Tephrochronology of marine sediments around the Island of Montserrat, Lesser Antilles volcanic arc

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ABSTRACT

The recent history of the Soufrière Hills Volcano, Montserrat, Lesser Antilles volcanic arc, is reconstructed using data obtained from recently drilled submarine cores. Tephra layers in these cores preserve a record of the volcanic history of Montserrat back to ~250 ka on the basis of micropaleontology and stable isotope stratigraphy. Stratigraphic relationships identified in the cores collected in 2002 and 2005 document the fate of both pyroclastic flows entering the ocean to the east of Montserrat and carbonate-rich turbidites sourced from the carbonate platforms surrounding the islands of the Lesser Antilles. Using oxygen isotope stratigraphy, micropalaeontological analysis and Carbon-14 dating, it can be shown that three significant volcanic events, including the on-going eruption, have occurred over the last 12 ka. Preceding this was a time of volcanic quiescence, with three carbonate-rich turbidite events being documented in many of the cores. Our data suggest that these events occurred during Marine Isotope Stage 2, following the Last Glacial Maximum (LGM) and onset of post-glacial sea level rise.

INTRODUCTION

The island of Montserrat lies in the Lesser Antilles volcanic arc that formed as a result of the subduction of the Atlantic Plate beneath the Caribbean Plate. Arc volcanism was initiated at 40 Ma (Bouysse *et al*. 1990). To the north of Dominica, the arc is divided into two groups of islands (Figure 1). The outer group is older, with thick carbonate platforms covering a volcanic basement. The inner group consists of volcanic rocks younger than 20 Ma and includes all the active volcanoes (Bouysse *et al*. 1990), including Montserrat.

The island of Montserrat has a well-documented eruption history (Harford *et al*. 2002) based on dating of on-shore ash and other pyroclastic deposits. Andesitic rocks resulting from dome-forming eruptions dominate the geology with the island preserving remnants of lava domes, dome talus breccias, dome-collapse pyroclastic flow deposits, lahar and debris avalanche deposits (Harford *et al*. 2002; Le Friant *et al*. 2004). Three volcanic centers have been identified: Silver Hills (2600 to 1200 ka), Centre Hills (at least c. 950 ka to c. 550 ka) and the South Soufrière Hills-Soufrière Hills complex (at least 174 ka to the present).

Prior to 1995 there had been no volcanic activity in recorded history and many non-geologists thought the volcano to be extinct. Earthquake swarms began in January 1992 and the eruptions began in July 1995. The first major eruption was on the 21st of August 1995 when Plymouth (the main town and centre of government) was blanketed in ash (the cloud of which caused 15 minutes of darkness). This was followed by dome growth in the crater during September 1995. Collapse of this dome and the formation of pyroclastic flows began in March 1996, and on the 17th September 1996 a series of dome collapses lead to the first magmatic explosion with an ash plume rising to 40,000 feet and ~600,000 tonnes of ash being deposited on the southern half of the island. Early in 1997 parts of Plymouth were buried and on the 1st July 1997 most of the town (now evacuated) was engulfed (Figure 2). In subsequent years the majority of the pyroclastic flows have travelled east into the Tar River Valley, burying the old airport. Since 1997 the dome has continued to grow and collapse (20th March 2000, 29th July 2001, 12th - 13th July 2003, 20th May 2006). After two years of continual dome-building activity the Soufrière Hills volcano produced the largest documented historic dome collapse for any volcano on the 12th - 13th July 2003. The collapse occurred over an eighteen hour period, yielding >$210x10^6$ m^3 of pyroclastic material which avalanched down the Tar River Valley and into the ocean (Trofimovs et al., 2006, fig. 3). Since that eruption there was another large dome collapse on the 20th May 2006 (in less than one hour) which has been followed by the formation of a new, and even larger, dome (cover photo).

The Montserrat Volcano Observatory was established on 18th July 1995 and in January 2003 moved to a new purpose-built location. The Montserrat Volcano Observatory website [www.mvo.ms] provides a continuous record of the on-going eruption and a stunning picture gallery of the development of the volcano.

