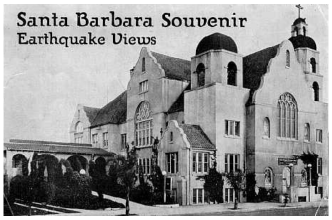

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USE OF SUBSIDENCE RATE AS PROXY FOR RESONANCE PERIOD

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ABSTRACT

The current practice to incorporate site effects in seismic hazard estimates is to use the time-averaged shear-wave velocity to 30 meters for site amplification. However, current efforts are made to improve site amplification estimates by adding information about the sediment depth or the resonance periods. Recent studies have shown the ability of InSAR Permanent Scatterer approach to densely map present-day ground motion in urban area with a millimetric precision for relative average annual displacement rate. Except anthropogenic causes, the long-term subsidence is caused by compaction of sediments due to increasing overburden. Since both resonance periods and subsidence rate increase with thickness and softness of soil, both data should be correlated. We test this idea on Grenoble city which is located in an alpine valley filled with thick late quaternary deposits and for which all necessary data are available: SAR images, resonance periods, bedrock depth, shear-wave velocities, geological and geotechnical drillings, levelling data. Results show that the subsidence rate is linearly correlated with the resonance periods and is mostly caused by compaction of the entire sedimentary column.

INTRODUCTION

There is a growing interest to incorporate site effects in seismic hazard estimates (e.g. shaking maps, earthquake scenario, insurance models). The current practice is to use for site classification the average shear-wave velocity in the upper 30 meters (Vs30). Since site conditions are usually not known with the appropriate spatial coverage, a growing attention is paid to proxies. Recently, Wald and Allen (2007) proposed to use as a proxy for Vs30 the surface topography: a large slope is related to rock or stiff soil, while a small slope testify of soft soils. However, current efforts are made to improve site amplification estimates by adding information about the sediment depth or the resonance periods (e.g. Zhao et al., 2006; Fukushima et al., 2007; Cadet et al., 2011). Recent studies have shown the ability of Spacebone radar interferometry (InSAR) time-series approach to densely map present-day ground motion in urban area with a millimetric precision for relative average annual displacement rate (Ferretti, 2001; Colesanti, 2003). Except anthropogenic causes (pumping, underground infrastructure), the long-term subsidence is caused by compaction of sediments due to increasing overburden. Subsidence rates can thus often be related to the distribution and thickness of compressible sediments (Galloway et al. 1998), and then can give indications about sediment thickness or about spatial changes in mechanical properties. These are the same factors which actually control the fundamental period of a site $T_0 = 4h/V_S$, where Vs is the average S-wave velocity over the hard seismic bedrock, and h the corresponding thickness. Since both resonance periods and subsidence rate increase with thickness and softness of soil, both data should in principle be correlated. We test this simple idea on Grenoble city which is located in a valley filled with thick late quaternary deposits and faces both large site effects (Lebrun et al., 2001; Cornou et al., 2003) and moderate subsidence as indicated by historical levelling data (Ménard et al., 2009).

EVIDENCE OF SUBSIDENCE IN GRENOBLE BASIN FROM HISTORICAL LEVELLING DATA

In Western Alps indeed, the IGN (French Geodetic Survey) levelling comparisons (1886-1969-1992) have revealed several sedimentary valleys exhibiting significant subsidence phenomena (subsidence rate > 1 mm/year) (Fig. 1). At the scale of the Y-shaped Grenoble valley, comparison of levelling data over the period 1902-1979 along a profile crossing the Isère valley from the West to the East show maximum of subsidence rate (2-3 mm/year) in the valley center (Fig. 1). At the local scale of the Grenoble old town, a 1880-2002 comparison reveals a sagging movement increasing from the northern edge of the valley to the center part, reaching 43 cm about 1 km from the valley edge.

