Re-Os Model Ages for Eclogite Xenoliths from the Colorado Plateau, USA

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ABSTRACT

The ~30 Ma ultramafic diatremes of the Colorado Plateau are unique because their emplacement through the cratonic Colorado Plateau follows the subduction of the Farallon plate beneath North America. Eclogite xenoliths in the diatremes are texturally and chemically similar to eclogites exposed in high pressure metamorphic terrains associated with subduction metamorphism. Phanerozoic Re-Os model ages were obtained for some of the eclogite xenoliths, suggesting that they represent fragments of the subducted Farallon Plate. The isotopic data thus may provide direct evidence that young subducted oceanic lithosphere was sampled by mantle-derived magmas in the Colorado Plateau.

Keywords: Eclogite xenoliths, Re-Os, Isotopes, Colorado Plateau

1. INTRODUCTION

Helmstaedt and Doig (1975) proposed that eclogite facies xenoliths in diatremes from the Colorado Plateau could represent subducted remnants of Phanerozoic oceanic lithosphere, in particular the Farallon Plate. The subduction hypothesis for generating mantle eclogite has since gained considerable favour, especially for high P-T eclogites in kimberlites (Helmstaedt and Schulze, 1988; Snyder *et al.*, 1993; Jerde *et al.*, 1993; Jacob *et al.*, 1994; Pearson *et al.*, 1995; Rudnick, 1995; Viljoen *et al.*, 1996; McCandless and Gurney, 1997). The initial premise of Helmstaedt and Doig (1975), which was based largely on observational evidence, however, requires the precise ages of the protoliths. The Re-Os isotopic system, though not immune to disturbance by metasomatism, has proven to be a valuable means of dating mantle-derived rocks, and has been applied to eclogite xenoliths from a variety of locations (Pearson *et al.*, 1995; Menzies *et al.*, 1998). To constrain the genesis of the Colorado Plateau eclogites, we applied this isotopic system to a selection of eclogite xenoliths that are the most likely examples of subducted Phanerozoic oceanic lithosphere based on modelling by McCandless and Gurney (1997), which suggest that carbon and sulphide-bearing eclogites are the most likely to be Phanerozoic in age. These samples may be modified by mid-ocean ridge processes that introduced the carbon and sulphur, but can still yield usable Re-Os model ages provided that the bulk Re/Os igneous composition is not rendered unusable by the mid ocean ridge processes.

2. GEOLOGIC SETTING

The igneous host for the eclogites of this study is the Moses Rock diatreme, part of the cluster of ultramafic diatremes that comprise the Navajo Volcanic Field, located in the central Colorado Plateau (Fig. 1). The Colorado Plateau is a thick portion of the continental lithosphere that has remained relatively stable since the Proterozoic. The 25 - 30 Ma ultramafic diatremes are contemporaneous with minette volcanism to the east in the Colorado Plateau, and with subduction-related magmatism to the northwest and southeast of the Colorado Plateau (Fig. 1; Helmstaedt and Schulze, 1991). Eclogite xenoliths in the Garnet Ridge, Mule Ear, and Moses Rock diatremes comprise about 1 % of the crystalline xenolith population, the remainder being mainly igneous and metamorphic xenoliths from the Precambrian basement (Helmstaedt and Schulze, 1991). The two most common eclogites consist of metabasic eclogites - zoned almandine-rich garnet, omphacite, and rutile +/- pyrite, phengite or lawsonite; and the jadeite-clinopyroxenites – jadeite-rich pyroxene +/- garnet, rutile or pyrite (jadeite clinopyroxenites; Helmstaedt and Schulze, 1988). Metabasic eclogites have spillitic bulk composition, and many examples exhibit relict igneous textures, whereas the jadeite-clinopyroxenites do not have an igneous bulk composition, and resemble jadeite pods in high pressure subduction terranes (Helmstaedt and Schulze, 1988; 1991). Less common are eclogites that consist of garnet, omphacite, rutile and lawsonite, with lawsonite comprising up to 50 % of the rock. The lawsonite-rich eclogites resemble metarodingites, and are inferred to represent the eclogite-facies equivalent of rodingitized basalts or gabbros (Helmstaedt and Schulze, 1988). The

