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In Situ Stresses in the southern Bonaparte Basin, Australia: Implications for First- and Second-Order Controls on Stress Orientation

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Abstract. Four-arm dipmeter logs from six wells and a Formation MicroScanner (FMS) image log from one well in the southern Bonaparte Basin were interpreted for *in situ* stress indicators. Results of the analysis reveal a consistent NE-SW *in situ* maximum horizontal stress (σ_{Hmax}) orientation (055°N). This orientation is parallel to the average σ_{Hmax} determined in the northern Bonaparte Basin, the onshore Canning Basin, and in New Guinea. The data support the interpretation that the NE-SW σ_{Hmax} orientation in the area reflects a first-order stress pattern controlled by plate boundary forces along the northeastern margin of the Indo-Australian Plate (IAP) and contradict the suggestion that NE-SW σ_{Hmax} in the northern Bonaparte Basin is a second-order effect associated with boundary induced flexural stresses. Numerical modeling suggests that the divergence of σ_{Hmax} from an orientation parallel to plate motion can be explained by the heterogeneous nature of the northeastern boundary of the IAP.

Introduction

Most tectonic plates exhibit stress patterns that correspond with their absolute plate motion direction. For example, stress orientations in western Europe, midplate North America and South America are relatively uniform and are clearly aligned with absolute plate velocity and ridge torque directions [*Richardson*, 1992]. The IAP distinguishes itself by the discordance between regional σ_{Hmax} orientations and its direction of plate motion. Indeed the IAP is unique in exhibiting a regional stress rotation from roughly N-S in the Indian subcontinent to NW-SE around the Ninety East Ridge, E-W at the western end of the Australian North West Continental Shelf (Carnarvon Basin) and NW-SE at its its eastern end (Bonaparte Basin) [*Hillis et al.*, 1997]. Global intraplate stress maps are available at http://www-gpi.physik.uni-karlsruhe.de/wsm/maps.

Elastic finite element modeling by *Cloetingh and Wortel* [1986] and *Coblentz et al.* [1998] has shown that variable σ_{Hmax} orientations within the IAP and the observed NE-SW oriented SHmax in the Bonaparte Basin can be explained by the heterogeneous plate boundary forces acting along its northeastern boundary. This boundary comprises continental collision in the Himalayas, subduction of oceanic crust in the Sunda Arc, continental-island arc collision in the Banda Arc, continental collision in New Guinea, subduction of oceanic IAP at Solomon and New Hebrides Trenches, subduction of the Pacific Plate beneath the IAP at the Tonga-Karmadec Trench and continental collision in New Zealand (Figure 1).

In contrast, *Castillo et al.* [1998] argued that the well constrained NE-SW σ_{Hmax} orientation in the northern Bonaparte Basin was not a plate boundary force controlled first-order stress orientation, but rather reflected bending–induced stresses associated with the flexural bulge on the outer rise of the down going IAP of the type described by *Bradley and Kidd* [1991]. *Castillo et al.* [1998] suggest the regional first-order stress orientation is N-S and sub-parallel to the relative plate motion convergence direction. Supporting evidence is partly based on the N-S oriented stress indicators to the north of the outer rise in the Northern Bonaparte Basin (Laminaria-1, Jahal-1 and Barnacle-1; Figure 2), and two (Conway-1 and Beluga-1; Figure 2) south of the main body of NE-SW oriented stress indicators.

Prior to this study stress orientations in the southern Bonaparte Basin were unknown. The southern Bonaparte Basin is removed from any flexural stresses associated with plate collision and bending and was selected for analysis in order to help discriminate whether the first-order stresses in the area are NE-SW as suggested by *Coblentz et al.* [1998] or, as suggested by *Castillo et al.* [1998] the NE-SW trend in the northern Bonaparte Basin is due to flexural effects and superimposed on a first-order trend that is parallel to plate motion. This question is of some significance because it pertains to the issue of whether indeed the Australian continent is the only one in which first-order σ_{Hmax} orientation is discordant with direction of plate motion.

