BEHAVIOUR OF RIGID FOUNDATION ON LAYERED SOIL

Data report on tests BG-04 to BG-08.

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CUED/D-SOILS/TR-331

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1.Introduction

In current available methods for the dynamic analysis of SSI problems the 'State of the Art' is to estimate the dynamic impedance functions associated with rigid but massless foundations. Most of these solutions are available for uniform soil deposits which are modelled as homogeneous half space. It is however, very rare to find naturally occurring uniform deposits of homogeneous soils. Layered soil appears in many natural (alluvial, lacustrine and marine deposits), man made hydraulic fills and tailing dams, which have all been very susceptible to liquefaction flow failures in the past (Amini & Qi (2000)). Thus centrifuge tests were planned on layered soil for which numerical solutions are available for a very limited number of stratifications. In reality most of sites consist of inhomogeneous soil whose seismic behaviour under different magnitudes of earthquakes is different from homogeneous sites.

Previous earthquakes such as Kobe (1995), Northridge (1994), and Loma Prieta (1989) have depicted the role of local site conditions in modifying and changing the characteristics of strong motions. Different amount of structural damage has been reported in the same general area depending upon the local site variations. Liquefaction adds further complexity to the problem due to the softening of the soil deposit. The onset of liquefaction alters the ground motion, and can lead to progressive attenuation of the earthquake's high-frequency components transmitted to the ground surface. This phenomenon has been observed in the field (Zeghal & Elgamal, (1994)) and corroborated by many centrifuge tests (Dobry et al. 1994) for homogeneous loose soil. As the surface accelerations can still retain the low frequency components it is debatable whether the attenuation reduces the potential for surface damage to structures? Tokimatsu et al. 1996 concluded that local site effects including those resulting from soil liquefaction were responsible for reducing the damage to superstructures located near coast lines in the Kobe earthquake. In stratified soil these attenuations may not be as significant and localised loose patch may affect the overall dynamic response of the ground.

As regards remediation for such liquefiable sites, the current design practice is to treat the liquefiable soil deposit before a new structure is built upon it. The question of how the treated soil foundation system will respond to the earthquake shaking and how effective the improvement techniques will be in reducing foundation settlement are even more complicated than the evaluation of the untreated soil foundation system. There is a clear need for criteria on how much soil should be treated, both horizontally and in depth in order to achieve significant settlement reduction. Some centrifuge tests (Hausler et al. 2002, Coelho et al.

2003) comment on the possibility that the settlement may not be reduced even if 100% of the entire liquefiable soil is densified.

Thus the understanding of local site effects, especially in the presence of layered soil, on strong ground motion is of particular importance for the mitigation of earthquake disasters as well as future earthquake resistant design. Table 1 presents the general configuration of the centrifuge tests reported in this technical report. The test series consisted of four centrifuge tests on different types of soil stratifications. The data from the benchmark tests performed on homogeneous loose soil are reported in an accompanying technical report TR-330.

Table 1: Test scheme for layered soil

Test identification	Ground stratification	Embedment	Average relative density	Comments
BG-04	Horizontal stratification (dense-loose-dense)	1.5m	Dense 85% Loose 45%	Thickness of loose layer 2.5m
BG-05	Horizontal stratification (dense-loose-dense)	1.5m	Dense 85% Loose 45%	Localised loose patch
BG-07	Vertical stratification (loose-dense-loose)	1.5m	Dense 85% Loose 45%	Localised densification underneath the structure
BG-08	Vertical stratification (loose –dense-loose)	1.5m	Dense 85% Loose 45%	Localised densification underneath the structure for the entire depth of liquefiable soil.

2. Test layout and instrumentation

Figure 1 shows the general arrangement for the centrifuge tests performed on layered ground extending to a depth of 8.5m. As summarised in Table 1, test BG-04 (Figure 1) consisted of a loose layer (R_D 45%) having a thickness of 2.5m deposited uniformly between dense layers having a R_D of 85%. This corresponds to a field situation where the depth of the liquefiable layer is estimated to be more than 10m and remediation is desired, or where the ground is naturally inhomogeneous and layered. Test BG-05 (Figure 2) had a localised loose layer exactly at the same location as BG-04 but limited in its lateral extent. The lateral extent of the localised patch was limited to B (3m) on either side from the centreline where B is the breadth of the raft. The superstructure consisted of a very rigid structure having a low natural time period.