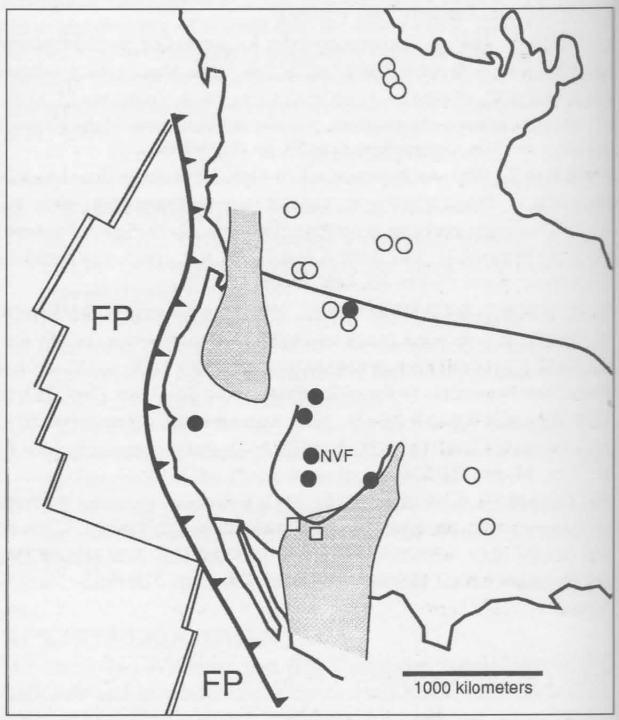


Figure 1. Location map of Navajo Volcanic Field (NVF), located in the center of the Colorado Plateau (U-shaped line). Approximate position of the Farallon Plate (FP; Kula Plate not shown) and convergent margin is indicated at the time of eruption of the diatremes (~30 Ma). Subduction-related magmatism during this period is indicated by the stippled areas. Latites containing eclogite xenoliths are indicated by squares. Other mantle-derived magmatism, roughly contemporaneous with the Navajo Volcanic Field, is indicated by solid circles (~40 to 3 Ma). Mantle-derived magmatism associated with the Laramide Orogeny (~90 - 50 Ma) is indicated by the open circles. Modified after Helmstaedt and Schulze (1991) and McCandless (1998).

least common eclogites are garnet-clinopyroxenites that exhibit partial or complete conversion from pyrope + diopside to pyrope-almandine + omphacite + chlorite, interpreted as fragments of mantle wedge, hydrated by volatiles driven off of the subducting slab (Helmstaedt and Schulze, 1988).

Camp Creek and Chino Valley latites, located just south of the Colorado Plateau (Fig. 1) also contain eclogites, and a selection of these has been studied for their Re-Os composition (Esperança *et al.,* 1997). These localities seem to lack the low-temperature alteration assemblages and relict igneous textures preserved in eclogite xenoliths from the Colorado Plateau (Arculus and Smith, 1979; Schulze and Helmstaedt, 1979; Esperança and Holloway, 1984; Helmstaedt and Schulze, 1991).

3. RESULTS

We specifically focused our studies on carbon and sulphur-rich eclogites because they may be the most representative samples of Proterozoic or younger oceanic lithosphere (i.e. McCandless and Gurney, 1997). The selected eclogites from the Colorado Plateau contained ~1 % by volume of sulphides. The sulphides may have been introduced by hydrothermal processes at mid-ocean ridges, but the Re/Os systematics of the samples may still yield useful model ages if the chemical changes occurring during alteration are taken into account. Sulphide-rich portions of each eclogite that were free of alteration were selected, fragments were powdered in an alumina mill, 2 grams were loaded into Carius tubes, and a modified dissolution/distillation technique (after Freydier *et al.,* 1997) was employed to ensure recovery of Re and Os from sulphides. The data were obtained by NTIMS with total blanks with this technique at ~4 pg. Pertinent data are summarised in Table 1.

