Shallow shear wave reflection surveys in the Wellington CBD

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ABSTRACT

Seismic reflection profiles using shear waves provide constraints on the thickness of sediments beneath the Wellington CBD. New shear wave source and acquisition methods were trialled for use in urban environments to investigate shallow sedimentary basins. Converting the two-way travel time axis on the stacked seismic section to depth required a velocity model for each location based on direct velocity measurements made from local downhole seismic logs. Basement depths at Wellington Girls College and Waitangi Park are estimated to be 180 ± 19 and 220 ± 25 m, respectively. These depths are up to 77% greater than previous estimates based on gravity modelling, 3D mapping of borehole depths, and microtremor analysis. At Wellington Girls College, near-surface sediments are horizontally layered, whereas, at Waitangi Park, sediment and basement offsets are interpreted. These offsets are attributed to the Aotea Fault, which is interpreted as a complicated, three-step, laddered structure. A near-surface seismic survey was undertaken at Miramar Polo Ground, where a logged borehole allowed us to benchmark our interpretations against the subsurface geology. These new estimates of basement depth in the Wellington Basin will provide constraints for geological models that predict how shaking from earthquakes will vary across the city due to variations in the basin's depth and shape.

1 INTRODUCTION

Many of the cities of the world are built on sedimentary basins. Although basins often have flat terrain that is attractive to build on, basins can act like a natural resonance chamber where seismic waves are amplified. Wellington CBD is situated in a small steeply dipping, fault-bound, sedimentary basin with the Wellington Fault to the NW and the recently discovered Aotea Fault to the SE (Barnes et al., 2019) (Figure 1). In fault-bounded sedimentary basins, edge effects produced by trapped waves can increase amplification close to the basin edge (Kawase, 1996). The energy of a seismic wave is a function of wave amplitude and speed. If the wave slows down as it enters a basin, the amplitude must increase to conserve energy (Sheriff and Geldart, 1995). Thus, knowledge of the 3D shape of a basin is needed, and seismic reflection is the widely used geophysical method to do this (Kearey et al., 2002). Three locations around Wellington were selected for S-wave reflection surveying: Miramar (Miramar Polo Grounds), Thorndon (Wellington Girls College) and Te Aro (Waitangi Park) (Figure 1).

