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Abstract. Heat flow measurements in 4 deep drillholes near Voisey Bay, Labrador, have yielded the lowest value ever reported in the Canadian Shield, 22 mW m^{-2}. This very reliable estimate is also one of the lowest continental heat flow values world wide. It requires the crust to be very poor in radioelements in this part of the Archean Nain Province. It also strongly supports the view that mantle heat flow is low (< 15 mW m^{-2}) throughout the Canadian Shield, with no trend of increasing mantle heat flow near the edges of the continent. It also raises questions about the controlling mechanism for rifting and the opening of the Labrador Sea at 100 Ma.

1. Introduction

It has been known for some time that the heat flow is low in Precambrian shield areas. In continents, the surface heat flow includes the contribution of crustal heat production and the heat flow from the mantle. Standard estimates of the heat flow from the mantle in cratons are in the range of 20 − 28 mW m^{-2} [*Sclater et al.*, 1980]. However, recent heat flow studies [*Jaupart et al.*, 1998 and references therein] have suggested that the mantle heat flow is lower than most previous estimates, i.e. in the range of 12 − 15 mW m^{-2} throughout the entire Canadian Shield.

The continental margin of Labrador was the focus of renewed geophysical, geological and geochemical investigations as part of the Eastern Canadian Shield Onshore Offshore transect (ECSOOT) of Lithoprobe [*Hall et al.*, 1995; *Clowes*, 1997]. The Labrador coast, north of the Grenville Front tectonic zone, mainly exposes high-grade Archean gneisses of the Nain Province (Figure 1). It is divided into two major blocks, Saglek and Hopedale, consisting of 3.8-3.3 Ga granulites to the north and of mid- to late-Archean (3.1-2.8 Ga), high- to intermediate-grade rocks to the south (Fig. 1). Amalgamation of the two blocks occurred at ca. 2.5 Ga, across a postulated suture zone, and was followed by uplift to current exposure levels prior to 2.0 Ga [*Connelly & Ryan*, 1996] . The Paleoproterozoic Makkovik orogen, to the south, separates the Hopedale block from the Grenville Province. The Makkovik belt consists of reworked Nain gneisses and Paleoproterozoic continental margin rocks that are well correlated with the Ketilidian mobile belt of southern Greenland. Rifting and opening of the Labrador Sea occurred at 100 Ma.

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The southern part of the Nain Province and adjacent Paleoproterozoic terranes to the north of the Grenville Province were affected by protracted anorogenic bimodal magmatism during the Mesoproterozoic (1.45-1.25 Ga) resulting notably in widespread anorthosite-granite plutons of the Nain Plutonic Suite (Fig. 1). The latter is host to the Voisey's Bay base metal deposit [*Li & Naldrett*, 1999] where the heat flow measurements were carried out.

2. Heat flow and heat production measurements

Heat flow and heat production data are presented for 4 drillholes near Voisey Bay. These drillholes were logged at two sites: *Discovery Hill*, and *Eastern Deeps*, separated by ≈ 4 km (Fig. 1). Within each site, the drillholes are ≈ 200 m apart. The heat flow Q is determined from the

