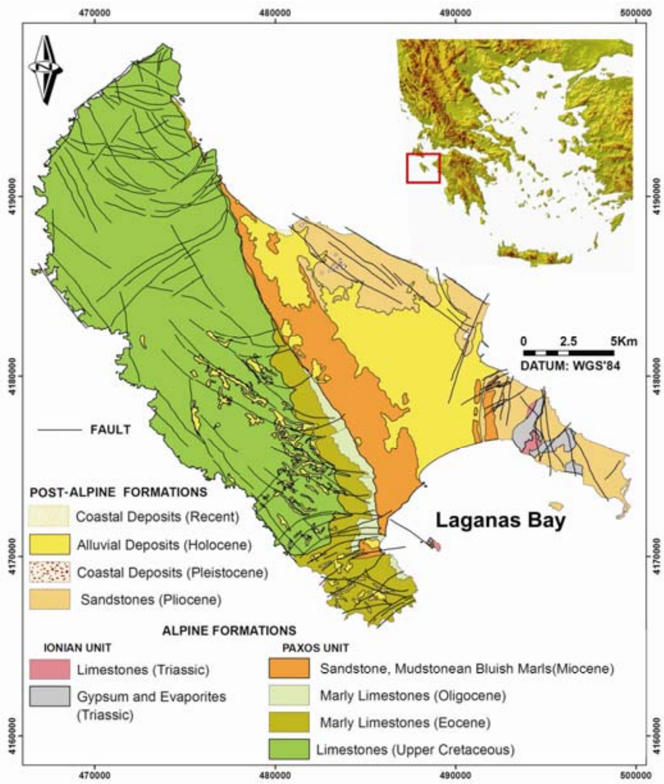


Figure 1. Detailed Geological Map of Zakynthos Island, showing also the main faulting features (IGME, Geological Map of Greece, 1983)

2. THE GPS MEASUREMENTS

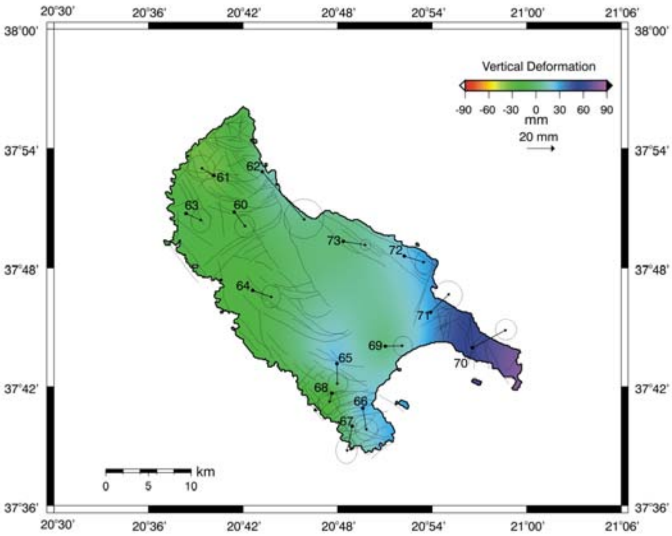
The GPS network in Zakynthos was first installed in 2005 [10] (and re-measured in 2006 and 2012). Fourteen (14) stations were distributed around the island focusing mainly on the northern and the southern parts, which are the most fractured zones of the island. The data were analyzed with the Bernese GPS software v.5.2 [11]. Final IGS (International GNSS Service) products (e.g. satellite orbits and clocks) were used to calculate daily coordinates and tropospheric parameters. Overall rms errors of about 1.0-5.3 mm and 2.0-8.1 mm for the horizontal and vertical components of displacement, respectively, were achieved for the majority of the stations (at a 90% confidence level).

Station No. 73 was chosen as a local reference station because of its location on the center of the island in an alpine basement of the Paxos unit and thus, its anticipated better geological and tectonic stability as compared to other parts of the island. The station was operating continuously during all campaigns and tied to the ITRF2008 using the observational data from a number of IGS Reference Frame Stations in Europe (http://www.epncb.oma.be/). This station has a horizontal motion to the SSE direction with respect to ITRF2008 (V_{East}=9.1±1.4 mm/yr and V_{North}=-9.2±1.3 mm/yr), while the vertical component is rather stable (V_{Up}=-1.9±1.8 mm/yr). The overall behaviour of station No. 73 which is consistent with the anticipated regional motion [6], [10], [12] has to be particularly considered, since it represents the local reference point not only for the DGPS measurements, but also for the interferometric analysis.