Two types of eclogites were analysed for Re-Os isotopes. An early Mesozoic Re-Os model age for metabasic eclogite MR21 (205.1 Ma) suggests that it may be a fragment of subducted and eclogitised Farallon Plate, as the oldest sea floor in the Pacific Plate (a preserved mirror image of the Farallon Plate) is about 200 Ma (Fig. 2a). The slightly older Phanerozoic Re-Os model ages of 402.4 and 334.1 Ma for metabasic samples MR22 and MR23 (Fig. 2a) could represent earlier subduction beneath North America, or the product of eclogitised Farallon Plate MORB that inherited radiogenic Os shortly after eruption on the seafloor. One metabasic eclogite, MR51, has a Proterozoic model age of 1344 Ma, similar to a Re-Os model age obtained for a websterite by Esperança *et al.* (1997). These data support an earlier subduction event that could explain magmatism in southwestern North America at ~1.4 Ga (Esperança *et al.,* 1997).

In comparison, a jadeite-clinopyroxenite (MR24) that has a T_{ma} of 2278 Ma, which is older than known basement rocks in the region, and which lacks igneous textural and chemical characteristics, could represent early subducted material that has been isolated from subsequent igneous modification. A similar Re-Os model age of 2310 Ma was obtained for an eclogite by Esperança *et al.,* (1997). When all the Re-Os isotope data are considered, they could represent a record of subduction of oceanic lithosphere beneath North America that extends back to nearly 2 Ga.

Table 1. Re-Os data for eclogites from the Colorado Plateau.

sample	Re, ppb	Os, ppb	$^{187}Re/^{188}Os$	$^{187}Os/^{188}Os$	T_{ma}
metabasic eclogite					
MR21	1.447	0.105	68.4	0.362	205.3
MR22	0.769	0.048	82.7	0.682	402.4
MR23	1.055	0.331	15.5	0.213	334.1
MR51	0.139	0.064	10.8	0.365	1344
jadeite-clinopyroxenite					
MR24	0.181	0.318	2.79	0.220	2278

T_{ma} determined using $\lambda = 1.666\text{x}10^{-11}$ (Smoliar *et al.,* 1996), $^{187}Os/^{188}Os$ = 0.1287, and $^{187}Re/^{188}Os$ = 0.4243 (Meisel *et al.,* 1996).

4. DISCUSSION

4.1 Previous studies

Isotopic studies of Rb-Sr and Sm-Nd were performed by Wendlandt *et al.,* (1993) in an effort to constrain the age of the protoliths of the Colorado Plateau eclogites. The samples of that study were divided into two groups based on major and trace element characteristics. Group I eclogites have low SiO_2, and low Na_2O contents, with REE patterns broadly similar to N-MORB. Group II eclogites have variable but higher SiO_2 and Na_2O, with V-shaped REE patterns that are unlike those of any common igneous rocks (Roden *et al.,* 1990). Group I eclogites are probably equivalent to metabasic eclogites, and Group II eclogites are equivalent to jadeite-clinopyroxenites of Helmstaedt and Schulze (1988). Three additional eclogites analysed by Wendlandt *et al.,* (1993) may be metabasic or lawsonite-eclogites, based on the observed complex mineral zoning (Helmstaedt and Schulze, 1988). Wendlandt *et al.,* (1993) demonstrated that a number of the eclogites experienced metasomatism that introduced LREE, SiO_2 and Na_2O. This metasomatism disturbed the Nd and Sr isotopic compositions placing the eclogite xenoliths well off from a 1900 Ma Sm-Nd isochron defined by lower crustal xenoliths from the same diatremes (Wendlandt