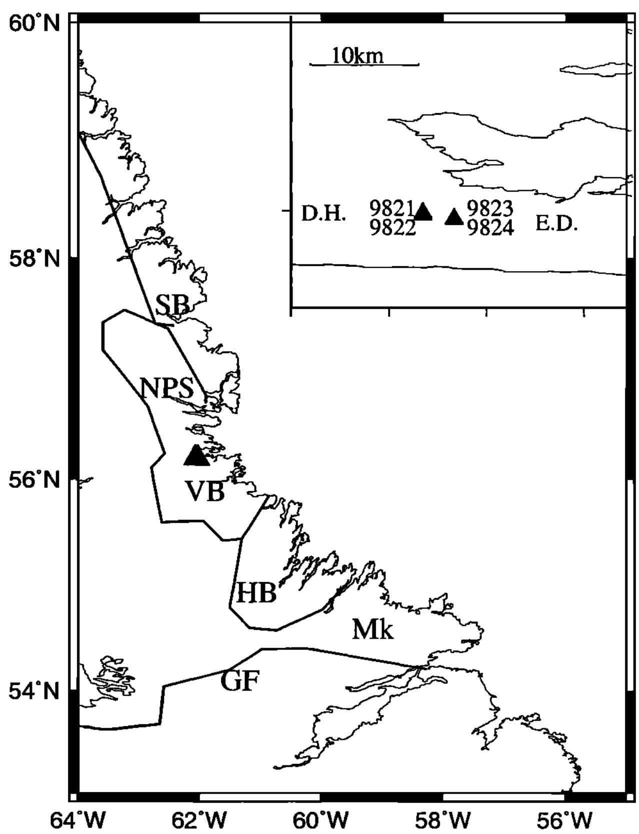

Figure 1. Location of Voisey Bay (VB) in Labrador. SB: Saglek Block, HB: Hopedale Block, NPS: Nain Plutonic Suite, Mk: Makkovik, GF: Grenville Front. Inset: Location of the drillholes Near Voisey Bay: *Discovery Hill* (D.H.) and *Eastern Deeps* (E.D.).

Table 1. For each borehole, the table gives the location, altitude, dip at the collar of the drillhole, depth interval used for heat flow determination, number of conductivity samples used (Number of samples measured), average thermal conductivity, average temperature gradient over the depth interval, mean heat flow, standard deviation, correction for post glacial warming, adjusted heat flow. The quality of the heat flow value is rated A as discussed in *Pinet et al.* [1991].

Site Hole number	Latitude	Longitude	Altitude m	Dip deg	Δh m	N_k (N_t)	$<k>$ W m^{-1} K^{-1}	G mK m^{-1}	Q mW m^{-2}	σ_Q mW m^{-2}	ΔQ mW m^{-2}	Q_c mW m^{-2}
Voisey Bay												22 (**A**)
Discovery Hill												
9821	56°19' 39"	62°06' 30"	59	55	190-685	6(7)	1.88 †	10.9	20.4	0.12	1.2	21.6
9822	56°19' 48"	62°06' 30"	123	60	236-623	6(6)	1.88 †	10.6	20.0	0.17	0.9	20.9
Eastern Deeps												
9823	56°19' 09"	62°03' 17"	152	90	330-890	8(8)	2.33/1.88 ‡	9.7	21.0	0.17	0.9	21.9
9824	56°19' 14"	62°03' 17"	158	89	649-937	7(8)	1.95 ‡	10.7	20.8	0.12	0.8	21.6

† We have used the mean conductivity of the 15 samples of orthogneiss which is the exclusive lithology in the section of the drillholes where we calculated the heat flow.

‡ We have calculated the equivalent conductivity based on the mean conductivity of all the collected samples of each lithology.

measurements of the temperature gradient in boreholes and of the conductivity of rock samples:

$$Q = k\frac{\partial T}{\partial z} \quad (1)$$

where k is the thermal conductivity, T is temperature and z is depth. The measurements procedures were described by *Mareschal et al.* [1989] and *Pinet et al.* [1991]. Stable temperature gradients were obtained over several hundreds of meters (Table 1 and Figure 2). The topography is well marked at Voisey Bay, more notably near *Discovery Hill*; however, because the boreholes are deep, there is no need for topographic correction. Indeed, at *Discovery Hill*, for the same reference level, the two logs give consistent temperature and temperature gradients at depth, in spite of the difference in elevation. At the *Eastern Deeps*, the two drillholes also give very consistent temperature gradients. A correction for the effect of Pleistocene glaciations was applied to the data based on the climatic model of *Jessop* [1971]. This was done for consistency with previously published values although there are questions about the amplitude of such correction [*Sass et al.*, 1971; *Mareschal et al.*, 1999]. At Voisey Bay, where the ground surface temperature is low, the climatic correction is small (≈ 1 mW m^{-2}).

Each conductivity determination relies on five individual measurements on samples of different thicknesses, which allows an assessment of conductivity variations due to small-scale mineralogical heterogeneities. At *Discovery Hill*, the section of the drillhole where we calculated the heat flow cross almost exclusively the orthogneiss of the Hopedale block. Therefore, we have used the mean conductivity of all the collected orthogneiss samples to determine the heat flow. At *Eastern Deeps*, the lithology is more complex with syenite and troctolite intruded in the ortho and paragneisses. For these two drillholes, we have calculated the equivalent conductivity for alternating layers. In this calculation, we have used the mean conductivity of all the collected core samples of each lithology. The small perturbation of the heat flow profile at 700 m in drillhole 9923 coincides with the intersection of a thin syenite slice which is more conductive than the surrounding gneisses.