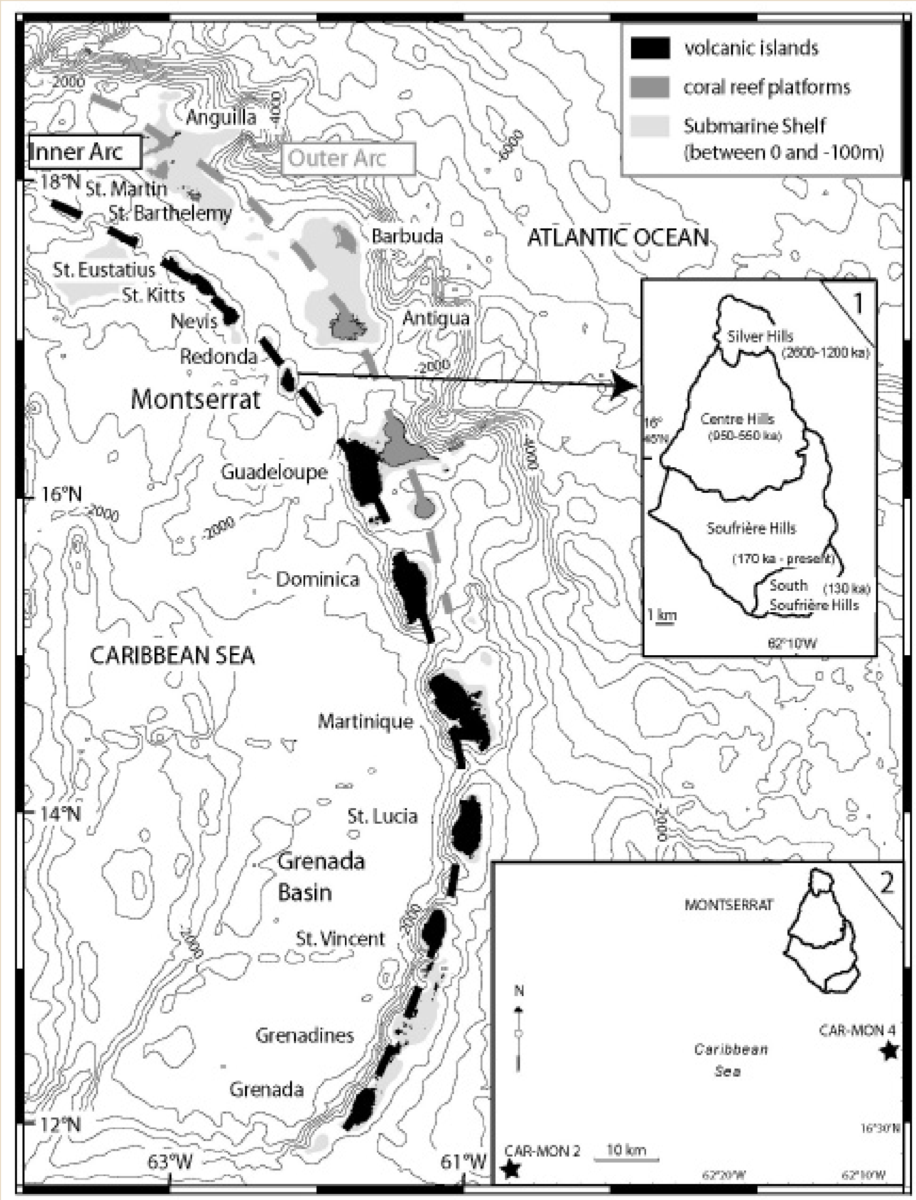

Figure 1. The geodynamic setting of Montserrat (West Indes). Contour interval is 250 m and 2000 m isolines are in bold. Volcanic islands are black and sub-aerial coral reef platforms dark grey. The < 100 m deep submarine shelves are light grey. The lower insert map shows the location of the CAR-MON 2 borehole.

Because almost 90% of the erupted material, ash and pyroclastic flows enter the surrounding ocean much of the research on the history of the volcano has switched from on-shore surveying to mapping of the ocean floor and coring of marine sediments.