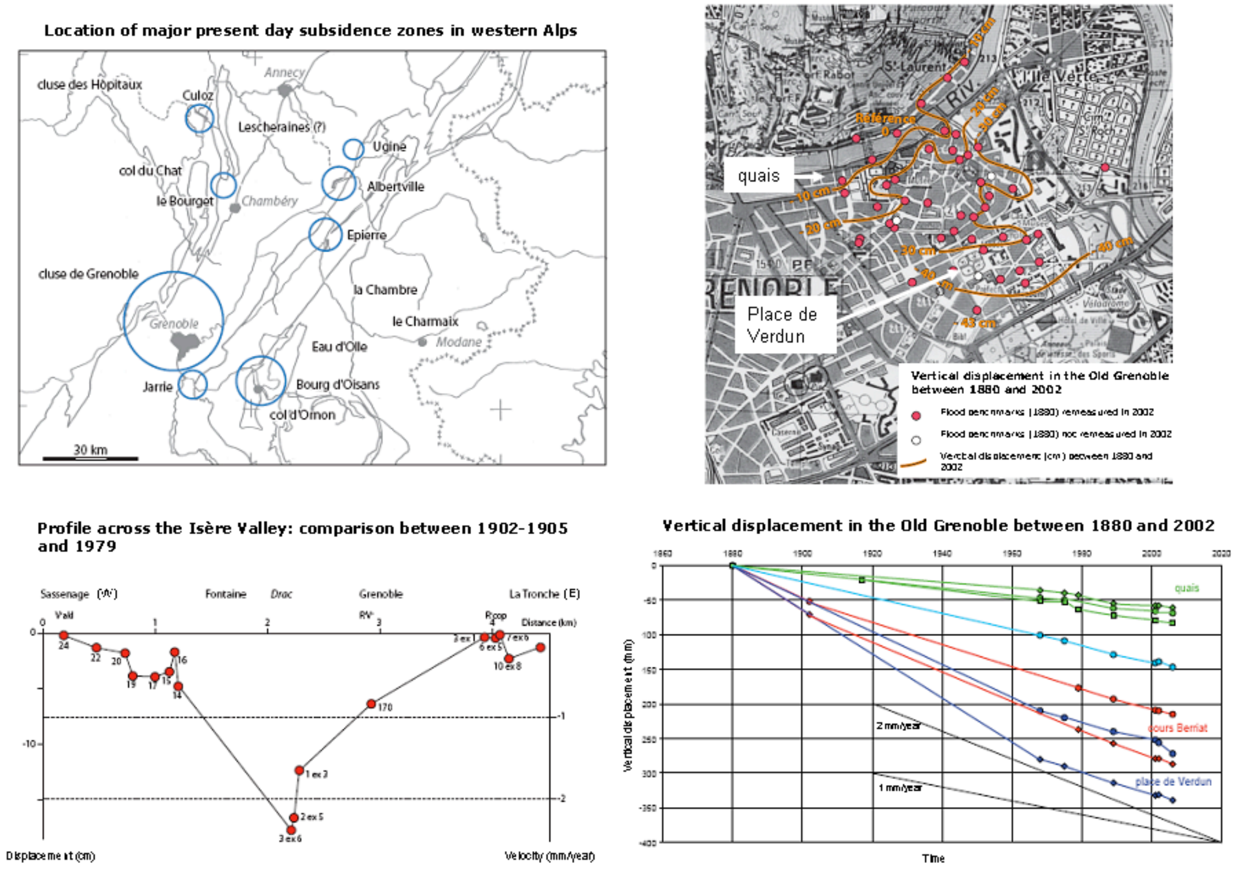

Fig. 1: Location of major present day subsidence zones in western Alps (top left); Vertical displacement between 1902-1905 and 1979 along a profile crossing the Isère valley (bottom right); Vertical displacement in the Old Grenoble between 1880 and 2002 (right panel). From Ménard et al. (2009)