In spite of small differences in lithology, heat flow estimates from individual boreholes are very consistent together and yield a site averaged value of 22 mW m^{-2}. We consider that this value is very robust and meets the criteria for A rating [*Pinet et al.*, 1991].

The concentrations of U, Th and K in core samples were measured following the technique described in *Mareschal et al.* [1989]. Consistency of mean heat production from neighboring boreholes provides an estimate of the sampling uncertainty.

The heat production for each of the two locations is given in Table 2a. The slightly higher heat production measured at *Eastern Deeps* is due to the presence of felsic intrusions near the surface. These are likely to be shallow because the heat flow is equally low at both sites. Table 2b lists the heat production per rock type for all the samples collected at Voisey Bay.

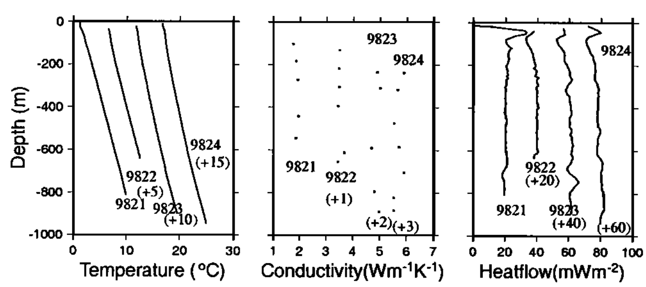

Figure 2. Temperature, thermal conductivity, and heat flow profiles for the 4 drillholes at Voisey Bay. Each thermal conductivity value is based on 5 individual measurements.

3. Discussion

The heat flow estimate of 22 mW m^{-2} is the lowest value reported so far in the Canadian Shield where very few values below 28 mW m^{-2} have been found [*Mareschal et al.*, 2000]. In North America, a very low value reported for the site of Spencer (Iowa) over an ultramafic intrusion [*Roy et al.*, 1968]

Table 2a. Heat production per location at Voisey Bay.

Location	N	U (ppm)	Th (ppm)	K(%)	A (μWm^{-3})
Discovery Hill	14	0.3	2.5	2.4	0.4
Eastern Deeps	15	0.8	4.8	1.3	0.7

Table 2b. Heat production for main rock types sampled at Voisey Bay.

Rock type	N	U (ppm)	Th (ppm)	K(%)	A (μWm^{-3})
Orthogneiss	20	0.4±0.5	2.1±4.5	1.7±1.2	0.4 ± 0.4
Paragneiss	2	0.6±0.5	13.7 ± 18.2	2.7 ± 0.6	1.3 ± 1.4
Syenite	3	0.4 ± 0.1	2.1±0.3	3.2±0.4	0.5 ± 0.1
Troctolite	3	2.4±3.9	11.9 ± 20	0.9±0.9	1.5± 2.5

was never explained. *Decker et al.* [1980] have reported a low value (24 mW m^{-2}) in the Wyoming craton over an anorthosite of the same age as the rocks in the Nain plutonic suite. Very low values (18-22 mW m^{-2}) have been reported in the Shield of west Africa by *Chapman & Pollack* [1974]. These values are based on shallower drillholes than those logged at Voisey Bay.

Kukkonen et al. [1998] have reported very low heat flow values in Finland (< 10 mW m^{-2} before climatic correction). They attribute these low values to the effect of last glaciation and estimate the heat flow after correction to range between 20 and 40 mW m^{-2}. Because the present surface temperature at Voisey Bay is lower (0 °C) than in Finland (4 °C), the effect will be smaller at Voisey Bay. Analysis of heat flow variations in a very deep (1800 m) drillhole in Sept-Iles, Québec, suggests that the standard heat flow correction might be slightly underestimated [*Mareschal et al.*, 1999]. For conditions at the base of the glacier similar to those of Sept-Iles, the correction at Voisey Bay would be < 3 mW m^{-2}.