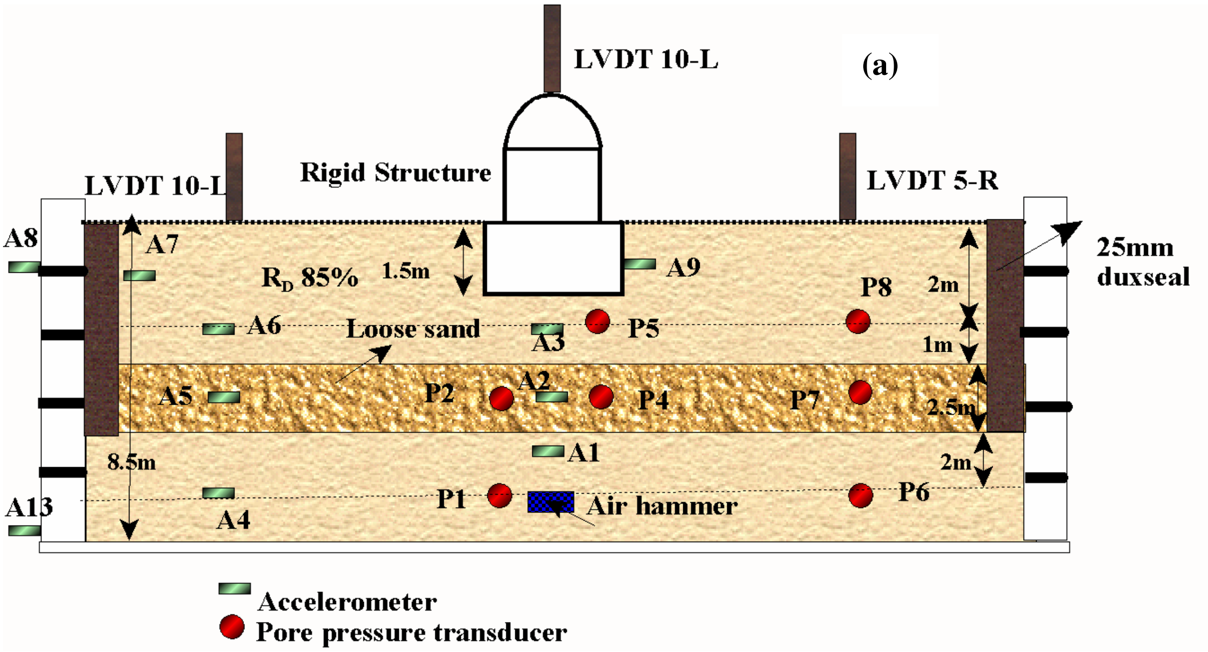


Figure 1: Instrumentation and test layout for BG-04 in prototype scale.

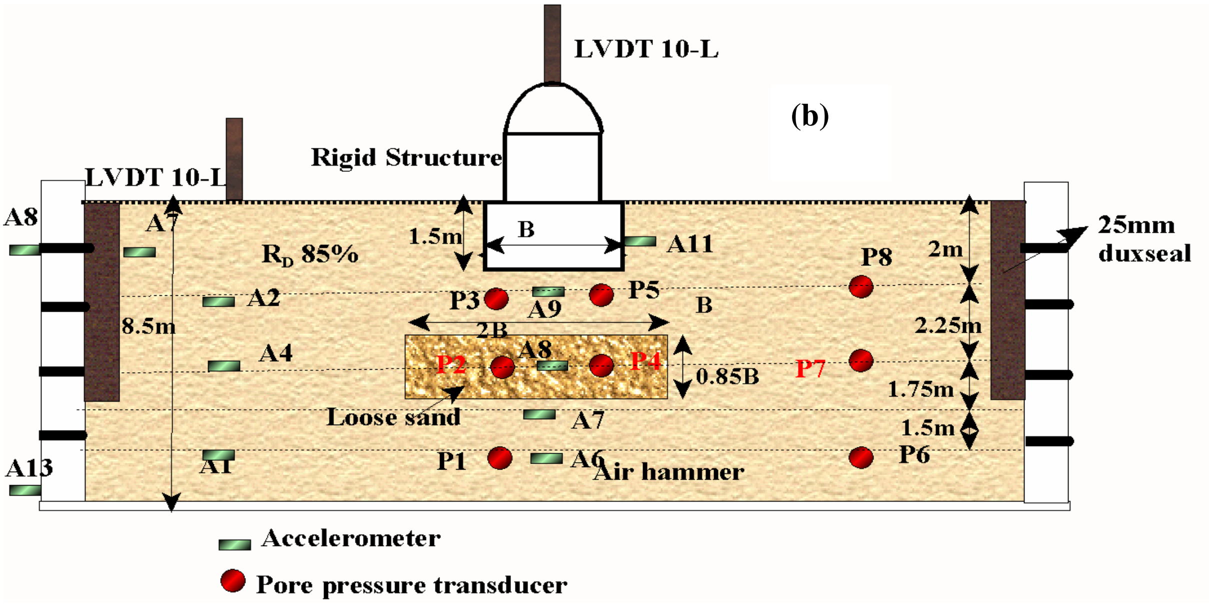


Figure 2: Instrumentation and test layout for BG-05 in prototype scale.