THE "CARAVAL" CRUISE (2002)

In February-March 2002 the "Caraval" cruise of the R.V. *L'Atalante* gathered marine survey data from the area adjacent to Montserrat and collected a number of cores. For our initial stratigraphical studies, core CAR-MON 2 (16º 27.699' N; 62º 38.077' W) was selected as it preserves the longest (575 cm) record and contains a number of discrete ash-fall events within a pelagic carbonate succession. This core was sampled by taking a one centimetre wide quarter segment of the split core every five centimetres (except in the immediate vicinity of visible sedimentary events). Data from the CAR-MON 2 core are shown in Figure 3.

The samples collected for micropalaeontological investigation and stable isotope analysis were prepared at the University of Plymouth. At all stages in the processing, samples were soaked, washed and filtered using de-ionized water. This ensures that no dissolution of the delicate carbonate microfossils, particularly pteropods (holoplanktonic gastropods), occurred during preparation. Samples were washed on a 63 µm stainless steel sieve. The <63 µm fraction was collected, dried and homogenized in an agate pestle and mortar to be used for stable isotope analysis. Samples for micropalaeontological analysis (>63 µm size fraction) were filtered, dried, weighed and stored. Counts of the foraminifera and the pteropods were undertaken on the >150 µm size fraction. The <150 µm size fraction was inspected for species content only.

The *Globorotalia menardii* complex (Figure 4) provides a record of climatically-induced migration events that can be used in the correlation of marine cores (see, for example, Reid *et al.* 1996, figs A1, A2). The *G. menardii* record (Figure 3) was established by counting a minimum of 300 planktic foraminifera in the >150 µm size fraction. The *G. menardii* zonal boundaries are identified at levels where the *G. menardii* component of the fauna drops below, or rises above, 1% of the total planktic foraminiferal fauna. The Z, Y, X, W and V zones are clearly delineated and are similar to those determined in core EN8 (16º 17.9' N; 62º 56.4' W) by Reid *et al.* (1996, fig. A2). The variations in the *G. menardii* population record a cyclical pattern that can be replicated in other cores. As *G. menardii* is normally more abundant in warm water, the distribution of this taxon records a number of warm/cool oscillations within MIS 5, a periodicity of ~8,000 years.

Stable isotope ($\delta^{18}O$, $\delta^{13}C$) analysis was performed at the NERC Isotope Geosciences Laboratory, British Geological Survey, Keyworth, and details of the equipment and procedures used are given in Le Friant *et al.* (2008). The homogenized <63 µm samples contain not only a range of calcareous nannofossils but include small/broken foraminifera, pteropod fragments, calcified dinoflagellates and other calcitic/aragonitic debris.

CAR-MON 2, located to the south-west of Montserrat, is the longest and most carbonate-rich of the boreholes recovered in 2002. By comparison to published data, the $\delta^{18}O$ record (Figure 3) can be used to identify isotope 'events' down to Marine Isotopic Stage 8 (MIS 8.2), indicating that this core has a sediment record extending back to ~250,000 years b.p.. Using this $\delta^{18}O$ record and the known ages of the various events and MIS boundaries, an age:depth curve has been constructed that allows our colleagues to document the changing activity and petrological character of the volcano through time (Le Friant *et al.*, 2008, fig. 6).

An interesting question that has yet to be

Figure 2. The ruins of Plymouth Cathedral and the remains of the still active Soufrière Hills volcanic centre. This photograph was taken in May 2005 when access to the area was still possible during daylight hours. Barnaby Bear is not a resident of Montserrat but belongs to Montpelier Infants School in Plymouth (U.K.) and who went on the visit to Montserrat to help the children learn about volcanoes.

answered is the effect of the ash falls on benthic and planktic organisms (see work by Hess & Kuhnt, 1996, on Mt Pinatubo). In December 2007, the R.R.S. *James Cook* (Cruise JC18) returned to the area to investigate both this issue and a range of other scientific objectives. Some of the cores recovered indicate that the major ash fall following the May 2006 eruption may have a 'kill layer' at its base in which much of the planktic fauna hit by the ash is now buried.