The mean thermal conductivity at Voisey Bay is low (2 W m^{-1} K^{-1}). Refraction effects could not account for the low heat flow values. Refraction effects are marked near the edge of the insulating body [*Guillou-Frottier et al.*, 1996]. At Voisey Bay, the poorly conducting gneisses are the dominant lithology at the regional (>50 km) scale. Also, the values are identical at two sites 4 km apart.

Low heat flow sites provide robust constraints on the heat flow from the mantle, which obviously must be < 22 mW m^{-2}. Some information on the crustal structure can be inferred by extrapolating the seismic refraction profile obtained on the continental shelf ≈ 100 km offshore [*Reid*, 1996]. It shows a very homogeneous and thinner than normal crust (≈28 km), with no evidence for a high velocity lower crust. A seismic profile perpendicular to the coast shows that, as expected, the crust thickens westward [*Chian et al.*, 1995]. We can thus assume the crust to be >30 km at the site.

The average heat production within the sections sampled by the drillholes is in the range 0.4 – 0.7 μW m^{-3}. For the orthogneiss alone, by far the dominant lithology, heat production averages 0.4 μW m^{-3} (Table 2b). This value is comparable to that of other gneissic units within the Nain Province. For example, the geochemical data reported by *Schiotte et al.* [1993] for the Okak area, located in the Saglek block ≈ 200 km north of Voisey Bay, yield average heat production values of 0.5 μW m^{-3} (n=19) for typical granulite gneisses and 0.7 μW m^{-3} (n=10) for granitoid lithologies. These units in the granulite facies correspond to deep crustal rocks that are depleted in radio-elements (U and Th) by melting [*Schiotte et al.*, 1993]. Assuming the crust at Voisey Bay is entirely made of Okak-like granulite gneisses, then the crustal heat production is at least 12 mW m^{-2} yielding a mantle heat flow of ≈ 10 mW m^{-2}, at the low end of estimates obtained in other parts of the Canadian Shield [*Pinet et al.*, 1991; *Jaupart et al.*, 1998]. Alternatively, the crust may have been underplated and/or ponded by ultrabasic magmas during Mesoproterozoic formation of the Nain Plutonic Suite. Assuming that one half of the crust is made of gabbro and anorthosite, with a very low heat production of 0.1 μW m^{-3}, and the other half of granulite gneisses still yields a crustal heat production ≥ 8 mW m^{-2}, thus the mantle heat flow must be ≤ 14 mW m^{-2}.

There are no previous heat flow estimates in Labrador, but heat flow measurements were made in the Ketilidian Province of Southern Greenland [*Sass et al.*, 1972], which was separated from the Makkovik, its counterpart in Canada, after the opening of the Labrador sea. The heat flow values, 38 – 42 mW m^{-2}, in Greenland are higher than at Voisey Bay, but are associated with anomalously high surface heat production (≈ 6 μW m^{-3}) which could account for the difference if the surface rocks extend to 3 km.

In the Labrador Sea, there are two heat flow estimates of 48 and 59 mW m^{-2} [*Pye & Hyndman*, 1972]. Recent still unpublished measurements yield heat flow values in the range 75 – 80 mW m^{-2} for the Labrador sea [K. Louden, personal communication], much higher than heat flow values from old ocean basins [*Lister et al.*, 1990]. These values are also higher than those through continental crust on either side of the Labrador Sea (Figure 3). The sea-floor heat flow data provide values of the local mantle heat flow because oceanic crust is thin and poor in radioelements. Thus, there is a large increase of mantle heat flow from continent to ocean over a horizontal distance of ≈ 500 km. This increase is consistent with laboratory experiments of interaction of continents with the convecting mantle [*Guillou & Jaupart*, 1995].