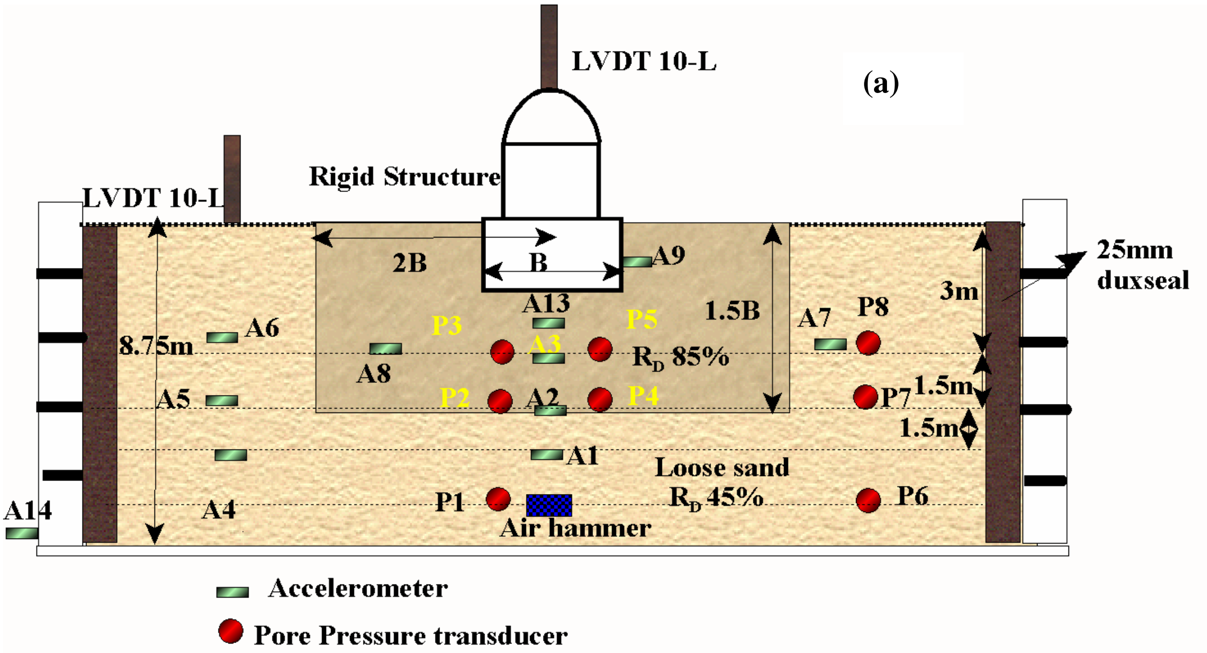


Figure 3: Instrumentation and test layout for BG-07 in prototype scale.

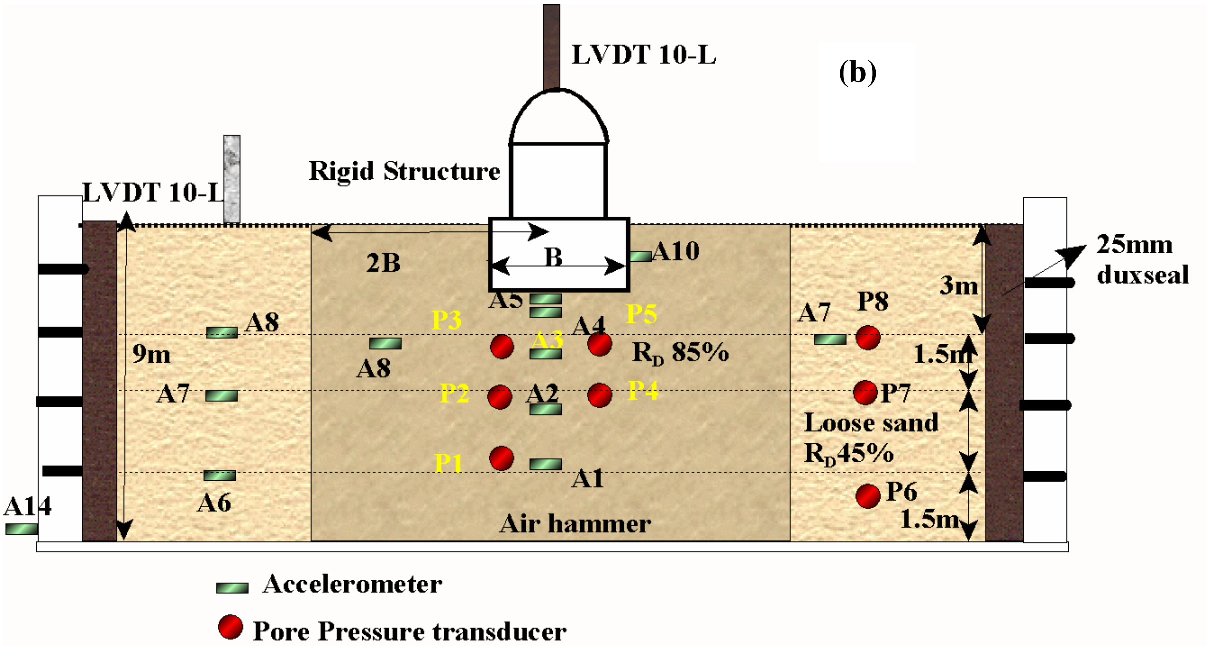


Figure 4: Instrumentation and test layout for BG-08 in prototype scale.