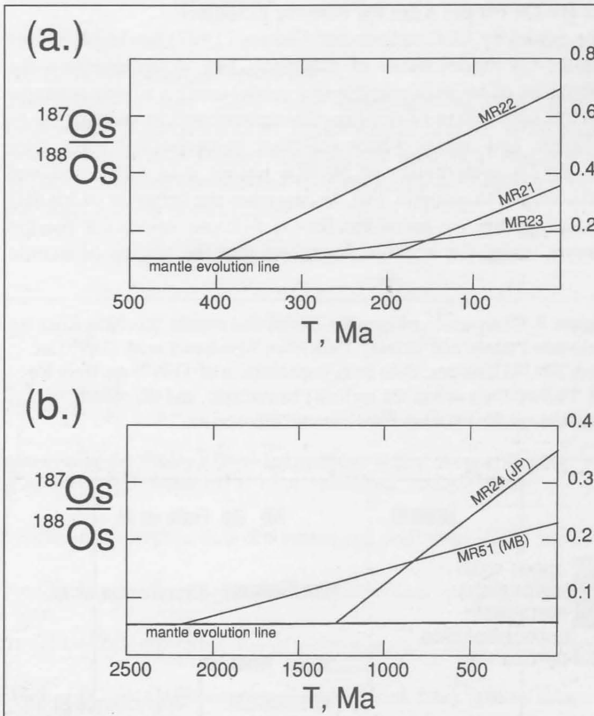


Figure 2. Re-Os model age plot for Colorado Plateau eclogites (**a**) metabasic eclogites with Phanerozoic ages (**b**) metabasic eclogite (MB) and jadeite-pyroxenite (JP) with Proterozoic ages. Note the difference in slopes for the metabasic eclogites, with older samples having lower measured $^{187}Os/^{188}Os$.

et al., 1993). Rb-Sr isochrons yield 500 - 900 Ma ages, whereas Sm-Nd ages for the eclogite whole rock and mineral separates define 21 Ma isochrons, and probably record the age of the transporting magmas (Wendlandt *et al.,* 1996). This is also supported by previous Sm-Nd and Rb-Sr studies (Roden *et al.,* 1990) that obtained Proterozoic ages for peridotite xenoliths from the Colorado Plateau diatremes, but the eclogites exhibited internal isotopic disequilibria, and Sm-Nd interpretations are equivocal.

Esperanca *et al.,* (1997) applied Re-Os isotope systematics to eclogite and websterite xenoliths from the Chino Valley and Camp Creek latites, located south of the Colorado Plateau (Fig. 1). The xenoliths analysed by Esperança *et al.,* (1997) yielded Proterozoic ages (~759, 785, 825, 901, 1337, 2310 Ma; Fig. 3). It was pointed out previously that a more restricted selection of eclogites occur in the latites. Helmstaedt and Schulze (1989) noted that eclogites in the latites exhibit severe alteration and partial melting, and the low-temperature eclogite assemblages (the best candidates for subducted oceanic lithosphere; Coleman *et al.,* 1965) would not survive in the hotter latite magmas.

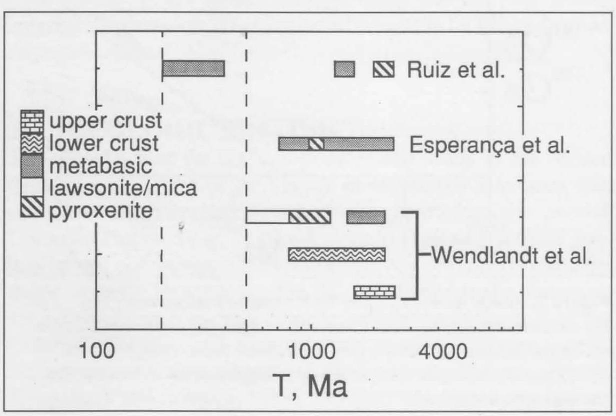
We selected low-temperature eclogite assemblages with high sulphide contents as the best candidates for subducted Phanerozoic oceanic lithosphere. This is based on the modeling of McCandless and Gurney (1997), who suggest that sulphides and biogenic carbon are more abundant on post-Archean seafloor ridges because increased ocean depth allowed seafloor hydrothermal vents to develop. Higher Re (0.14-1.45 Re vs 0.06 - 0.80; from Esperança *et al.,* 1997) and Os abundances (0.05 - 0.33 vs 0.01 - 0.19) for eclogites in the present study reflect the significance of sulphides in the samples.

4.2 Re-Os Model Ages for Mantle Eclogites

The model by McCandless and Gurney (1997) has implications for Re-Os model dates of eclogites. Fig. 4 summarizes the behaviour of MORB/eclogite in a model using a simple scenario for the subduction of oceanic lithosphere and its conversion to eclogite, and one in which sea-floor hydrothermal vents alter the Re-Os systematics of MORB before it is subducted and transformed to eclogite. Fig. 4a describes the behavior of MORB assuming that we know the Re-Os isotopic values for the the mantle under the oceanic floor, and that the degree of mantle melting required to produce MORB has varied little since the Proterozoic. If these conditions are met, the measured $^{187}Os/^{188}Os$ ratios for eclogites derived from Phanerozoic versus Proterozoic oceanic lithosphere may follow different evolutionary paths. Mesozoic eclogites should have high Re/Os ratios and high $^{187}Os/^{188}Os$ ratios (Fig. 4a). Subducted Proterozoic oceanic lithosphere should have a similar Re/Os ratio, but higher $^{187}Os/^{188}Os$ due to the time-integrated effects of ^{187}Re decay (Fig. 4a).