On a large scale, in southeastern Canada, there is a trend of increasing heat flow toward the margin, which has been explained by eastward thinning of the continental lithosphere [*Hyndman et al.*, 1979]. This analysis was based on heat flow data from provinces with different ages and crustal

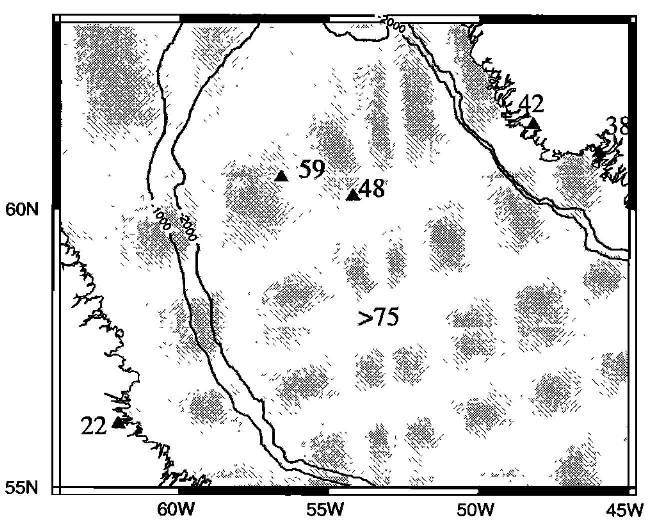

Figure 3. Heat flow values (in mW m^{-2}) for Labrador, Greenland, and the Labrador Sea. Several values > 75 mW m^{-2} were recently obtained in the Labrador Sea basin [K. Louden, personal communication]. The 1000 and 2000 m bathymetric contours have been superposed.

compositions. The high heat flow values were recorded on Appalachian crust with large heat production [*Pinet et al.*, 1991]. The low heat flow at Voisey Bay is found on Precambrian crust and rules out large variations of mantle heat flow beneath the continent. This suggests that, at least in this region, the transition zone between thick continental lithosphere and thinner oceanic lithosphere occurs beneath the margin.

Finally, the low heat flow at Voisey Bay, raises some questions about models of intracontinental rifting. The Labrador Sea opened through an old craton at 100 Ma [*Roest & Srivasatava*, 1989]. Seismic refraction studies have shown that the margin off Labrador is made up of a region > 100 km where continental crust has been stretched and a wide (>100 km) transition from continental to oceanic crust [*Chian et al.*, 1995]. The relatively wide region of stretching is not consistent with models of rifting that suggest that low heat flow at the time extension starts leads to a very narrow rift zone with little crustal extension [*Buck*, 1991] unless stretching occurred after the rifting stage.

4. Conclusions

The low heat flow at Voisey Bay near the coast of Labrador is consistent with estimates of the mantle heat flow in the 10-15 mW m^{-2} range.
It indicates that there is no increase in mantle heat flow near the edge of the continent where it is much lower than in the Labrador sea.

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References

Buck, W.R., Modes of continental lithosphere extension, *J. Geophys. Res.*, *96*, 20,161-20,178, 1991.

Chapman, D.S., & H.N. Pollack, Cold spot in west Africa: Anchoring the African plate, *Nature*, *250*, 477-478, 1974.

Clowes, R.M. (Editor), LITHOPROBE phase V proposal-Evolution of a continent revealed. LITHOPROBE secretariat, The University of British Columbia, Vancouver (B.C.), 1997.

Chian, D., K.E. Louden, & I. Reid, Crustal structure of the Labrador sea conjugate margins and implications for the formation of non volcanic continental margins, *J. Geophys. Res.*, *100*, 24,239-24,254, 1995.

Connelly, L.N., & B. Ryan, Late Archean evolution of the Nain Province, Nain, Labrador, Canada: Imprint of a collision. *Can. J. Earth Sci.*, *33*, 1325-1342, 1996.

Decker, E.R., K.R. Baker, G.J. Bucher, & H.P. Heasler, Preliminary heat flow and radioactivity studies in Wyoming, *J. Geophys. Res.*, *85*, 311-321, 1980.

Guillou, L., & C. Jaupart, On the effect of continents on mantle convection, *J. Geophys. Res.*, *100*, 24,217-24,238, 1995.

Guillou-Frottier, L., C. Jaupart, J.C. Mareschal, C. Gariépy, G. Bienfait, L.Z. Cheng, & R. Lapointe, High heat flow in the Thompson Belt of the Trans-Hudson Orogen, Canadian Shield. *Geophys. Res. Lett.*, *23*, 3027-3030, 1996.

Hall, J., R.J. Wardle, C.F. Gower, A. Kerr, K. Coffin, C.E. Keen, & P. Caroll, Proterozoic orogens of the northeastern Canadian Shield: new information from the Lithoprobe ECSOOT crustal reflection seismic survey, *Can. J. Earth Sci.*, *32*, 1119-1131, 1995.