DATA

Over the last ten years, extensive geophysical investigations (vertical and offset seismic profiles at a deep borehole, refraction and reflection seismics and gravity measurements) have been carried out in Grenoble, France, to determine the structure of the valley in terms of sediment thickness and layering, seismic velocities, and bedrock topography (Fig. 2a) (Vallon, 1999; Nicoud et al., 2002; Dietrich et al., 2009). These measurements have allowed to build a 3D numerical model of the Grenoble basin, which was adopted for the numerical benchmark test on third international ESG symposium held in 2006 (Tsuno et al., 2009, Chaljub et al., 2010). Besides these measurements, intensive microtremors surveys (single site and array noise recordings) have been carried out from 1999 to 2009 (Bettig et al., 2001, Lebrun et al., 2001; Hobiger, 2006; Guéguen et al., 2007; Kawase et al., 2006, personal communication) as well as temporary seismological recordings (Cornou et al., 2003; Cornou et al., 2009). Sensors used were mid-band velocimeters (Lennartz 5s, CMG40) and accelerometers amplified at low frequency. A total of 597 resonance periods are used in this study (Fig. 2b). Subsidence rates from interferometric data were estimated from the analysis of SAR images of the satellites ERS-1 and ERS-2 acquired in between 1992 and 2000. These data were processed by using the Permanent Scatterer approach (Colesanti, 2003) with a reference site located at the northern edge of the basin and provided 19101 estimates of average vertical displacement with a precision of about 0.5 mm/year on average (Fig. 2c). Subsidence rates from levelling data over the 1989-2001 time period were obtained at 112 measurement sites (Fig. 2d) (Ménard et al., 2009). The reference site is located nearby the reference site used for the InSAR data analysis.

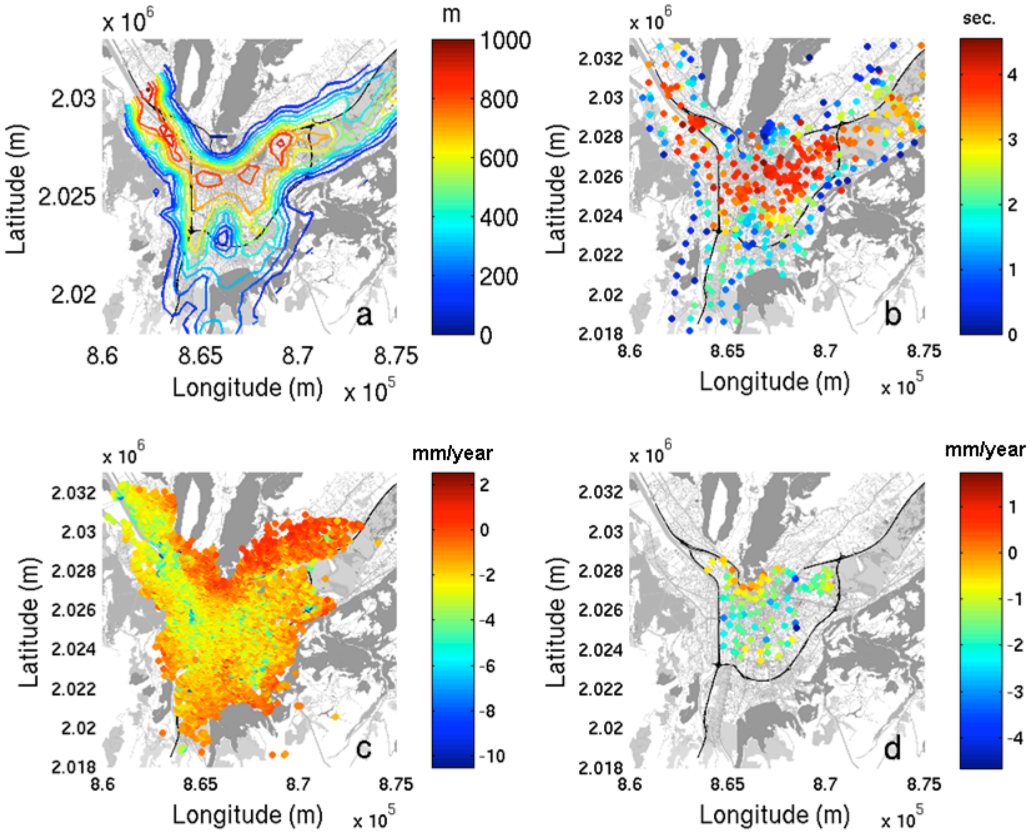

Fig. 2: *(a) Bedrock depth derived from gravimetric data (Vallon, 1999); (b) Resonance periods; (c) Subsidence rates derived from InSAR data and (d) levelling data.*

