Eos, Transactions, American Geophysical Union, Vol. 81, No. 42, October 17, 2000, Pages 481, 485, 486

Constraining Fault Growth Rates and Fault Evolution in New Zealand

Understanding how faults propagate, grow, and interact in fault systems is important because they are primarily responsible for distributing strain in the upper crust. They localize deformation and stress release, often producing surface displacements that control sedimentation and fluid flow, either by acting as conduits or barriers. Identifying fault spatial distribution, quantifying activity, evaluating linkage mechanisms, and estimating fault growth rates are key components in seismic risk evaluation.

Scientists from the National Institute of Water and Atmospheric Research (NIWA), New Zealand, and the Southampton Oceanography Centre, United Kingdom, are working on a collaborative project that aims to improve understanding of faulting processes in the Earth's crust. The program comprises two research cruises to survey the Whakatane Graben, New Zealand, which is a zone of intense seismicity, active extensional faulting, and rapid subsidence within the back-arc region of the Pacific-Australia plate boundary zone (Figure 1). Few places in the world offer the same opportunity to study the mechanisms by which major crustal faults have grown from small- to large-scale structures capable of generating moderate- to large-magnitude earthquakes.

The aim of the project is to provide new insights into fundamental questions such as: how do faults interact and link to form fault systems; and how do fault propagation and linkage change with time? One of the most exciting results from the work in the Whakatane Graben is the potential for improving understanding of how faults grow and at what rates.

The first survey was funded by the New Zealand Foundation for Research Science and Technology and took place in November 1999. Conventional marine geophysical data were collected. The second cruise, funded by the British Natural Environment Research Council, is scheduled for January 2001. It will focus on the acquisition