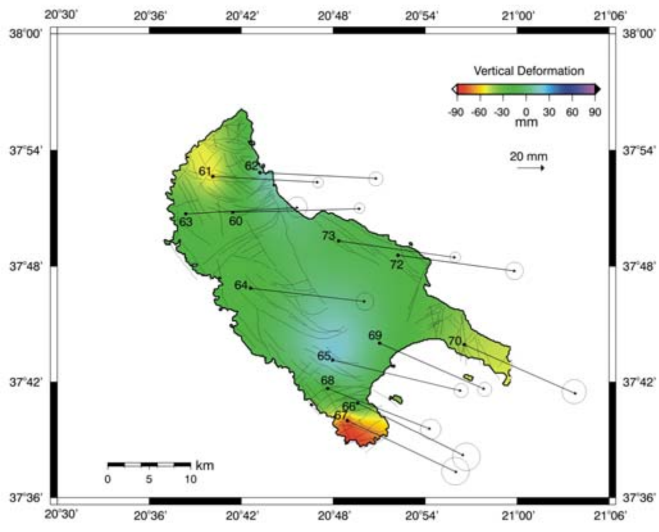
Fig. 2a presents the motion vectors with respect the ITRF2008 for the first re-measurement period 2005-2006. It is evident that a horizontal extension of the southern part of the island had occurred in the area around Laganas Bay which seems to be "opening". This deformational pattern may be attributed to an increase of the seismicity in the area during that period. An earthquake M_w=5.6 occurred offshore to the south of the island on October 18, 2005; thereafter, a significant sequence of at least four earthquakes (M_w=5.5 to 5.7) occurred in the same region between April 4-12, 2006 [13], [14]. Analytically, in the southern part of the island the western part exhibited a southwestern motion with magnitude ranging from 15-20 mm, while its eastern part had magnitude of about 30 mm but towards the SSE. The central part of the island appears rather stable. The northern part, however, presents an inconsistent pattern with a westward motion that prevailed for most of the stations. The vertical deformation is expressed with uplift mostly in the southern part bounding the area of Laganas Bay, with values up to 60 mm in the western part. The extreme northern part had generally subsided by 12-30 mm.

For the second re-measurement period (2006-2012) the horizontal deformation is consistent with the anticipated southwestern motion of the area with respect to the ITRF (Fig. 2b). However, in the northern half of the island the vectors show a westward motion (about 80 mm) while to the south a southwestern motion prevails (of the same amplitude). The vertical deformation shows significant subsidence for the whole of the island, with the higher amplitudes taking place to the south (more than -50mm), in the areas where the strongest uplift took place in the previous period (2005-2006). The later may indicate a rebound of the whole area to the state that existed before the outbreak of the seismic activity during 2006.

The strong differentiation in the motion between the northern and the southern parts of the island, observed mainly in the first re-measuremnt period (2005-2006) but also in the second period (2006-2012), highlights the different kinematic status of the two areas as has been described in previous works [6], [10].



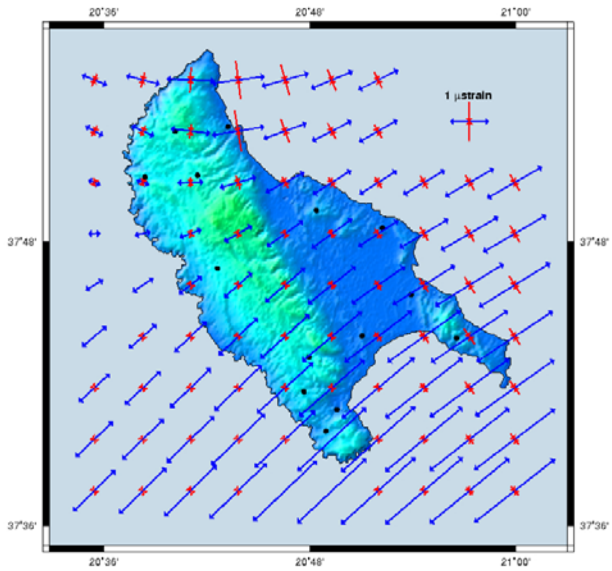
(a)