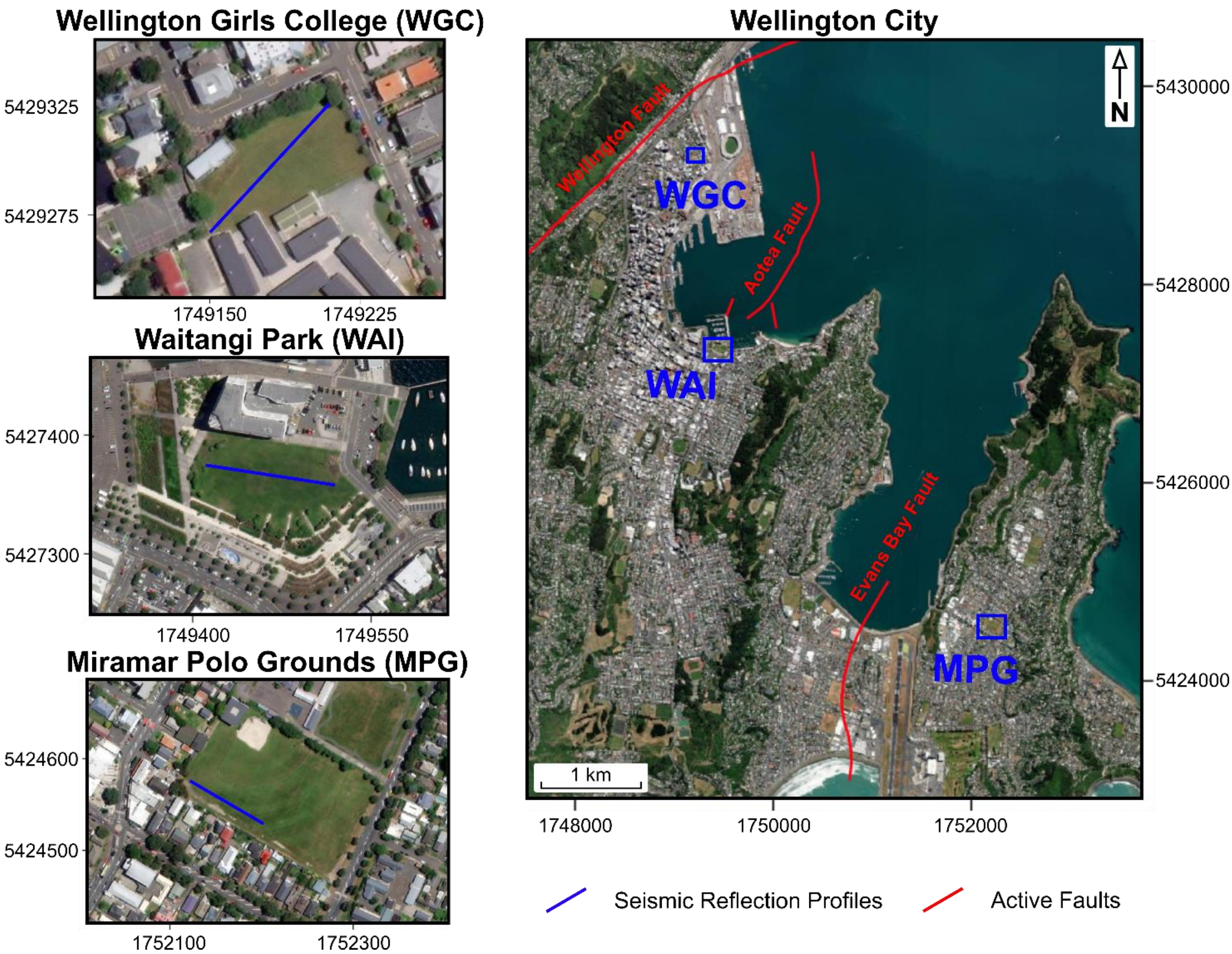

Figure 1: Map of Wellington city showing survey locations at Wellington Girls College, Waitangi Park and Miramar Polo Ground. Seismic reflection profiles are shown as blue lines. Major active faults are shown as red lines (GNS Science, 2016). Map projections is in New Zealand Transverse Mercator (NZTM).

1.1 Seismic reflection method

P- and S-waves can be used for seismic reflection studies, with the P-wave being the faster wave and easiest to determine in a seismic record. However, shear-waves have some advantages when studying shallow basins because they are lower velocity, shorter wavelength, and lower frequency, which give better resolution than P-waves for basins less than about 200 m in thickness (Pugin et al., 2004). However, a key challenge for S-wave surveys is generating shear energy at the Earth’s surface. A new shear wave seismic source based on a USGS model was locally manufactured for urban geophysics surveying (Haines, 2007). Two angled aluminium alloy strike plates are mounted on either side of the metal frame with ground spikes, which can be struck with a sledgehammer, either inline or at right angles to the seismic line. This way, horizontal and vertically polarised shear waves can be generated and transferred to the subsurface. Data were recorded on a 48-channel multichannel seismograph with horizontal 10 Hz geophones, which were orientated in the field to have their vibration axis either inline or at right angles to the seismic array to record SV and SH waves, respectively (Kearey et al., 2002).

Surveys in urban environments have a high degree of anthropogenic noise, and processing steps are undertaken to increase the signal-to-noise ratio. We used a combination of common–depth point (CDP) stacking, frequency filtering, deconvolution and F-K filtering (Sheriff and Geldart, 1995) to boost the signal-to-noise ratio. Shot gather and CDP-stacked seismic sections are recorded in two-way travel time (TWTT) and converting the time axis to depth requires a velocity model. The subsurface at each location is broken into distinct geological intervals. Local downhole seismic logs and boreholes from the NZ Geotechnical Database and the GNS Science Urban Database are used to define estimates on the Vs for each interval and geological contact at each location. Root-mean-squared velocity (V_{rms}) is the average wave speed between the surface and a subsurface reflector which is used to convert TWTT to depth. Details on how V_{rms} is obtained can be found in Kearey et al (2002). From estimates of V_{rms} for a series of reflectors in the subsurface we can determine the interval velocity between any two reflectors using the Dix equation (Kearey et al., 2002).