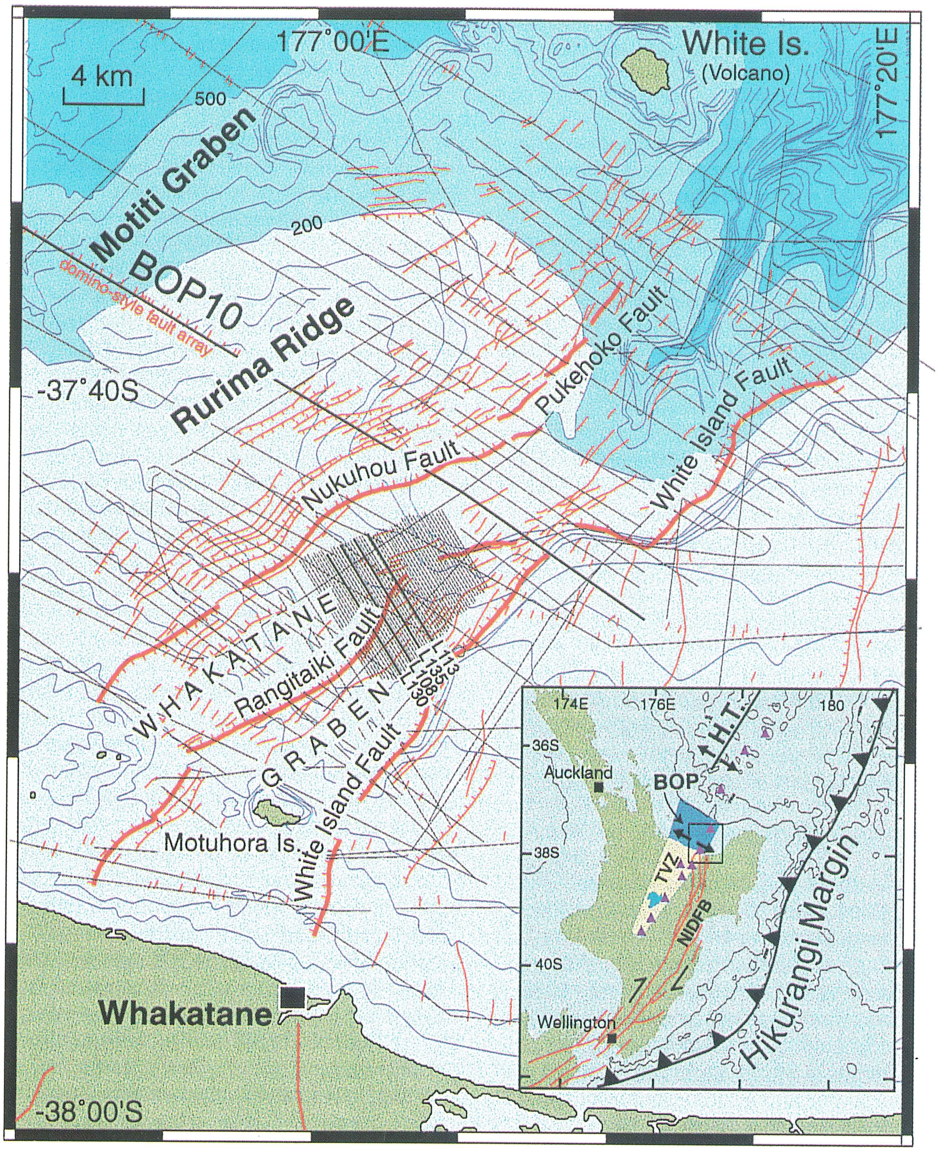

Fig. 1. Shipboard interpretation map of the Whakatane Graben showing the major active faults and the positions of the multichannel seismic reflection and 3.5-kHz profiles (gray lines). Faults are marked in red, the larger ones in bold. Ticks on major faults indicate the direction of down-throw. The White Island Fault represents the eastern boundary of the active Whakatane Graben, while the Rurima Ridge marks its western border. The 150-m line spacing used for the pseudo three-dimensional seismic experiment is visible in the center of the graben. Blue lines are bathymetric contours in meters. (Profiles shown in Figures 2 and 3 are indicated in bold with line numbers.) Inset: Regional setting around New Zealand North Island. The Bay of Plenty (BOP) and Havre Trough (HT) correspond to the continental and oceanic part, respectively, of the back-arc system associated with the Hikurangi subduction zone. The Taupo Volcanic Zone (TVZ; light yellow onshore and navy blue offshore) is a zone of intense active normal faulting that encompasses a line of active arc volcanoes (purple triangles). The North Island Dextral Fault Belt (NIDFB) is an active transcurrent fault system that runs on the upper plate along Hikurangi Margin and traverses the North Island of New Zealand from Wellington to the Bay of Plenty. Arrows indicate the main direction of active extension across the Havre Trough and Bay of Plenty and strike-slip along the NIDFB.

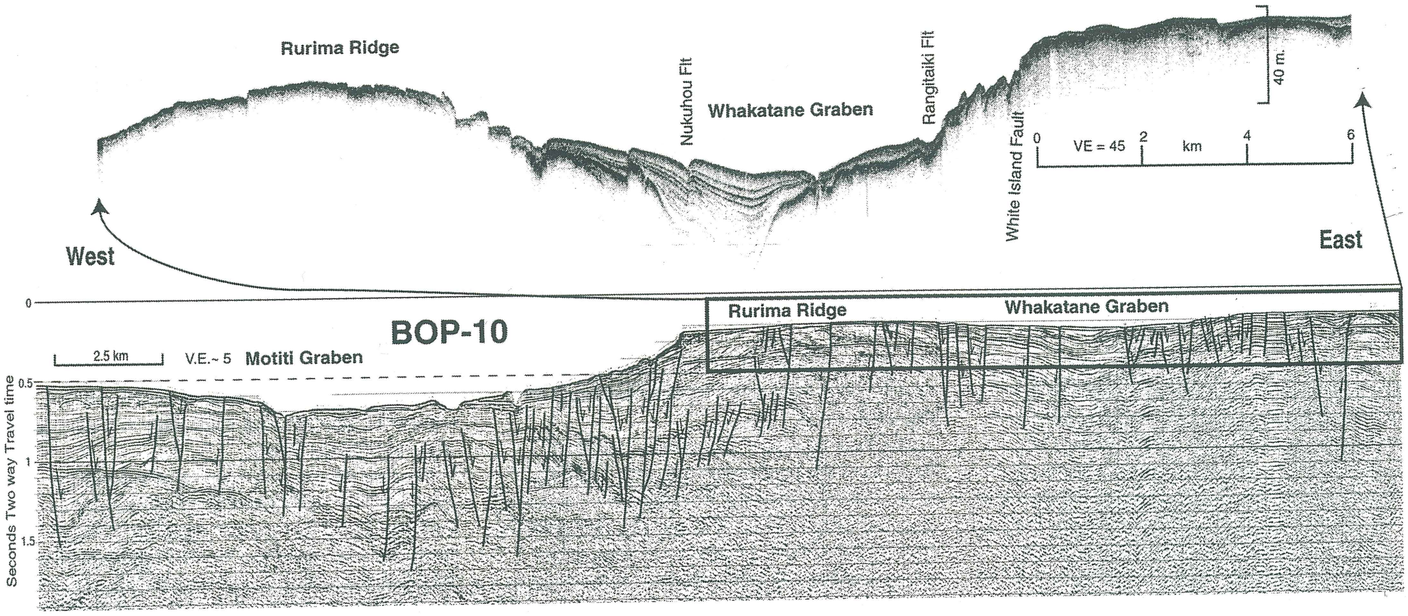

Fig. 2. Concomitant 3.5-kHz profile and seismic reflection profile (BOP10) across the Bay of Plenty (location in Figure 1). Note that the most recently active faults are readily identified from the 3.5-kHz profiles and are concentrated in the Whakatane Graben and on Rurima Ridge. The most recent fault activity has created an asymmetrical graben with the western boundary being marked by a number of faults with relatively small displacement, while the eastern boundary is sharply defined by the White Island Fault.

of high-frequency shallow seismic and side-scan sonar data.