Figure 4b shows what would happen to MORB if sulphides that precipitated from hydrothermal vents are incorporated into MORB before conversion to eclogite. Present-day seafloor hydrothermal vents (SHV) precipitate sulphides when hydrothermal vent fluids contact cold seawater. Primary sulphide accumulations at SHV can be significant structures rising several hundred meters above the seafloor. The sulphide structures eventually collapse to form metalliferous sediments, subsequently undergoing hydrothermal alteration and mixing with fallout from the hydrothermal plume (Ravizza *et al.,* 1996). In contrast to seawater, with infinitesimally small concentrations of Re and Os, the products of SHV can contain significant amounts of Re and Os, with extremely radiogenic $^{187}Os/^{188}Os$ ratios for the latter

Figure 3. Comparison of ages for crustal and mantle xenoliths from the Colorado Plateau and vicinity. Data from Wendlandt *et al.* (1993) are from Sm-Nd isotopes. Data from Esperança *et al.* (1997) are from Re-Os. Dashed lines define the earliest Phanerozoic, and the oldest possible age for Farallon Plate oceanic lithosphere.



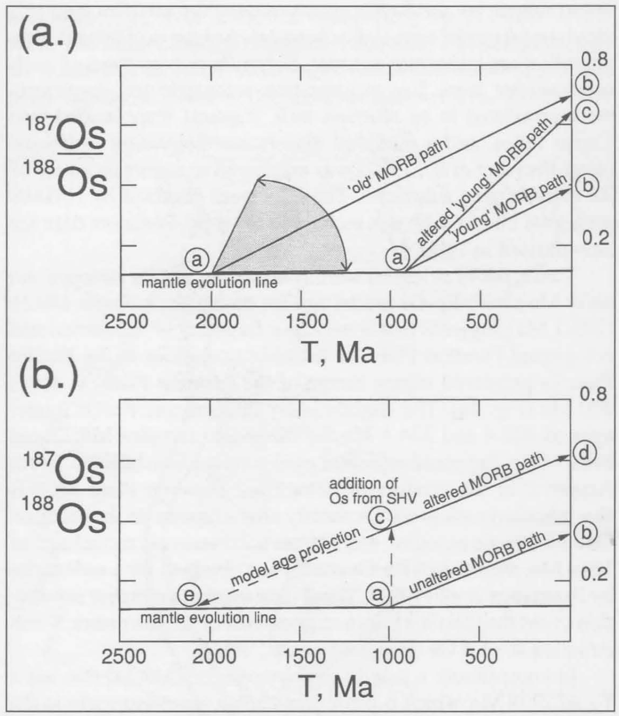


Figure 4. Re-Os systematics for MORB. The results are extended to mantle eclogite xenoliths, assuming a single stage process for conversion of MORB to mantle eclogite during subduction. **(a)** Under ideal conditions, for two different MORB samples extracted from the mantle, $^{187}Re/^{188}Os$ ratios should be similar, but the older sample should have a higher measured $^{187}Os/^{188}Os$ ratio (points a to b). The extreme variation in $^{187}Re/^{188}Os$ actually observed for mantle eclogites is indicated by the stippled region (this study, Menzies *et al.,* 1998; Pearson *et al.,* 1995). Path a - c for a sample formed at 1000 Ma indicates the effect of addition of Re only to MORB by processes in seafloor hydrothermal vents. Re addition only will create a higher $^{187}Re/^{188}Os$ ratio, which results in a higher measured $^{187}Os/^{188}Os$, but will still project back to the correct model age for the sample. **(b)** Addition of Os only to MORB will raise MORB from its normal Re-Os evolution path (a - b) to an elevated path (c - d). The measured $^{187}Os/^{188}Os$ ratio is higher (point d), which leads to an erroneously older model age projection for the sample (point e).