1.2 Miramar

Miramar Basin is a small peripheral basin to the main Wellington Basin on the Miramar Peninsular (Figure 1). At the western edge of the Miramar Polo Ground, a borehole intersects a distinct low-velocity peat layer at a depth of 32.3 m and a greywacke basement at 50.7 m (Begg et al., 1992). This borehole data provides a means to benchmark our method against measured geology at depth.

On the stacked seismic section, a clear high amplitude, low frequency (25 Hz) double event can be seen between 300 and 340 ms TWTT (Figure 2). Peat has a low S-wave speed (~120 m/s) (Zainorabidin and Said, 2015), producing a high impedance contrast (density and/or velocity contrast) with the surrounding sediment, this is one estimate and there is considerable variability in the reported S-wave velocities for peat. However, for our purposes, the adoption of a single value is sufficient to demonstrate the seismic response to a thin low-velocity layer. Seismic wavelength (λ) is given by velocity/frequency (v/f); thus, for f = 25 Hz and v = 120 m/s, the wavelength in peat is ~4.8 m. The rule of thumb is that the top and bottom of a layer can be resolved if the thickness of the layer is $\geq\lambda/4$ (Sheriff and Geldart, 1995; Kearey et al., 2002), which is roughly 1 m. The geological log shows the peat layer to be 2.7 m thick, so our interpretation is that the top and bottom of the peat layer have been resolved (Figure 2). We adopt a V_{rms} for the S-wave of 225 and 270 m/s for TWTT's of 300 and 375 msec, respectively, for depth conversion to the top of the peat layer and the approximate base of the Quaternary sedimentary sequence.

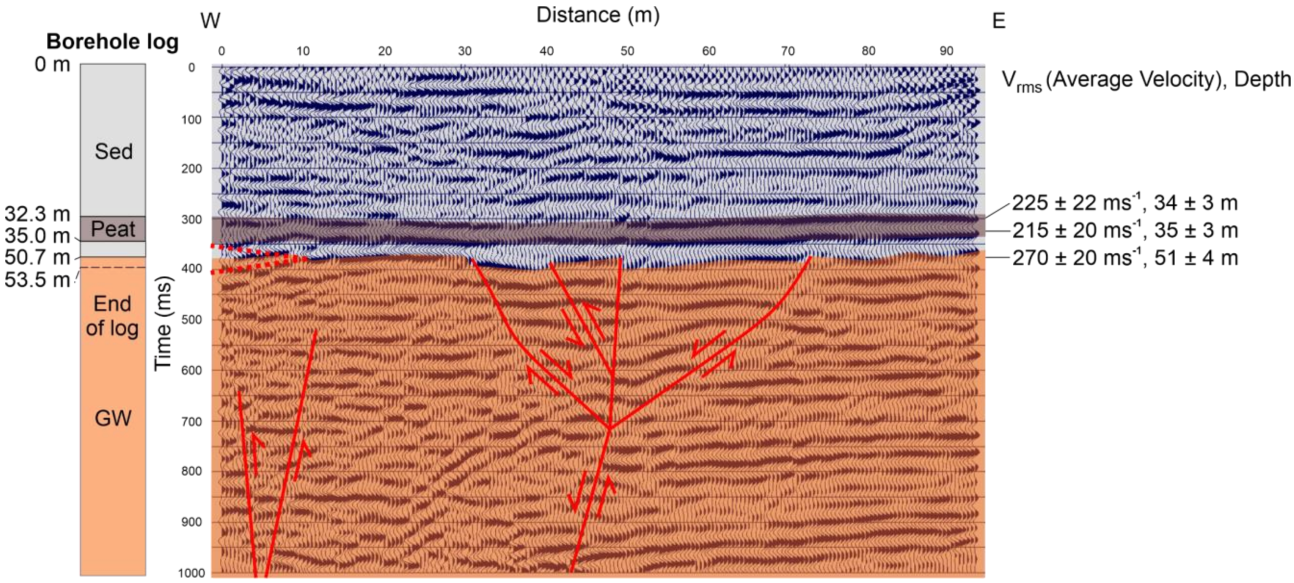

Figure 2: Stacked CDP seismic section from Miramar Polo Grounds. The interpreted basement contact is shown in orange. Borehole located to the west of the seismic section has been summarised to include

sediments, peat and greywacke basement. An interpreted negative flower structure observed in the centre of the profile is taken as evidence of strike-slip displacement with minor extension. Contact uncertainty at the edges of the stacked section are shown as red dashed lines.