This study of the Whakatane Graben will represent the most detailed regional investigation of active marine faults undertaken anywhere in the New Zealand region. Arguably, it could also become a case study of extensional fault growth and continental rift development of global significance.

Active Faulting in the Whakatane Graben

The reason why the Whakatane Graben—an active young rift less than 2 million years old—is ideal for making the necessary measurements is that the rates of tectonism and sedimentation are both high, with sediments providing a high-fidelity record of fault behavior. Moreover, the actively deforming Late Pleistocene sediments are well dated by volcanic ash deposits [*Pillans and Wright*, 1992]. Of particular value has been the integration of multichannel seismic reflection profiles, high-resolution sediment profiler records (3.5 kHz and future high frequency seismic profiles), and core data to facilitate quantitative measurements of fault displacement and extension rates, both along individual normal faults and across the whole graben at a variety of scales.

Back-arc extension associated with the Hikurangi subduction system is recognized along a narrow northeast-trending normal fault system, which marks the eastern boundary of the Quaternary Taupo Volcanic Zone (TVZ, Figure 1) of New Zealand's central North Island. Extension has resulted in the formation of the 18-km-wide Whakatane Graben, which spans the Bay of Plenty coastline and extends northeastward for about 50 km across the continental shelf to water depths of 300 m on the upper slope. Subsidence within the offshore graben is estimated to average 2–2.5 mm/yr over the last 100,000 years (100 ka). Extension across the Whakatane Graben is at least 3.5 mm/yr, accounting for half of the 7 mm/yr extension across the 40-km-wide TVZ [*Wright*, 1990]. Active faulting recorded in the Late Pleistocene sediments reveals repeated movement over at least the last 50 ka. Onshore, a recent example of violent fault displacement within the Whakatane Graben occurred during the 1987 Edgecumbe earthquake, Magnitude 6.3 [*Beanland et al.*, 1989], which resulted in major infrastructure damage costing over U.S.$150 million.

Of particular importance for establishing fault growth rates is the presence of a well-constrained record of the sedimentary layers, including post-glacial shorelines and ash deposits recovered in sub-bottom sediment cores less than 6 m in length. The presence of extensive, thick (3–6.5 cm) volcanic ash layers offers the potential for imaging them using high-frequency seismic techniques, as they provide coherent high amplitude reflectors (Figures 2 and 3).

R/V *Tangaroa* Cruise

In November 1999, NIWA undertook a 25-day geophysical cruise aboard R/V *Tangaroa* that provided extensive coverage of the offshore TVZ, including the Whakatane Graben. The data acquired includes multichannel seismic reflection and refraction profiles, high-resolution 3.5-kHz sediment profiles, magnetic and gravity measurements, sidescan sonographs, and core samples. Across the Whakatane Graben, the seismic profile spacing is less than 1 km normal to the graben axis. On-board interpretation shows an exceptionally well-developed array of normal faults widely distributed over the graben. Outstanding 3.5-kHz profiles enable imaging of many normal fault displacements greater than 50 cm within the top 40 m of sediment.

A pseudo three-dimensional seismic reflection experiment was conducted over part of the active fault zone, where we identified several fault strand terminations and relays within the Late Pleistocene sequence. The pseudo three-dimensional seismic experiment consists of a 7-km x 5-km area with a line spacing of 150 m. Each line consists of conventional, two-dimensional, multi-channel seismic reflection and 3.5-kHz profiles. The area was previously surveyed using a side-scan sonar to provided detailed information on the acoustic reflectivity associated with fine bathymetric features and variations in the nature of the seafloor.