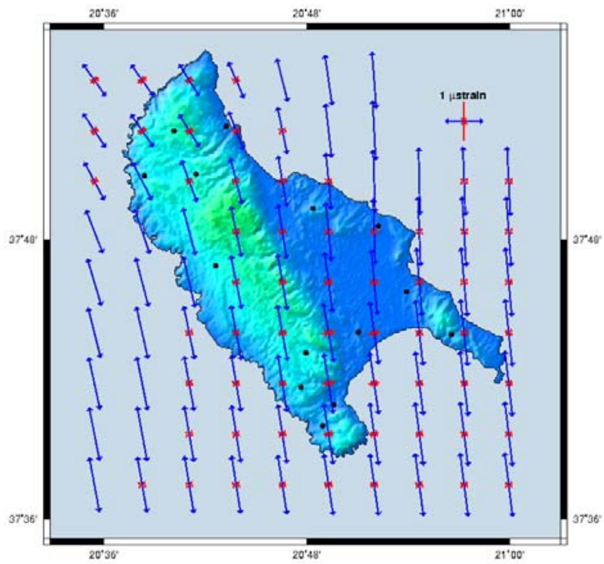
(b)

*Figure 3. Horizontal and Vertical displacement (mm) of the Zakynthos Island GPS network observed for the period **(a)** 2006-2012 and **(b)** 2006-2012 (ITRF2008)*

The horizontal strain-rate field was calculated based on the horizontal GPS velocities for both periods (Fig. 3). The strain-rate results have been produced for a correlation length of 4 km and error estimate (σ) of 2 mm (s/w used: grid_strain, [15]). For the first period, a clear differentiation between the northern and the southern parts of the island is observed. Extension predominantly took place in the south with a NE-SW direction, while slight compression occurred in the north. For the second re-measurement period (2006-2012), the extension remained but the axis rotated to an almost N-S direction. Both periods reflect the different tectonic and kinematic characteristics between the two parts of the island (northern and southern). The former may be related to a possible large extensional deformation mechanism that is taken place along a N-S striking axis crossing the island, almost parallel to the main geological contact of the area (limestones to the west, post-alpine formations to the east, see Fig. 1).



(a)



(b)

*Figure 3. Calculated Strain Field in Zakynthos Island based on GPS observations for the period **(a)** 2005-2006 and **(b)** 2006-2012.*

3. THE PSI DESCRIPTION

Differential SAR Interferometry (DInSAR) is based on pixel-by-pixel computation of the so-called interferometric phase using two satellite radar acquisitions – such differential phase is a measurement of what has changed in the time interval (35 days for ESA satellites ERS and ENVISAT) between the two images. Apparent phase variations between two satellite scenes can be caused by actual ground displacement or by atmospheric effects that delay electromagnetic wave propagation. The PSInSAR™ technique (i.e. [16], [17]) allows the atmospheric effects to be estimated and then removed by combining data from a long time series of SAR images (such as those available in the ESA-ERS archive) which were acquired from late 1991.

The approach is based on a few basic observations: atmospheric artifacts show strong spatial correlation within individual SAR acquisitions but are uncorrelated in time and, conversely, target motion is usually strongly correlated in time, exhibiting varying degrees of spatial correlation depending on the type of deformation (e.g. subsidence due to water pumping, fault displacements, localized sliding areas, collapsing buildings, etc.). In order to improve the accuracy of ground displacement estimations, only scatterers minimally affected by temporal and geometrical decorrelations are selected for processing [16], [17]. Differential phase contributions generated by atmospheric effects can be separated from stable ground signals (known as Permanent Scatterers, or PS) if the temporal span of SAR data used is wide enough (typically about 30 images). Given the high spatial correlation of the Atmospheric Phase Screen (APS), even a sparsely populated grid of measurements allows a reasonable sampling of atmospheric phase contributions, typically providing a PS density of at least 3 – 4 PS/km^2.

After the removal of the APS, sub-meter elevational accuracy is achievable and millimetric terrain displacements can be detected, through the exploitation of extensive temporal satellite data archives. In particular, target velocity in the line of sight (LOS) of the satellite can be estimated with accuracy often greater than 1 mm/year, allowing accurate verification of deformational models, a key issue for risk assessment. Results of multi-interferograms analysis are mapped with individual time-series data and LOS velocities available for each PS (typical coordinate system used is WGS'84). Common to all differential interferometry applications, the results are computed with respect to a ground control point (GCP) of known elevation and motion.