Methodology-Stress Analysis

A borehole breakout is a stress-induced enlargement of a circular borehole (Figure 3). Far-field stresses re-distribute around the borehole to re-equilibrate after the removal of rock. The circumferential stress at the borehole wall is maximised parallel to the minimum horizontal stress orientation (σ_{hmin}) and minimised parallel to σ_{Hmax} in a vertical wellbore. Where the maximum circumferential stress exceeds the rock strength, failure at the borehole wall causes fragments to 'spall' into the wellbore, enlarging the borehole in the σ_{hmin} orientation [*Gough and Bell*, 1981] (Figure 3). Breakouts exhibit a particular signature on four-arm caliper logs that can be discriminated from drilling-induced features such as washouts, mudcake and key-seating using strict selection criteria. The selection criteria used in this study are those presented by *Hillis et al.* [1997].

If fluid pressure within the borehole exceeds the minimum circumferential stress a vertical tensile fracture parallel to σ_{Hmax} will propagate away from the wellbore (provided the

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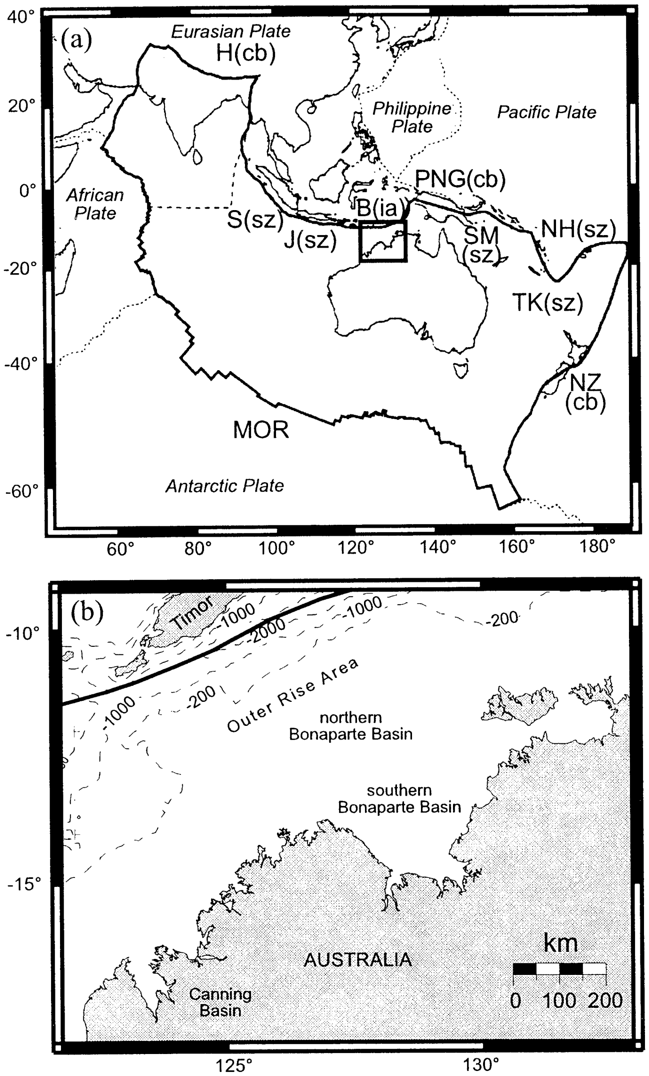

Figure 1. (a) Indo-Australian Plate with boundaries as defined by *Minster and Jordan* [1978]: cb = collisional boundary; sz = subduction zone; and ia = island arc. H = Himalayas; S = Sumatra Trench; J = Java Trench; B = Banda Arc; PNG = Papua New Guinea; SM = Solomon Trench; NH = New Hebrides Trench; TK = Tonga-Kermadec Trench; NZ = New Zealand; and MOR = Mid Ocean Ridge. From *Coblentz et al.* [1995]. Boxed area defines the Bonaparte Basin area illustrated in Figure 1b. (b) Geographical elements of the Bonaparte Basin and surrounding areas. Solid line indicates the plate margin.