COMPARISON BETWEEN SUBSIDENCE RATE DERIVED FROM LEVELLING AND INSAR DATA

In order to check reliability of subsidence rate derived from InSAR data, we first compared them with levelling data. Both datasets having very different spatial distribution and number of samples (Fig. 2), we have tested different methods to compare the two datasets. Finally, we found that the most robust comparison (i.e. the less sensitive to cell size and InSAR data weighting) was obtained by averaging InSAR-based subsidence rates within 200 m grid cells size centered at the levelling sites. Such grid cell sizes allow to account for most of the levelling data (100 over a total of 112 measurements, Fig. 3a) and a number of InSAR subsidence rate estimates exceeding 5 within a grid cell. Comparison shows that both datasets provide very similar subsidence rate that ranges from 0 to -4 mm/year (Fig. 3b). The rather large dispersion of InSAR estimates is mainly caused by very local subsidence due to large size buildings or local road infrastructures (Fig. 3c-d).

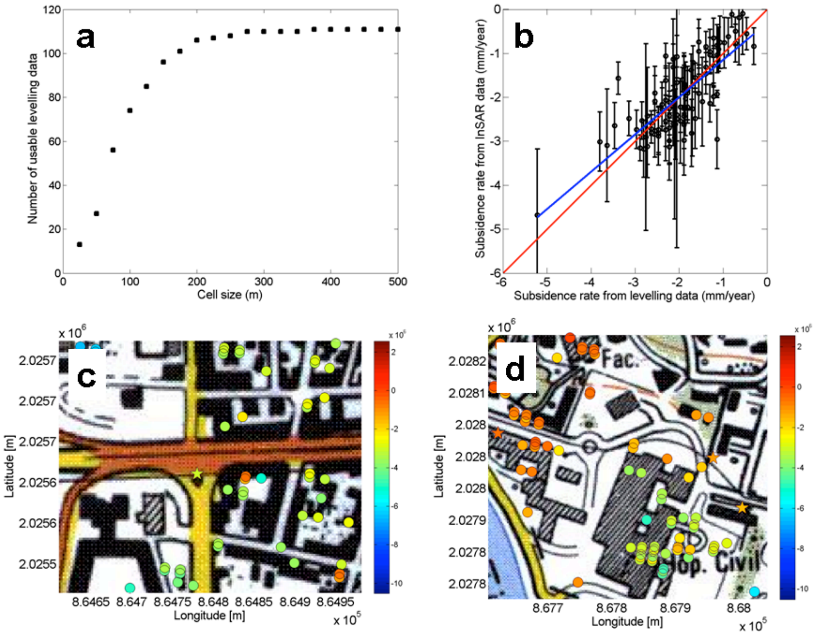

Fig. 3: (a) Number of usable leveling data for the comparison between subsidence rate derived from leveling and InSAR data as a function of grid cell size; (b) comparison between subsidence rate derived from InSAR and leveling data (the red curve stands for the 1:1 correlation while the blue curve indicates the regression line) ; (c) and (d) local zoom of InSAR (circles) and levelling (stars) subsidence estimates