INTERPRETATION AND DISCUSSION

Our on-shore/off-shore correlation (Le Friant *et al.* 2008) suggests that the Soufrière Hills and South Soufrière Hills magmatic system has been active in several discrete, intense pulses with much longer periods of either dormancy or a low-level of activity. We have observed that the critical marker bed of several basaltic scoria and ash layers (Figure 3, 270-330 cm) has also been identified as visible tephra layers in other cores. These tephra layers are correlated with the activity of the South Soufrière Hills volcano, that is constrained by several high quality age dates (Harford *et al.* 2002).

Our data define an eruptive history for the Soufrière Hills Volcano and the South Soufrière Hills Volcano extending back at least 250 ka. At least 14 eruptive periods have been recognised in the core CARMON 2. There is a good agreement between the on-land dome eruptions and the off-shore record, but new events have also been recognized from the marine data. Eight dome eruption periods have been identified from which several dome eruptions are new and have not yet been correlated with on-shore data. The three new dome eruptions have been identified at ~246 ka, 216-220 ka, and 43-45 ka. The absence of on-shore deposits can be explained by erosion but also by numerous flank-collapse events which occurred on the South Soufrière Hills- Soufrière Hills Volcano and which have destroyed some parts of the volcano (Le Friant *et al*. 2004).

THE JR123 CRUISE

In May 2005 the R.R.S. *James Clark Ross* re-visited the Montserrat area, concentrating on the marine area to the east and south of the Tar River Valley. Over 50 vibrocores and a number of box cores were taken from a range of locations. The thickness of tephra from the 12th-13th July 2003 eruption can be correlated (Figure 5) through the cores taken along the axis of the Bouillante-Montserrat Graben, although the final toe of the submarine flow was not sampled in 2005. Using the same borehole locations, an isopach plot of the cumulative thickness of the 1995-2003 Soufriére Hills deposits that have entered the sea via the Tar River Valley has been constructed (Trofimovs *et al.* 2006, fig. 3). These deposits clearly follow the submarine topography, especially adjacent to the two volcanic centres on the eastern side of the graben.

Each core recorded a number of events, both volcanogenic (turbidites formed through pyroclastic surges, and ash falls) and biogenic (calcareous turbidites formed as material has been shed off the nearby carbonate platforms) in origin. Through logging, grain size analysis, and component analysis these events have been fully documented and correlated throughout the cores (Figure 5). Primarily this dating has been undertaken using micropaleontology, high resolution oxygen isotope stratigraphy and a number of carbon-14 dates, as described for