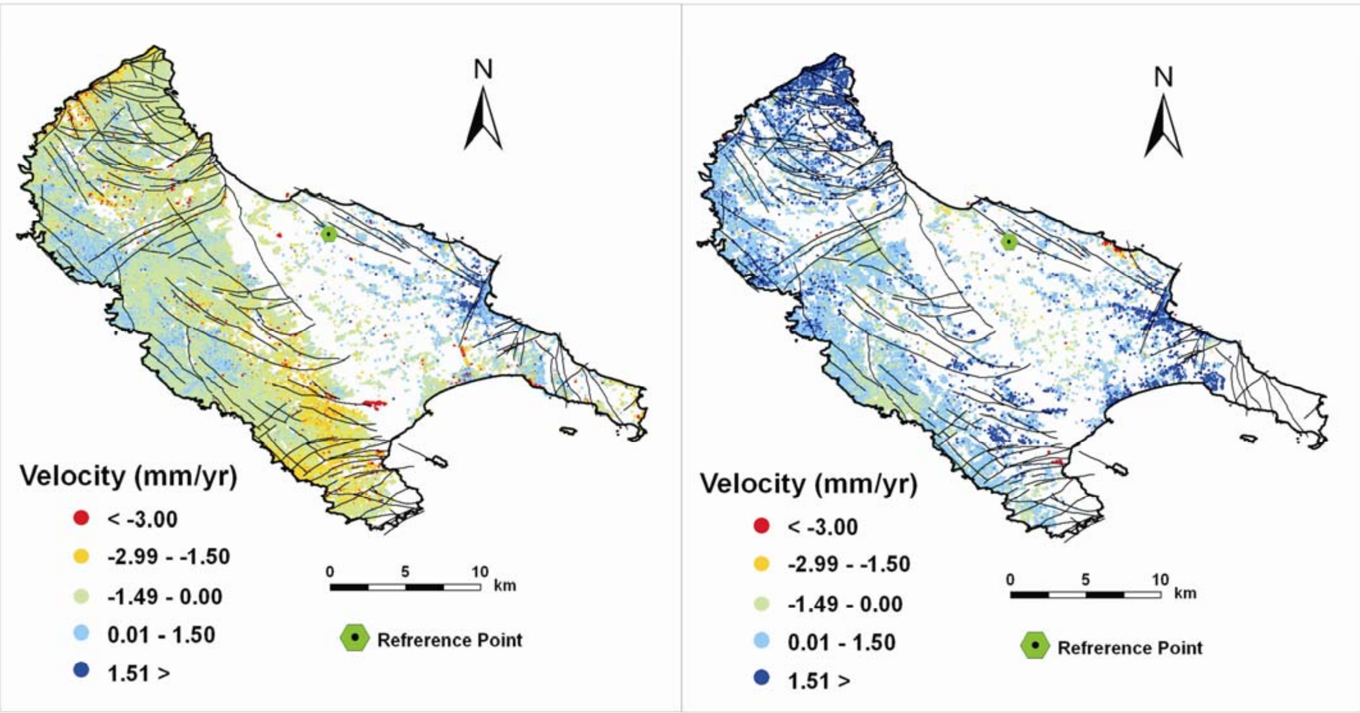
The angles of θ and δ are 12.4^o and 22.5^o, respectively. These values slightly change for the ERS and ENVISAT, as well as for ascending or descending acquisition geometry. It appears that the vertical component of ground deformation is about 93% of LOS. The PS InSAR technique is therefore more sensitive to the vertical deformation.

For Zakynthos Island, thirty nine descending images were used for the ERS PS InSAR product covering an area of about 560 km^2 for the period 1992-2000. The ENVISAT data set consisted of twenty one images covering the period 2003-2010 with more than 52,000 PS points. A point in the vicinity of No. 73 GPS reference station (Fig. 2) was selected as a reference point for the PS InSAR product, having coordinates Lat. 37.8212^o and Long. 20.8045^o, and showing relatively stable vertical motion as has been described above (V_{Up}=-1.9±1.8 mm/yr).