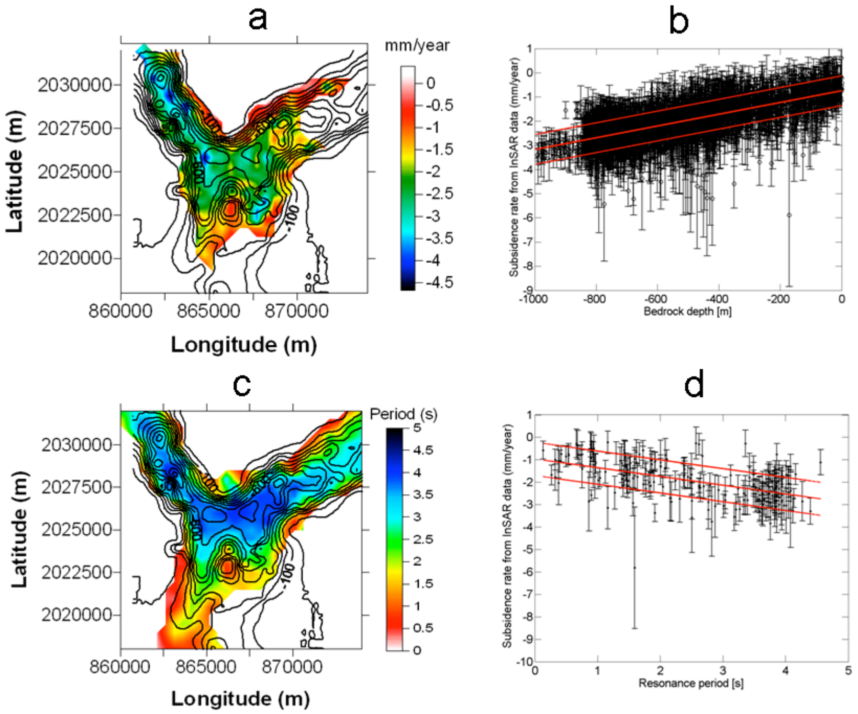

Fig. 4: (a) Map of subsidence rate derived from InSAR data overlaid by the iso-contour lines of bedrock depth (in meters); (b) comparison of bedrock depth and InSAR data averaged over 200 m grid cells size (the red line indicate the linear regression +/- standard deviation); (c) grid map of H/V resonance periods overlaid by the iso-contour lines of bedrock depth (in meters); (d) subsidence rates derived from InSAR data averaged over 300 m grid cells size centred at the H/V site location as a function of resonance periods (the red line indicate the linear regression +/- standard deviation)

COMPARISON BETWEEN SUBSIDENCE RATE, BEDROCK DEPTH AND RESONANCE PERIODS

As shown in Fig. 4a, InSAR-based subsidence rates averaged over 500 m grid cells size are very well correlated with bedrock depth: larger is the bedrock depth, larger is the subsidence rate. Comparison between both datasets averaged over 200 m grid cells size indicates a linear correlation between subsidence rate and bedrock depth (Fig. 4b). Note that in Fig. 4b the standard deviation on the bedrock depth is not displayed for sake of clarity and because the bedrock depth variation is small within such small grid cell. For the comparison between subsidence rates and resonance periods (Fig. 4c), we disregarded H/V data from small-size noise array measurements in order to get a spatial coverage of H/V sites (475 sites) as uniform as possible over the Grenoble basin. Then, we averaged subsidence rate within 300 m grid cells size centered at the H/V sites which allow to account for most of the H/V data (280 over 475 sites). As shown in Fig. 4d, subsidence rate (d) is – at first order - linearly correlated with the resonance period (T) through the following regression law :d (mm/an) = -0.39 T (s) –0.96 which was found to be rather robust over different grid cell sizes.

DISCUSSION

The infilling of the valley results from the successive action of two glacial-interglacial cycles. Every cycle starts with an erosive phase, followed by a sedimentation phase. The oldest cycle starts with the Riss glacial period and finishes with the interglacial Riss-Würm period. The second cycle includes the Würm and the Holocène periods. The associated deposits infill nowadays the main part of the valley. Within every cycle, the erosive phase is followed by the installation of a lake witch spreads up to 50 km down to Grenoble. The lake is then infilled with fine homogeneous sediments (sandy or clayey silts). These lake deposits are finally covered with heterogeneous alluviums coming from 2 rivers, which are the Drac river, coming from the South, and the Isère river, coming from the North East . Grenoble city is mainly located on the Drac deposits whereas the influence of the Isère river is limited to narrow area in the North and North East part of the studied area (Couturier, 1974). In order to better understand origin of the observed subsidence in the Grenoble basin and to check a possible correlation between subsidence rate and spatial heterogeneity of surface deposits, we investigated about 600 borehole log data spread over Grenoble City center and defined 3 types of lithologic profiles for the uppermost 20 m (Tsuno et al, 2010). The first type of profiles contains only coarse material composed of gravels and sands (Fig. 4a, red dots). The second type contains fine deposits composed of silt and peat lying on gravels up to approximately 10 m from the ground surface (Fig. 5a, blue dots). The last type is intermediate between the first and the second types (Fig. 5a, magenta dots). Such changes in the surfical lithology is caused by the dynamics of the energetic Drac river that involved rapid granulometry changes both horizontally and vertically. In the north-east of Grenoble City, superficial soft-soil deposits consist of a thick soft-soil layer caused by the twisty stream of the Isère River (Fig. 5a, green dots) (Couturier, 1974). Although the most superficial layers contain geological materials having different susceptibilities to compaction, we could not find any correlation between the measured subsidence and the spatial distribution of the compressible surface layers. On contrary we found that spatial depth variation of the surficial deposits interface is rather correlated to the spatial bedrock depth variation (Fig. 5b, Tsuno et al, 2010). Provided also the absence of large tectonic movement, it is thus very likely that the subsidence is mainly caused by compaction of the entire sedimentary column due to overloading of natural and anthropogenic origins (Prokopovich, 1986; Stramondo et al., 2008).