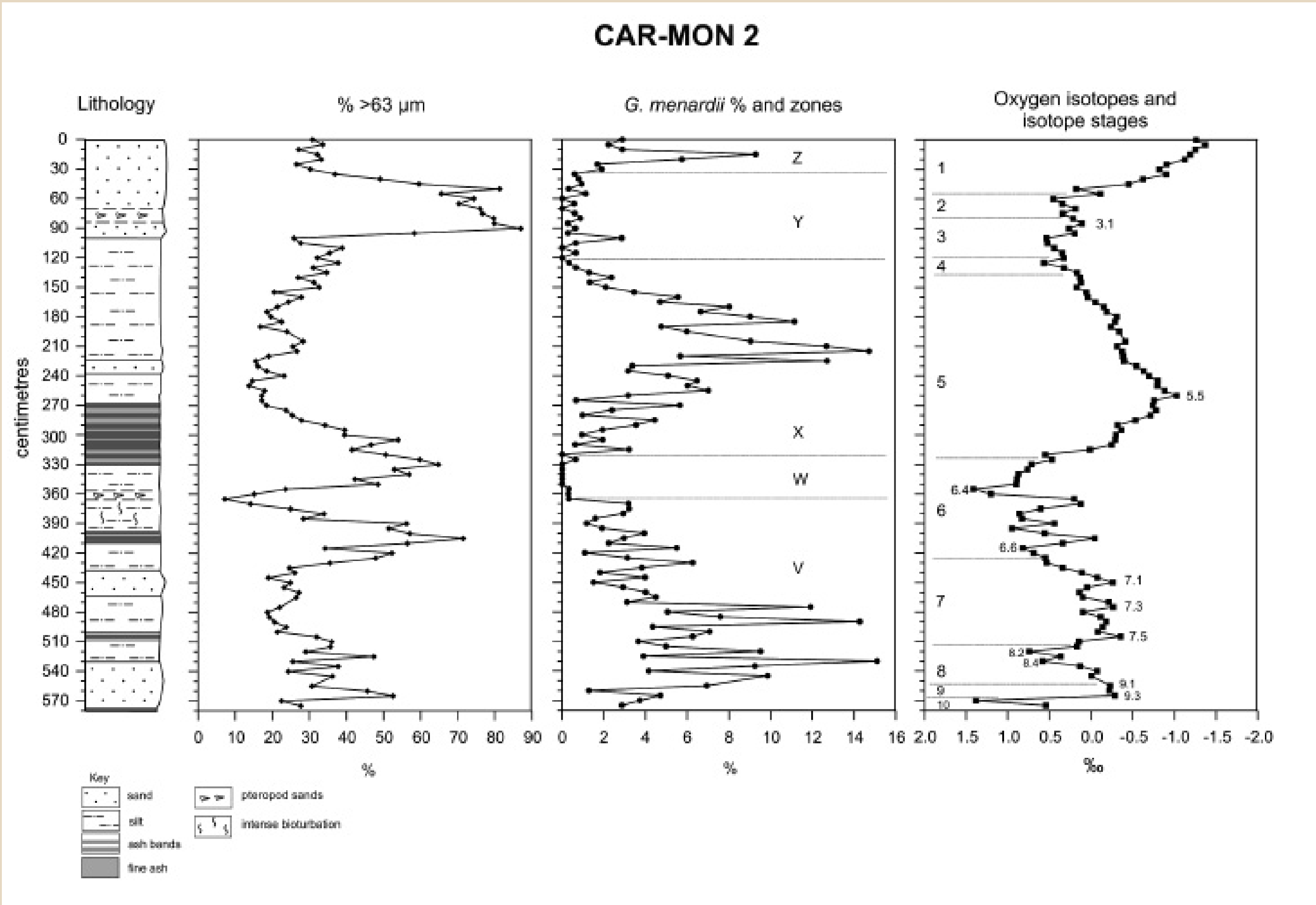

Figure 3. Sediment log, grain size chart, $\delta^{18}O$ isotope record and **G. menardii** *record for the CAR-MON 2 core.*

the CAR-MON 2 core. These data have allowed us to constrain the ages of all these events and this work, once complete, will provide a complete geochronology of the various events occurring around the volcanic island of Montserrat.

Figure 4. **Globorotalia menardii s.l.** ***typical of the specimens used in the construction of the V - Z zones shown in Figure 3.***

Data so far appear to indicate three periods of volcanic activity (including the recent phase) occurring over the last 12 Ka, during MIS 1. This activity was preceded by a period of volcanic quiescence. During this time three biogenic turbidites are observed and correlated within the cores, and have been dated to occur during MIS 2. This was a time of sea level lowstand this may have led to the generation of biogenic turbidites, as carbonate is known to have been shed from the platforms observed around the islands of the Lesser Antilles and elsewhere in the Caribbean Sea and Western Atlantic Ocean. Samples from these biogenic turbidites contain abundant coral fragments, bryozoans, gastropods and other shallow-water debris. In many samples abraded specimens of the benthic foraminiferid *Amphistegina* dominates the fauna indicating transport of sediment from environments more normally associated with 50-150 metres water depth. Work on the source of these turbidites is ongoing.

SUMMARY

The eruptive history of the Soufrière Hills volcano, prior to its recent period of activity, was incompletely known from subaerial deposits that have been subjected to repeated destructive or erosional events. A multidisciplinary study (micropaleontology, stable isotope stratigraphy, carbon-14 dating, igneous petrology and geochemistry) of recently drilled cores from the sea floor in the vicinity of Montserrat has shown that there has been intermittent, quite violent, activity separated by long periods of quiescence over the last 250 ka years.