The ERS descending (1992-2000) and the ENVISAT (2003-2010) PSI velocity products are presented in Figs. 4a and 4b, respectively. It is noteworthy that most of the PSI points (more than 80%) are located on the western half of Zakynthos where the limestone regime prevails. Conversely, the PSI points are limited and usually located on man-made structures on the eastern half of the island which consists of alluvial and soft sedimentary formations.

Considering the ERS PSI deformational velocity (Fig. 4a), a slight uplift (1-1.5 mm/yr) is observed along the extreme western part of the island, while a moderate subsidence (about -2mm/yr) is noticed at its southwestern part. The largest amplitudes of subsidence (>3mm/yr) occurred at the northern cliffs of the island where landslide phenomena have been recorded. At the southeastern part, a local area of limited extent is noticed with slight uplift (about 1.5 mm/yr) that is attributed to local faulting. The ground differential motion along faulting zones is apparent in this image, especially at the multi-fragmented northern and southern parts of the island.

Considering the descending ENVISAT deformational velocity (Fig. 4b), the PSI points are an order of magnitude lesser as compared to the ERS images. In areas where a slight subsidence was taking place at the western half of the island during the same period as the ERS descending velocity field (Fig. 4a), the motion had changed to a slight uplift (about 1.5 mm/yr). That change in the ground motion is more evident at the southwestern part of the island. The eastern part, though, maintained the same deformational pattern for both periods of the ERS and ENVISAT descending images. However, a stronger uplift occurred at the southern part (i.e., at Laganas Bay), most probably due to the increase seismicity that took place offshore to the south during 2005-2006.



(a) *(b)*

Figure 4. ***(a)*** *The ERS (1992-2000) and* ***(b)*** *the ENVISAT (2003-2010) PSI deformational velocity maps of Zakynthos Island.*

4. DISCUSSION – CONCLUSIONS

During the last decade, a multi-disciplinary study of the broader central Ionian region, and particularly of Zakynthos and Cephalonia Islands, was carried out that included neotectonic studies, DGPS observations on established GPS networks over the area, and detailed seismological analyses [10], [18], [19]. The purpose of all these applied methodologies was to better understand the tectonic regime of the area, contributing thus to earthquake prediction research, since the study area is the most seismically active in Europe with the highest seismic energy release.

The PSI product of Zakynthos Island is a significant improvement and a very important contribution in the research already taking place in this area. The PSI deformational velocity map has provided a spatial coverage of the ground deformation of the area at a millimetre accuracy compared to the GPS point coverage. In this way, a direct comparison between DGPS and PSI results was feasible at a verification attempt. Active tectonism on a local scale was possible to be quantitatively recognised. Expected motions along major faulting zones were verified. The type of ground motion (uplift or subsidence) and the character of it (linear or non-linear) were accurately determined.

The PSI images of the two distinctive periods (1992-2000 and 2003-2010) uncovered the different kinematic states that occurred in the island during these years. In the first period (1992-2000), subsidence characterized the northern and the southern parts of the island while a different image (uplift) was derived for the period that the ENVISAT images covered (2003-2010). This distinct differentiation may be attributed to the occurrence of the seismic outbreak that occurred offshore to the south of the island. However, this differentiation may indicate a more regional change of the tectonic status that may be taking place in the broader area over the last decade [18].

The DGPS results for the period 2005-2006 also reflected the intense seismic activity that occurred in 2006. The results from the next period (2006-2012) showed that the area is calming, and intense subsidence is taking place in response; a condition that is in accordance with the ERS PSI image for the period 1992-2000, before the seismic outbreak of the years 2005 & 2006. The DGPS results for both observational periods show horizontal trajectories that when combined with the resulted strain field emphasized the different tectonic states of the northern and the southern parts of the island. Additionally, they revealed that there is a possible kinematic boundary crossing the island approximately in an almost E-W direction, in the central part of it, which has no surface exposure, and it is not evident in the local geotectonic map (Fig. 1).

Considering the PSI products with the DGPS results together with the available geotectonic information and seismic activity for the broader central Ionian region has proven particularly effective in understanding the tectonic behavior and its implications in such a complex environment. Especially, the integrated interpretation of the above different applied methodologies showed that after 2003 a change in the tectonic character of the area has taken place that may have led to the seismic outbreak of 2006.

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