This survey's unexpected outcome was the image of structure in the greywacke basement, which is rarely seen in P-wave reflection surveys in New Zealand (e.g. Baur et al., 2013). This could be because of the higher resolution of Vs, which can image structures that would be otherwise hidden. We interpret a negative flower structure (Figure 2) between 450 and 700 msec TWTT and adopt this as evidence for strike-slip faulting in the middle of the basin with minor extension (Badley, 1985).

1.3 Thorndon

Thorndon is an important part of the Wellington CBD where depth to basement is poorly constrained (Kaiser et al., 2019). During recent earthquakes, high ground acceleration levels were measured (Bradley et al., 2017). Wellington Girls College has the only large, grassed area in the Thorndon region suitable for a seismic reflection survey, so this area was chosen for investigation (Figure 1). The stacked seismic section shows a strong event at 300 msec TWTT, corresponding to a depth of about 48 ± 4 m for a V_{rms} of 317 ± 25 m/s (Figure 3). This reflector could be related to another peat layer or represent a change in sediment composition and higher Vs. The basement contact has a maximum depth of 180 ± 19 m and shows erosional channel features at the southern end of the profile. These could represent old drainage features with flow to the east. The higher frequency reflectivity in the top 200 msec is interpreted to be P-wave energy.

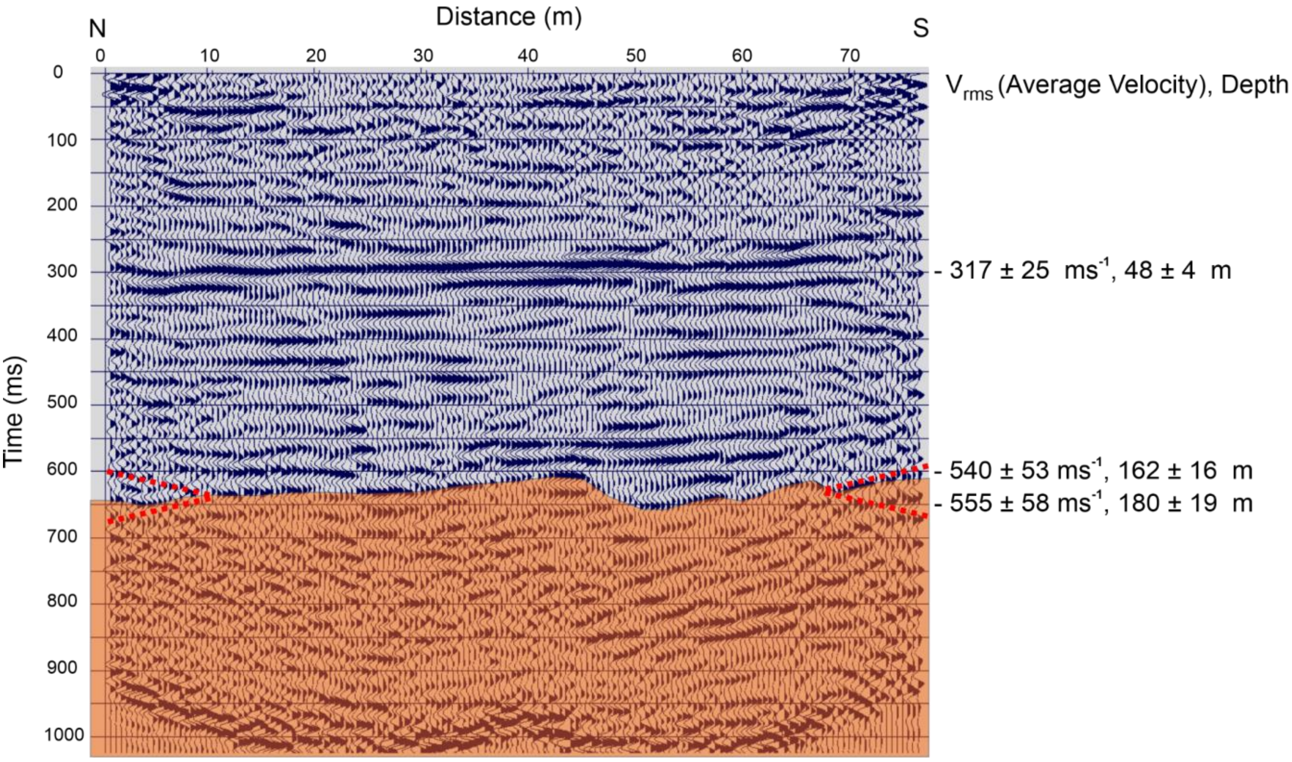

Figure 3: Stacked CDP seismic section from Wellington Girls College. The interpreted basement contact is shown in orange. Contact uncertainty at the edges of the stacked section are shown as red dashed lines.

1.4 Te Aro