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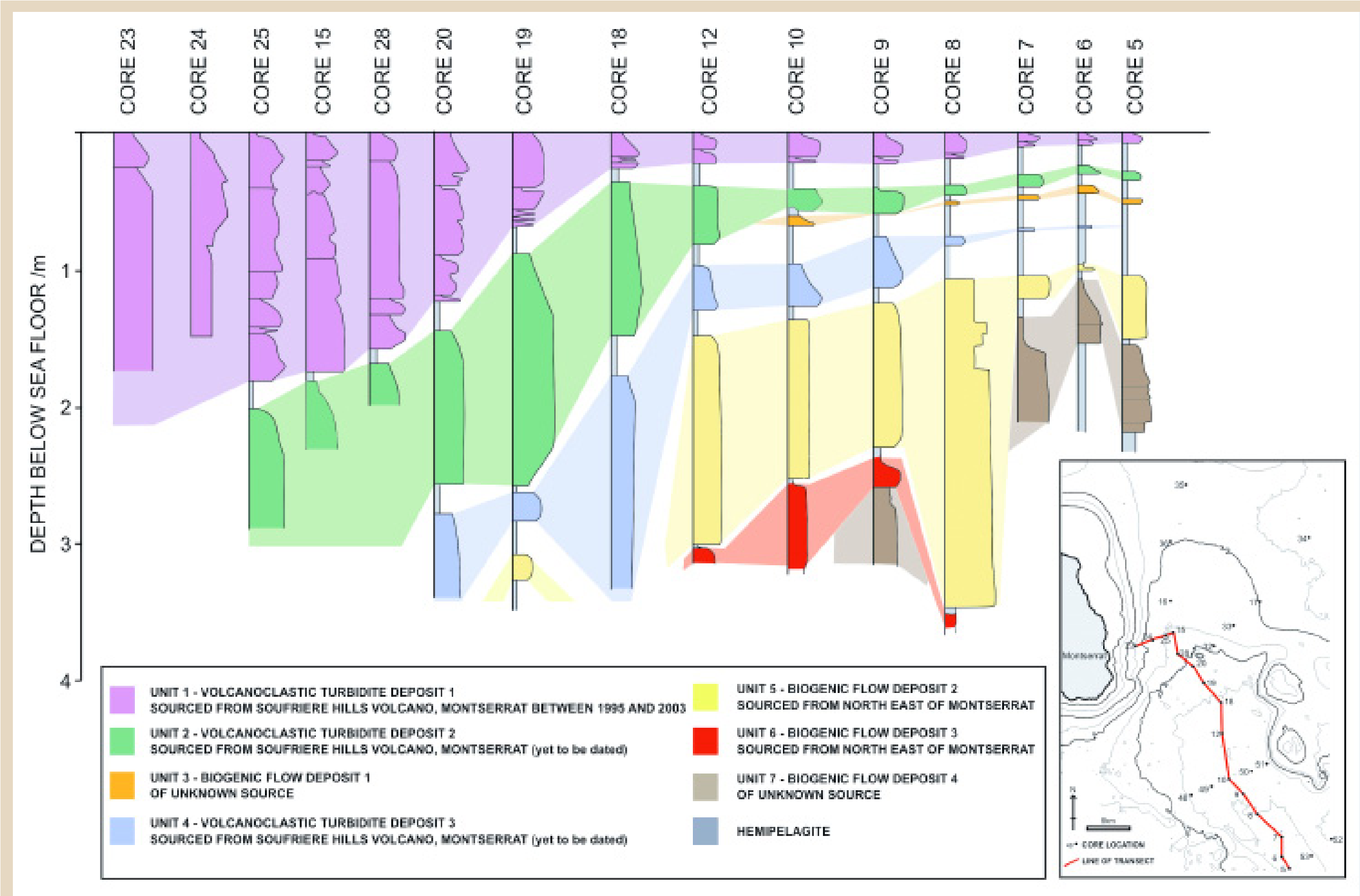

Figure 5. Correlation of cores along the axis of the Bouillante-Montserrat Graben.

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