Preliminary Observations

The R/V *Tangaroa* survey covered most of the back-arc rifting zone of the Bay of Plenty (Figure 1). This comprises a series of northeast-trending grabens and horsts, including from west to east the Motiti Graben, the Rurima Ridge, and the Whakatane Graben. In addition, a structural high exists to the east of the White Island Fault, where faults associated with the northern end of the North Island Dextral Fault Belt were imaged. This belt is an active transcurrent fault system that traverses the North Island of New Zealand from Wellington to the Bay of Plenty. The most active deformation is concentrated within the Whakatane Graben and the Rurima Ridge. The overall morphology of the presently active rift is asymmetric, with the White Island Fault controlling the eastern boundary [*Davey et al.*, 1995] and a series of small, east-dipping faults marking the western boundary on the Rurima Ridge (Figure 2).

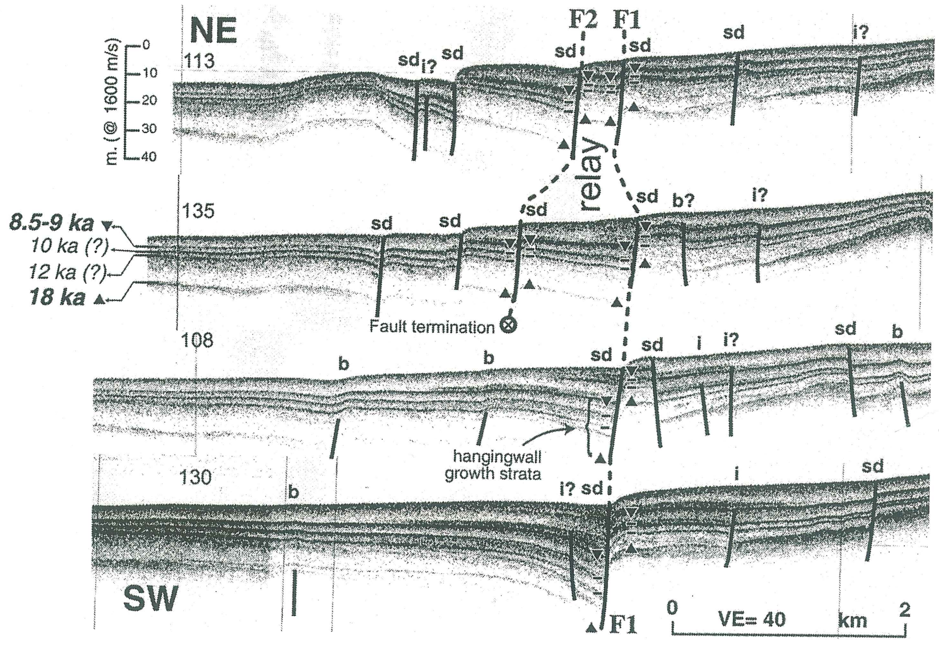

Fig. 3. 3.5-kHz records from the pseudo three-dimensional experiment (see Figure 1). The four profiles cross the Rangitaiki Fault and show one of the fault transfer and relay (crossed circle). Two reflection horizons are correlated with an erosion surface dated as 18 ka (?) and with an upper layer dated at 8.5–9 ka (?); two other reflectors are interpolated as 12 ka and 10 ka. The fault activity can be determined from analysis of growth strata. Active faults are identified either by blind faults (b) indicated by monoclinic folds or by seafloor displacements (sd). Sealed faults may be inactive (i).

Figure 2 shows concomitant 3.5-kHz and multichannel reflection profiles. The 3.5-kHz profile clearly reveals the positions of the most active recent faults within the Whakatane Graben and over the Rurima Ridge. The multichannel profiles image deformation to a depth of 1.5 s TWT (~1.5 km) and enable us to also identify recent faulting on the western edge of Rurima Ridge, where there is a domino-style fault array with fault spacing ranging from 0.2 km–1 km. We anticipate that integrating the 3.5-kHz and multichannel data to determine the extension rate across the back-arc from the faults will allow comparison with measurements of the present extension rates made using GPS data.

In a previous reconnaissance survey, Wright [1990] identified several major and numerous minor active faults between the coast and White Island. The much denser profile coverage of the present study facilitates improved mapping of the faults within the graben, including their segmentation. It enabled the construction of the preliminary map of active faults across the offshore Whakatane Graben shown in Figure 1. The fault map reveals complex fault segmentation and shows that the major active faults within the graben trend 050-060°E. The White Island Fault (WIF) trends 035–040°E, oblique to the graben axis, and is continuous along the length of the survey area. East of the WIF a series of normal faults splay at 005°W to 030°E and intersect with the WIF. This set of faults represents the northward continuation of the North Island Dextral Fault Belt. The style of faulting is consistent with transtension. These transtensional faults do not appear to extend west of the WIF into the active graben.