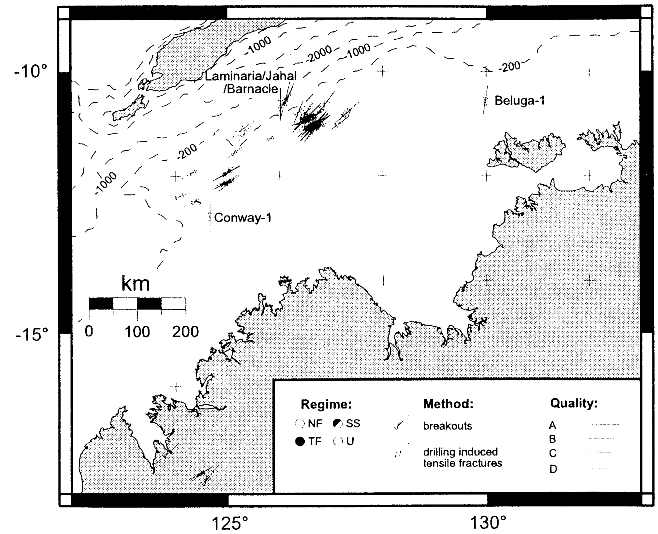

Figure 2. Regional stress map of the northern Bonaparte Basin/Outer Rise Area and Canning Basin after *Castillo et al.* [1998]. Long axes of crosses indicate mean σ_{Hmax} orientation in an individual well. The length of the long axes reflects the quality ranking as per *Zoback's* [1992] classification for the World Stress Map. NF, SS, TF and U are normal, strike-slip, thrust and undefined stress regimes respectively.

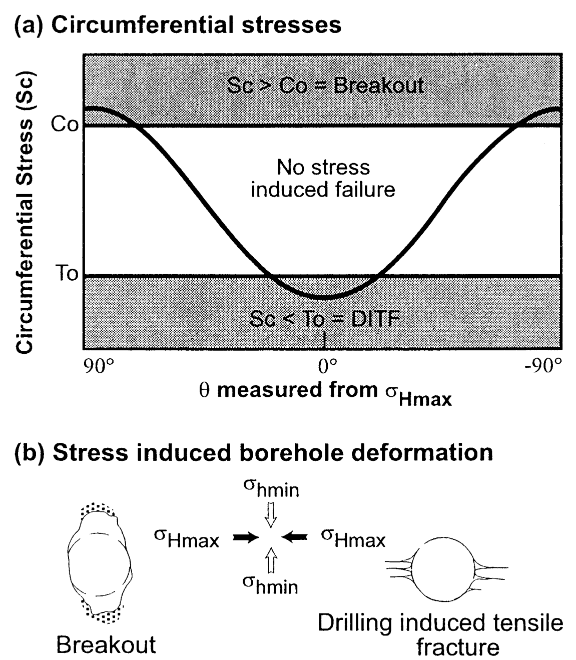

Figure 3. (a) Variation of circumferential stress (Sc) around a borehole as a function of θ measured from σ_{Hmax}. Where Sc is greater than the compressive shear strength (Co) of the borehole wall borehole breakout will tend to form parallel to σ_{hmin} and where Sc is less than the tensile strength (To) of the borehole a drilling induced tensile fracture will tend to form parallel to σ_{Hmax}. (b) Stress induced borehole elongations. A comparison of borehole breakout (compressive curvilinear shear failure) and drilling induced hydraulic fracture (extensional hydraulic fracturing).

stress regime is normal or strike-slip). These features, known as drilling-induced tensile fractures (DITFs) cannot be identified from caliper logs, however, they are identifiable on resistivity images as thin, planar, sinusoidal features. Like breakouts they are considered as reliable indicators of σ_{Hmax} orientation [*Hubbert and Willis*, 1957]. In comparison, breakouts are seen on images as relatively wide 'blobby' zones of low resistivity where the wellbore has been subjected to spalling. Breakouts and DITFs identified on image logs yield a more confident interp of the σ_{Hmax} orientation than the identification of breakouts solely from dipmeter logs.