The recently discovered (Barnes et al., 2019) offshore trace of the Aotea Fault likely extends onshore at or close to Waitangi Park (Fig. 1). Stronach and Stern (2021) used gravity methods to locate the onshore trace and a secondary splay on the western side of Mt Victoria. Although the gravity model points to the Aotea

Fault passing through Waitangi Park, its exact position and orientation are not well constrained. Our 108 m-long profile crosses the park on an almost west-east azimuth (Fig. 1). Seismic structure on this profile is more complex than at the WGC site, which is attributed to the complex, multi-stranded fault zone (Fig.4). A borehole on the northern boundary of Waitangi Park shows a sediment thickness of 45 m. We have adopted this as a depth constraint on our interpreted section (Fig. 4). We also interpret a positive flower structure on the eastern up-thrown side of the fault zone, which could accommodate strike-slip motion with some compression. A three-part, down-stepping, fault zone is interpreted rather than a single fault trace (Fig. 4). This fault zone accommodates a total of 180 ± 25 m of vertical offset, although the maximum sedimentary thickness in the seismic profile is 220 ± 25 m. Previous models at Waitangi Park have the maximum sedimentary thickness of the footwall of the Aotea Fault shallower at 140 m (Kaiser et al., 2019) and 155 m (Stronach and Stern. 2021).

The top 250 msec of the record contains distinctively higher frequency signals, which we interpret as P-wave reflections. These shallow reflections define a broad but subtle dome that reaches a peak above the surface projection of the main subsurface thrust fault (at a distance of 50 m). A similar domed structure is seen above the offshore seismic expression of the Aotea fault (Barnes et al., 2019). For an average P-wave speed in the sediments of 2 km/s, the maximum depth of the interpreted P-wave reflections is about 220 – 240 m, consistent with the S-wave interpretation.