(Fig. 5; Ravizza *et al.,* 1996). The addition of Re to MORB shortly after eruption will raise the $^{187}Re/^{188}Os$ ratio, which results in a higher measured $^{187}Os/^{188}Os$, but the calculated model age will still project back to the correct value for the sample (Fig. 4a). In contrast, addition of radiogenic Os to MORB shortly after eruption may flatten the slope to some degree, but more importantly, it raises MORB from its normal $^{187}Os/^{188}Os$ initial value (Fig. 4b, path a to b), to an elevated position (path c to d). The measured $^{187}Os/^{188}Os$ is higher, which leads to an erroneously older model age projection for the sample (point e).

It is evident that addition of Re to MORB at seafloor hydrothermal vent settings does occur, and can account for the wide range in $^{187}Re/^{188}Os$ ratios observed for mantle eclogites that represent subducted oceanic lithosphere (this study, Pearson *et al.,* 1995; Menzies *et al.,* 1998). More importantly, the addition of radiogenic Os to MORB at SHV settings will lead to older Re-Os model age projections, and can explain the anomalously old ages (> 4.5 Ga) consistently obtained for some mantle eclogites (Pearson *et al.,* 1995; Menzies *et al.,* 1998). The addition of Os by incorporation of SHV sulphides into MORB can also account for the higher Os contents and lower $^{187}Re/^{188}Os$ ratios observed in mantle eclogites from South Africa (Menzies *et al.,* 1998). Note, however, that there is no combination of Re and Os addition by these processes that will produce anomalously younger Re-Os model ages for mantle eclogite.

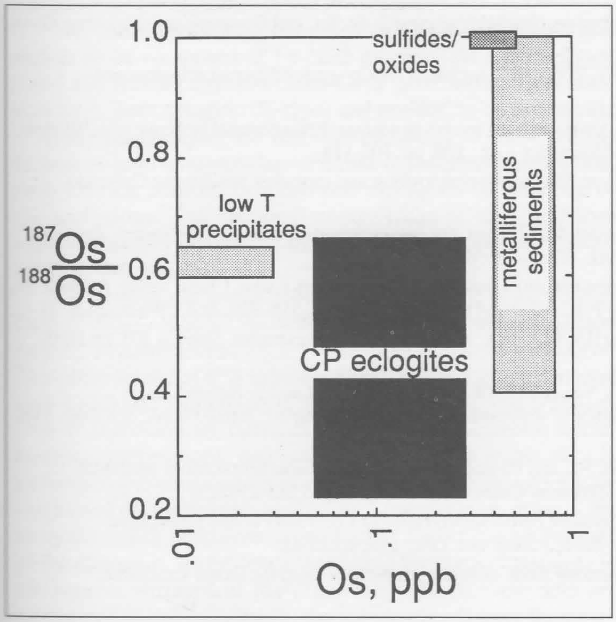


Figure 5. A comparison of $^{187}Os/^{188}Os$ and Os contents for Colorado Plateau eclogites (black box), with seafloor hydrothermal vent precipitates and sediments from the TAG area (stippled regions, data from Ravizza *et al.,* 1996).

One alternative consideration is that the addition of Re to the eclogite from the transporting igneous host rock could produce younger Re-Os model ages. Although kimberlites can have fairly high Re concentrations (0.1 - 2.0 ppb; Walker *et al.,* 1989), the ultramafic rocks that transported these xenoliths to the surface are more akin to lamproites (0.03 - 0.06 ppb; Lambert *et al.,* 1995) than to kimberlites. The eclogite xenoliths with Re concentrations of 0.14 - 1.45 ppb are unlikely to be affected by the transporting igneous host, and have no textural evidence of such a process having taken place.

It has been previously suggested that some multistage evolution process is necessary to explain the anomalous Re-Os isotopic behaviour of mantle eclogites (Pearson *et al.,* 1995; Menzies *et al.,* 1998). While the possibility of multistage evolution cannot be excluded for higher P-T and diamond-bearing eclogites, the reactions that occur at each stage need to maintain the bulk chemistries, trace element characteristics, and stable isotope compositions of the MORB protolith (Neal *et al.,* 1990; Jerde *et al.,* 1993; Jacob *et al.,* 1994; Pearson *et al.,* 1995; McCandless and Gurney, 1997). Given that seafloor hydrothermal vents are preserved in the geologic record well into the Proterozoic, are prolific on present-day seafloor ridges, and are unavoidably subducted, their interaction with MORB in the mantle should be anticipated.

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