Table 1. Summary of stress analyses in the southern Bonaparte Basin

Well	Type	Location		Depth Interval		N	Un-weighted			Length-weighted				Ecc-weighted		
		Lat	Long	Top	Bottom		Azi	SD	Q	SL	Azi	SD	Q	Azi	SD	Q
Caliper based interpretation																
Barnett-1	breakout	-14°32'	129°04'	691	2273	17	067	17	B	265.2	061	9	A	064	11	A
Barnett-2	breakout	-14°32'	129°03'	1841	2588	22	056	5	A	354.2	053	3	A	055	5	A
Cambridge-1	breakout	-14°17'	128°26'	735	1778	10	053	19	B	71.7	053	18	B	054	12	A
Jacaranda-1	breakout	-11°28'	128°10'	2817	3384	6	040	7	A	321.0	040	6	A	040	7	A
Kingfisher-1	breakout	-14°47'	129°07'	2198	3074	14	059	7	A	527.5	061	5	A	058	6	A
Sunbird-1	breakout	-14°34'	129°25'	700	1351	37	042	34	D	176.8	050	28	D	051	26	D
Image based interpretation																
Beluga-1	breakout	-10°34'	129°59'	2877	2876	1	030	0	E	38.0						
Beluga-1	DITF	-10°34'	129°59'	2530	3026	25	034	12	A	1.0	029	13	A			

Lat and Long are the latitude and longitude of the well locations, respectively, and depth interval is the range of depths. N is the total number, and SL is the total length of breakouts or DITF's in the well. Azi and SD are the mean σ_{Hmax} azimuth (000°-360°) of either breakouts or DITF's in the well, and their standard deviation in degrees as determined by directional statistical analysis. Q is the quality rating of the mean azimuth in the well following the World Stress Map scheme [*Zoback,* 1992]. Length is the depth interval over which the breakouts or DITF's occur, and ecc, is the difference between two caliper width readings when measuring a borehole breakout.

Hydrocarbon exploration was mainly concentrated in the southern Bonaparte Basin during the late sixties and seventies. Hence data from the area was acquired using the older High-Resolution Dipmeter Tool (HDT) and Stratigraphic High-Resolution Dipmeter Tool (SHDT), and therefore stress analyses are restricted to caliper-based observations only. In the eighties and nineties exploration has focused in the northern parts of the basin (Outer Rise area) for which significant image log data are available.

A caliper based stress interpretation of the Beluga-1 well has been included previously in a regional assessment of the stress field across the North West Shelf of Australia [*Hillis et al.*, 1997]. However, FMS image data have since become available for the well and due to Beluga-1's unique location, and the newly available image data, an updated analysis utilising breakouts and DITFs on the image log has been made for this study.

Results

Four-arm caliper logs (HDT/SHDT) acquired from six wells were analysed for borehole breakouts (Barnett-1, Barnett-2, Cambridge-1, Jacaranda-1, Kingfisher-1 and Sunbird-1). 106 distinct breakout zones were observed with a