Hyndman, R.D., A.M. Jessop, A.S. Judge, & D.S. Rankin, Heat flow in the maritime provinces of Canada, *Can. J. Earth Sci.*, *16*, 1154-1165, 1979.

Jaupart, C., J.C. Mareschal, L. Guillou-Frottier, & A. Davaille, Heat flow and thickness of the lithosphere in the Canadian Shield. *J. Geophys. Res.*, *103*, 15,269-15,286, 1998.

Jessop, A.M., The distribution of glacial perturbation of heat flow in Canada, *Can. J. Earth Sci.*, *8*, 162-166, 1971.

Kukkonen, I.T., W.D. Gosnold, & J. Safanda, Anomalously low heat flow density in eastern Karelia, Baltic Shield: a possible paleoclimatic signature, *Tectonophys.*, *291*, 235-249, 1998.

Li C., & A.J. Naldrett, Geology and petrology of the Voisey's Bay intrusion: reaction of olivine with sulfide and silicate solids, *Lithos*, *37*, 1-31, 1999.

Lister, C.R.B., J.G. Sclater, E.E. Davis, H. Villinger, & S. Nagihara, Heat flow maintained in ocean basins of great age: investigations in the north-equatorial west Pacific, *Geophys. J. Int.*, *102*, 603-630, 1990.

Mareschal, J-C., C. Pinet, C. Gariépy, C. Jaupart, G. Bienfait, G. Dalla-Coletta, J. Jolivet & R. Lapointe, New heat flow density and radiogenic heat production data in the Canadian Shield and the Québec Appalachians, *Can. J. Earth Sci.*, *26*, 845-852, 1989.

Mareschal, J.C., F. Rolandone, & G. Bienfait, Heat flow variations in a deep borehole near Sept-Iles, Québec, Canada: Paleoclimatic interpretation and implications for regional heat flow estimates, *Geophys. Res. Lett.*, *26*, 2049-2052, 1999.

Mareschal, J.C., C. Jaupart, C. Gariépy, L.Z. Cheng, L. Guillou-Frottier, G. Bienfait, & R. Lapointe, Heat flow and deep thermal structure near the edge of the Canadian Shield, *Can. J Earth Sci.* in press, 2000.

Nyblade, A.A., & H.N. Pollack, A global analysis of heat flow from Precambrian terrains: Implications for the thermal structure of Archean and Proterozoic lithosphere. *J. Geophys. Res.*, *98*, 12,207-12,218, 1993.

Pinet, C., C. Jaupart, J-C. Mareschal, C. Gariépy, G. Bienfait, & R. Lapointe, Heat flow and structure of the lithosphere in the eastern Canadian Shield, *J. Geophys. Res.*, *96*, 19941-19963, 1991.

Pye, G.D., & R.D. Hyndman, Heat-flow measurements in Baffin Bay and the Labrador Sea, *J. Geophys. Res.*, *77*, 938-944, 1972.

Reid, I. Crustal structure across the Nain-Makkovik boundary on the continental shelf off Labrador from seismic refraction data, *Can. J. Earth Sci.*, *33*, 460-471, 1996.

Roest, W.R., & Srivastava, S.P., Sea-floor speading in the Labrador sea: A new reconstruction, *Geology*, *17*, 1000-1003, 1989.

Roy, R.F., E.R. Decker, D.D. Blackwell, & F. Birch, Heat flow in the United States, *J. Geophys. Res.*, *73*, 5207-5221, 1968.

Sass, J.H., B.L. Nielsen, H.A. Wollenberg, & R.J. Munroe, Heat flow and Surface radioactivity at two sites in Greenland, *J Geophys. Res.*, *77*, 6435-6444, 1972.

Schiotte, L., B.T. Hansen, S.B. Shirey, & D. Bridgwater, Petrological and whole rock isotopic characteristics of tectonically juxtaposed Archaean gneisses in the Okak area of the Nain Province, Labrador; relevance for terrane models, *Precamb Res.*, *63*, 293-323, 1993.

Sclater, J.G., C. Jaupart, & D. Galson, The heat flow through oceanic and continental crust and the heat loss from the Earth, *Rev. Geophys.*, *18*, 269-311, 1980.

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