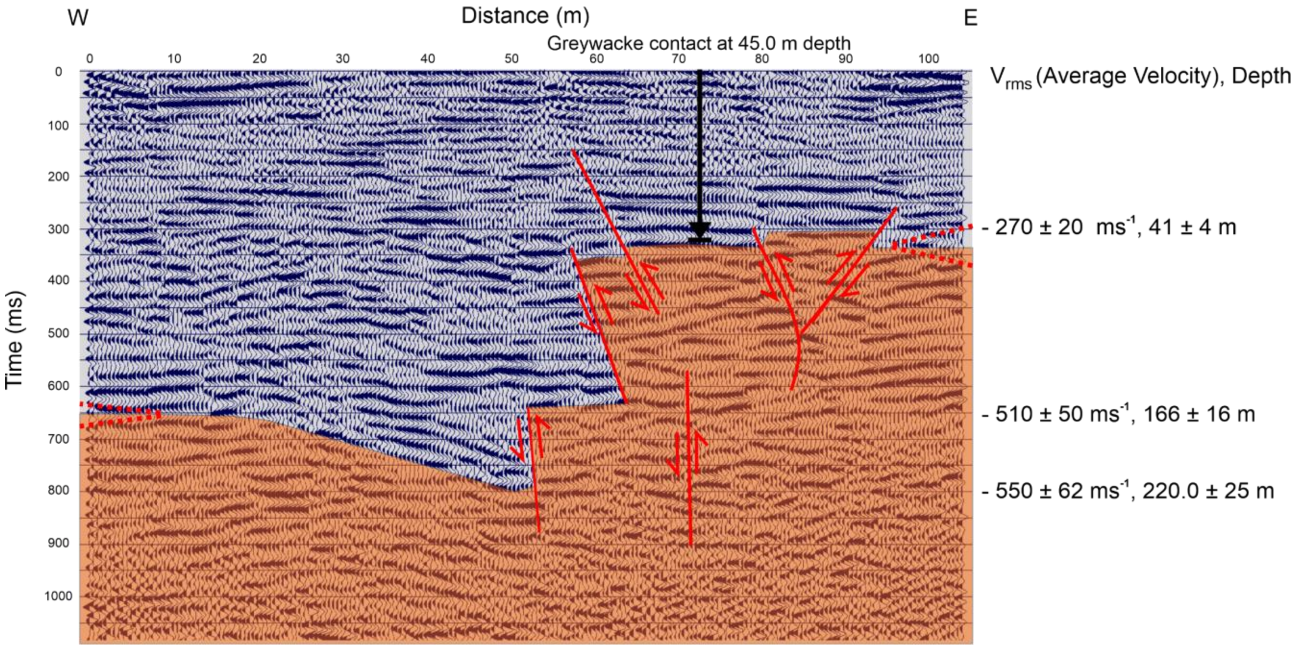

Figure 4: Stacked CDP seismic section from Waitangi Park. Interpreted basement contact is shown in orange. Borehole with greywacke contact at 45.0 m depth. Positive flower structure observed in the east of the profile is taken as evidence of strike-slip displacement with minor compression. Three reverse stepped thrust faults accommodate the vertical displacement of the Aotea Fault with an accumulated 180 ± 25 m of vertical offset. Contact uncertainty at the edges of the stacked section are shown as red dashed lines.

A comparison of basement depth estimates for this study and others shows the maximum difference is at Waitangi Park, where the seismic method gives a maximum depth of 77% higher than other methods (Table 1). This divergence is likely to be due to the assumed densities in gravity modelling that can give basin depth uncertainties that are of the order ±10% (Stronach and Stern. 2021). Previous Wellington Basin models (Kaiser et al., 2019; Semmens et al., 2010; Vantassel et al., 2018) used microtremor data to obtain depth estimates based on the horizontal to vertical spectral ratio (HVSR) and surface wave dispersion. These are 1-D methods, and the HVSR method requires assumptions that the local lateral variation is small compared to the wavelength associated with the main peak (Bignardi, 2017). Steeply dipping faults introduce complex 2D and 3D effects, making depth estimates less reliable (Kaiser et al., 2019). The accuracy of our new basin depth measurements depends on the velocity model we use to convert TWTT to depth. We estimate a ±10% uncertainty in average S-wave velocity, which would lead to similar uncertainty in our depth estimates. We suggest, therefore, that these latest seismic results are the most direct and robust determinations of basement depth for the Wellington CBD and should be adopted in future analyses of shaking from earthquakes. The drawbacks of shear wave reflection methods are the devoted seismic source and horizontal geophones required for acquisition, and potentially higher rates of attenuation for S-waves, compared to P-waves under some conditions.

Table 1: Greatest depth along each seismic profile compared to existing depth models of Kaiser et al. (2019), Semmens (2010) and Stronach and Stern (2023).

	This research	**Kaiser et al (2019)**	**Semmens (2010)**	**Stronach and Stern (2021)**
Wellington Girl College	180 ± 19 m	155 m	155 m	195 m
Waitangi Park	220 ± 25 m	140 m	50 m	155 m

1.5 Conclusion

Shear-wave reflection surveying is a viable, non-invasive, and efficient method of estimating basin thickness in urban environments along a 2D profile. Results from Wellington Girls College and Waitangi Park give basement depth estimates up to 77 % larger than previous methods based on microtremor and gravity interpretation. We show that the seismic depth results presented here have uncertainties of ± 10%, and the method, therefore, provides a robust means measuring basement depth in the Wellington Basin. These estimates can be incorporated into future 3D geological and ground shacking models for the Wellington Basin that will improve understanding of the seismic risk.

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