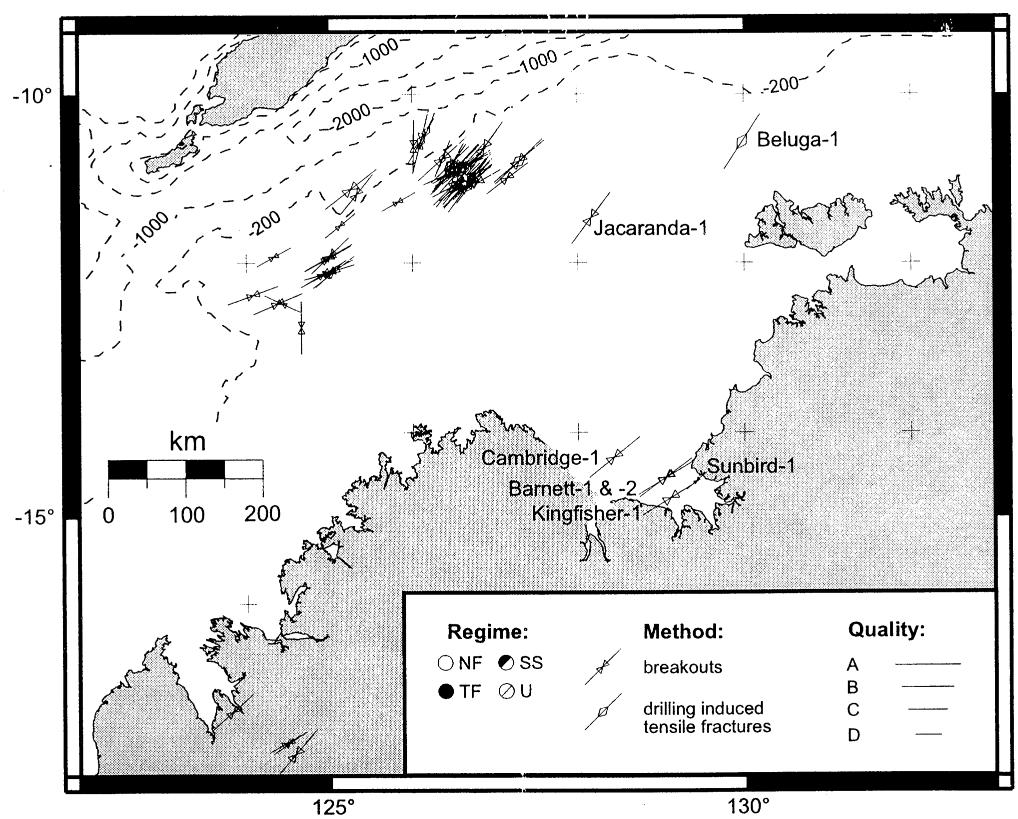

Figure 4. Regional stress map of the Bonaparte Basin and adjacent areas. Stress data includes σ_{Hmax} observations in the southern Bonaparte Basin, a reinterpretation of the Beluga-1 well and stress data presented in *Castillo et al.* [1998].

total length of 1715.4 m. Analysis of the Beluga-1 image log revealed 25 tensile fractures and a single borehole breakout covering a total of 39 m within the 494 m study interval. Mean σ_{Hmax} directions inferred from these analyses are presented in Table 1 and Figure 4.

Five wells in the southern Bonaparte Basin clearly indicate a NE-SW σ_{Hmax} orientation (055°N). Jacaranda-1 and the reinterpreted Beluga-1 show a sub-parallel σ_{Hmax} orientation of 030-040°N. These orientations correspond well with the stress indicators in the northern Bonaparte Basin/Outer Rise area and with first-order σ_{Hmax} observations made in the Canning Basin (Figure 2) and New Guinea [*Hillis et al.*, 1997].

Discussion

Stress orientations in the southern Bonaparte Basin were analysed in order to elucidate whether the NE-SW σ_{Hmax} orientation in the northern Bonaparte Basin/Outer Rise area reflects first order control by the plate boundary forces [*Coblentz et al.*, 1998], or is a second-order phenomenon due to the flexural stresses induced by bending of the downgoing IAP in the vicinity of its collision with the Banda Arc [*Castillo et al.*, 1998]. The wells analysed herein from the southern Bonaparte Basin are located some 500 km southeast of the outer arc rise and should not be affected by the bending-related stresses. Hence, if the NE-SW σ_{Hmax} orientation in the northern Bonaparte Basin/Outer Rise area is a second-order order phenomenon due to the flexural stresses, such an orientation would not be anticipated in the southern Bonaparte Basin. The more north-south oriented σ_{Hmax}, plate motion-parallel trend, upon which *Castillo et al.* [1998] suggest that the bending-related stresss are superimposed, would be expected to dominate.

The σ_{Hmax} orientation in the southern Bonaparte Basin is NE-SW, parallel to the direction in the northern Bonaparte Basin/Outer Rise area. Furthermore, the same NE-SW σ_{Hmax} orientation is exhibited in the onshore Canning Basin and in New Guinea. We suggest that this strongly implies that there is a major region from the Canning Basin to New Guinea, including the northern and southern Bonaparte Basins, in which first-order σ_{Hmax} is oriented NE-SW. We further suggest that the control on stress orientation in this region is related to the plate boundary forces. The elastic finite element modeling of *Coblentz et al.* [1998] has shown that a wide variety of plate boundary forces, all of which recognise the heterogeneity of the northeastern, convergent margin of the IAP, predict a NE-SW stress orientation in this area (their models 2, 3 and 4). This orientation is broadly due to stress focusing by the New Guinea continent-continent collisional segment of the plate boundary.