CONCLUSION

In this paper, we show the ability of InSAR Permanent Scaterrers approach to measure subsidence rate in the Grenoble basin. Subsidence rate, ranging from 0 to -4 mm/year, is at first order linearly correlated with resonance period and bedrock depth and is most likely caused by compaction of the entire sedimentary column. Such a correlation opens perspectives of application for deriving resonance periods maps from subsidence ones in other Alpine valleys which have similar sediment infilling properties (Lacave and Lemeille, 2006). However, other quantitative comparisons of available resonance period and subsidence rate maps at several different geological sites around the world should be done to confirm that the subsidence rate may serve as a physically-sounded proxy for resonance period.

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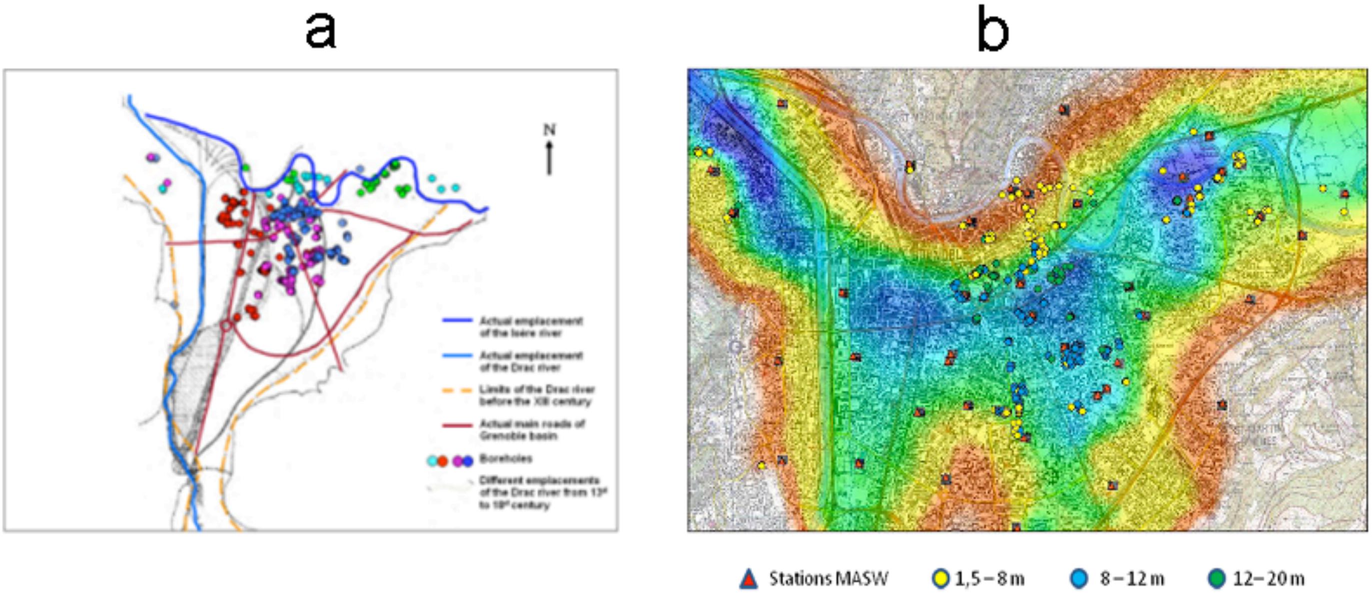

Fig. 5: (a) Historical map of the Drac River influence and locations of borehole log data. Dots indicate material type: red (gravels and sands), blue (fine deposits of silt and peat), magenta (gravels and fine deposits), green (fine deposits); (b) Depth interface of surface deposits (Yellow: 1.5 to 8m, Blue: 8 to 12 m, green: 12 to 20 m) and map the bedrock depth (from -100 m (blue) to -100 m (red))). From Tsuno et al. (2010).

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