An interesting feature is a major 4-km right step in the WIF at 37°44′S with corresponding change in orientation of normal faults within the graben. This may represent either a large-scale relay structure between two branches of the WIF or a reactivation of a pre-existing structure. This structure also coincides with the intersection of the northeast-trending normal fault system of the Whakatane graben with the north-trending North Island Dextral Fault Belt.

Potential for Constraining Fault Growth and Linkage

The pseudo three-dimensional seismic data are currently being analyzed, but as an indication of the quality of the data, we show four 3.5-kHz profiles (Figure 3) over the Rangitaiki Fault and associated faults (Figure 1). Two prominent reflectors have been identified by Wright [1990] as the 18 ka and 8.5–9 ka regional erosional surfaces associated with post-glacial rises in sea level, and two further reflectors have been tentatively interpolated as 10 and 12 ka. The 18 ka surface corresponds to the last glacial maximum. Evidence of rupture of the identified layers and measurement of the change in thickness of sedimentary units across the faults enable us to constrain the timing of faulting. Faults that have been active during the deposition of sedimentary units reveal growth thickening of the strata in the hanging wall of the faults (Figure 3). Figure 3 illustrates a fault termination and relay structure along the Rangitaiki Fault. Displacement transfer from segments F1 to F2 is indicated by growth faulting decreasing northward, from line 135 to line 113 along F1, and increasing from F1 to F2 on line 113. Work is proceeding on quantitatively determining how displacement is partitioned, not only along individual faults, but across the entire graben, and how this has changed with time.

Future Work

Physical property measurements have been made at the Southampton Oceanography Centre on cores collected in November 1999. These measurements will allow synthetic seismograms to be produced so the sediment stratigraphy (particularly the interbedded tephra) can be calibrated using both the 3.5–kHz data and the high-resolution seismic reflection profiles that will be acquired in January 2001. Chirp profilers use a high-frequency (swept) source with a predetermined and repeatable source frequency. They typically operate in the range of 1–10 kHz, offer vertical resolution on a decimeter scale in the top 30 m of unconsolidated sediment, and are being increasingly used for a range of applications in the marine environment [e.g., *Bull et al.*, 1998].

Volcanic ash chronology (tephrochronology) and radiocarbon dating will give age control on the imaged reflectors and enable an accurate evaluation of fault growth and displacement to be determined across the Whakatane Graben. An important component of the study is the combination of different acoustic techniques that image fault displacement over a wide range of stratigraphic resolution (0.2 m to > 100 m). The data set will provide previously unavailable constraints on models of fault growth [e.g., *Cowie and Scholtz*, 1992] because the temporal evolution of the faults will be determined.

Acknowledgments

This work is funded by the New Zealand Foundation for Research Science and Technology (FRST-CO1X0038) and the Natural Environment Research Council (GR3/11862), United Kingdom. We are grateful to the officers and crew of R/V *Tangaroa* for their dedication during TAN99-14 and to Ian Wright for advice and access to unpublished data from the Bay of Plenty during survey preparation. Comments from Ian Wright, Keith Lewis, John A. Goff, and an anonymous reviewer helped improve the final manuscript.

Authors

Geoffroy Lamarche, Jonathan M. Bull, Phil M. Barnes, Susanna K. Taylor, and Huw Horgan
For more information, contact Geoffroy Lamarche, NIWA, P.O. 14-901, Kilbirnie, Wellington, New Zealand; E-mail: g.lamarche@ niwa.cri.nz.

References

Beanland, S., K. R. Berryman, and G. H. Blick, Geological investigations of the 1987 Edgecumbe earthquake, New Zealand, *New Zealand J. Geol. Geophys.*, *32*, 73–91, 1989.

Bull, J. M., R. Quinn, and J. K. Dix, Reflection coefficient calculation from marine high resolution seismic reflection (Chirp) data and application to an archaeological case study, *Mar. Geophys. Res.*, *20*, 1–11, 1998.

Cowie, P.A., and C. H. Scholz, Displacement-length scaling relationship for faults: Data synthesis and discussion, *J. Structural Geol.*, *14*, 1149–1156, 1992.

Davey, F.J., S. A. Henrys, and E. Lodolo, Asymmetric rifting in a continental back-arc environment, North Island, New Zealand, *J. Volcanol. Geotherm. Res.*, *68*, 209–238, 1995.

Pillans, B., and I. C. Wright, Late Quaternary tephrostratigraphy from the southern Havre Trough, Bay of Plenty, northern New Zealand, *New Zealand J. Geol. Geophys.*, *35*, 129–143, 1992.

Wright, I. C., Late Quaternary faulting of the offshore Whakatane Graben, Taupo Volcanic Zone, New Zealand, *New Zealand J. Geol. Geophys.*, *33*, 245–256, 1990.