After re-interpretation of the Beluga-1 well, some approximately north-south oriented stress indicators are still observed in the northern Bonaparte Basin: viz. Conway-1, Laminaria-1, Jahal-1 and Barnacle-1. These contrast with the many wells in the area which exhibit NE-SW oriented σ_{Hmax}. It is suggested the north-south stress orientations in these wells reflect local effects superimposed on the regional NE-SW σ_{Hmax} orientation. Such effects may be related to proximity to nearby faults or folds which can cause stresses to be locally re-oriented [*Aleksandrowski et al.*, 1992; *Dart and Swolfs*, 1992; *Barton and Zoback*, 1994]. For a more detailed assessment of this hypothesis, further detailed structural data is required.

The results of this study are significant in that they confirm there is a major region of NE-SW oriented σ_{Hmax} on the northern Australian margin from the Canning Basin to New Guinea. This orientation is not parallel to the approximately north-south absolute motion direction of the IAP in the area. The velocity of the IAP motion is the third highest of all plates, and is significantly higher than that of several plates where the σ_{Hmax} orientation is parallel with the absolute plate motion direction such as western Europe, midplate North America and South America (0.72 deg/m.y. versus 0.04, 0.25 and 0.28 deg/m.y. respectively) [*Minster and Jordan*, 1978]. The magnitude of the IAP's velocity highlights the likelihood that the intraplate σ_{Hmax} stress pattern is dominated by the geometry of the plate and not basal drag forces. The first-order σ_{Hmax} stress orientation does indeed appear to be controlled by the boundary forces acting on the IAP.

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References

Aleksandrowski, P., O.H. Inderhaug, and B. Knapstad, Tectonic structures and wellbore breakout orientation, in *Rock Mechanics, Proceedings of the 33rd U.S. Symposium*, edited by J.R. Tillerson, and W.R. Wawersik, pp. 29-37, A.A. Balkema, Rotterdam, Netherlands, 1992.

Barton, C.A., and M.D. Zoback, Stress perturbations associated with active faults penetrated by boreholes: Possible evidence for near-complete stress drop and a new technique for stress magnitude measurement, *J. Geophys. Res.*, ***99*** (B5), 9373-9390, 1994.

Bradley, D.C., and W.S.F. Kidd, Flexural extension of the upper continental crust in collisional foredeeps, *Geol. Soc. Am. Bull.*, ***103***, 1416-1438, 1991.

Castillo, D.A., R.R. Hillis, K. Asquith, and M. Fischer, State of stress in the Timor Sea area, based on deep wellbore observations and frictional failure criteria: Application to fault-trap integrity, in *The Sedimentary Basins of Western Australia 2*, edited by P.G. Purcell, and R.R. Purcell, pp 325-341, Petroleum Exploration Society Australia, Perth, WA, 1998.

Cloetingh, S., and R. Wortel, Stress in the Indo-Australian plate, *Tectonophysics*, ***132***, 49-67, 1986.

Coblentz, D.D., S. Zhou, R.R. Hillis, R.M. Richardson, and M. Sandiford, Topography, boundary forces, and the Indo-Australian intraplate stress field, *J. Geophys. Res.*, ***103*** (B1), 919-931, 1998.

Dart, R.L., and H.S. Swolfs, Subparallel faults and horizontal-stress orientations: an evaluation of in-situ stresses inferred from elliptical wellbore enlargements, in *Structural and tectonic modelling and its application to petroleum geology*, edited by R.M. Larsen, H. Brekke, B.T. Larsen, and E. Talleraas, pp. 519-529, Elsevier, Amsterdam, 1992.

Gough, D.I., and J.S. Bell, Stress orientations from oil-well fractures in Alberta and Texas, *Can. J. Earth Sci.*, ***18***, 638-645, 1981.

Hillis, R.R., S.D. Mildren, C.J. Pigram, and D.R. Willoughby, Rotation of horizontal stresses in the Australian North West continental shelf due to the collision of the Indo-Australian and Eurasian plates, *Tectonics*, ***16*** (2), 323-335, 1997.

Hubbert, M.K., and D.G. Willis, Mechanics of hydraulic fracturing, *AIME Petroleum Transactions*, ***210***, 153-166, 1957.

Minster, J.B., and T.H. Jordan, Present-day plate motion, *J. Geophys. Res.*, **83**, 5331-5334, 1978.

Richardson, R.M., Ridge forces, absolute plate motions, and the intraplate stress field, *J. Geophys. Res.*, ***97*** (B8), 11739-11748, 1992.

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