Figure 3 & 4 presents the test configurations for BG-07 and BG-08. In these tests the effects of localised densification under the high overburden stresses imparted by the rigid foundation was investigated. The importance of correctly identifying the geometry to be densified is the key area of interest in this test series. The objective of this series of tests is to investigate whether SSI is significantly altered by the presence the densified patches under the foundation in liquefiable soils. In BG-07 the vertical depth of localised densification extends upto 1.5 times the width of the embedded base, as seen in Figure 3. The lateral extent of densification ranged up to 2B on either side of the foundation. The test results from this series were compared to the results obtained from test BG-08 where the entire depth of the liquefiable layer was densified as is common practice in most remediation measures.

3. Test Procedure

When the model is ready for testing the SAM actuator and the counterweight were loaded onto the centrifuge arm. The ESB box is loaded separately to cause minimum disturbance to the model. The model structure was then placed at appropriate location. Pre flight checks include checking the accumulator pressure for firing the earthquake, and the thickness of the counterweights.

Once both swings have swung up the centrifuge is accelerated in steps of 10g up to the required speed. A series of earthquakes was fired at 50g for each model. Each shaking event was followed by a stationary period to allow for dissipation of the developed excess pore pressures. The sequence of earthquakes fired generally followed the pattern shown in Table 2

.

Table 2: Typical earthquake sequence

Earthquake Id.	Model scale			Prototype scale		
	Frequency	Duration (s)	Typical peak input motion	Frequency (Hz)	Duration (s)	Typical peak input motion
1	30Hz	0.5	3.7g	0.6	25s	0.074g
2	40Hz	0.5	3.765g	0.8	25s	0.0753g
3	50Hz	0.5	5.295g	1	25s	0.1059g
4	Variable frequency	1.4-2	4.71g	Variable frequency	70-100s	0.0942g
5	50Hz	0.5	7.3g	1	25s	0.17g

4. Instrumentation

Instrumentation in these tests consisted of accelerometers and pore pressure transducers, pressure transducers and LVDT's suitably located to characterise soil responses during shaking. The soil used for these tests were highly liquefiable fraction E silica sand whose properties have been reported widely (Tan 1990). The instrument location was generally kept similar in all the tests so that the results could be compared easily. Table 3 presents a typical instrument location for test BG-07. The dimensions are presented in prototype scale.

Table 3: Instrument Identification

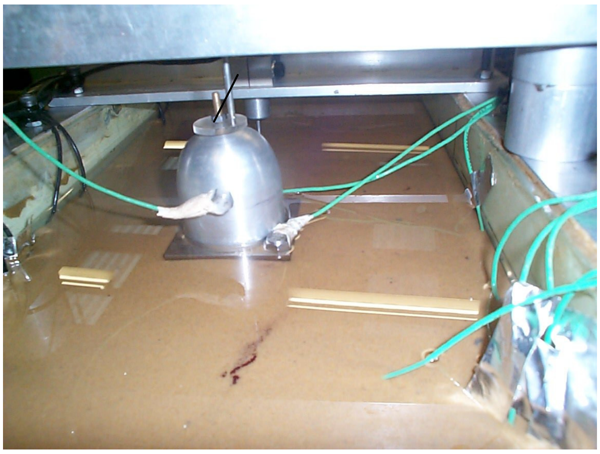
Instrument Identification	X (Along the length of ESB) (m)	Y (Along the width of the ESB box) (m)	Z (Height from the top of the soil surface) (m)
A1	14	5.8	6
A2	14	5.8	4.5
A3	14	5.8	3
A4	4	5.8	6
A5	4	5.8	4.5
A6	4	5.8	3
A7	23.5	5.8	3
A8	9.5	5.8	3
A9	On the structure		
A10	Mid height in structure		
A11	In the box		
A12	14	5.8	2
P1	12.5	5.7	7.5
P2	12.5	5.65	4.5
P3	12.5	5.7	3
P4	15.5	5.875	4.5
P5	15.5	5.875	3
P6	22.5	5.875	7.5
P7	22.5	5.8	4.5
P8	22.5	5.8	3

5. Results

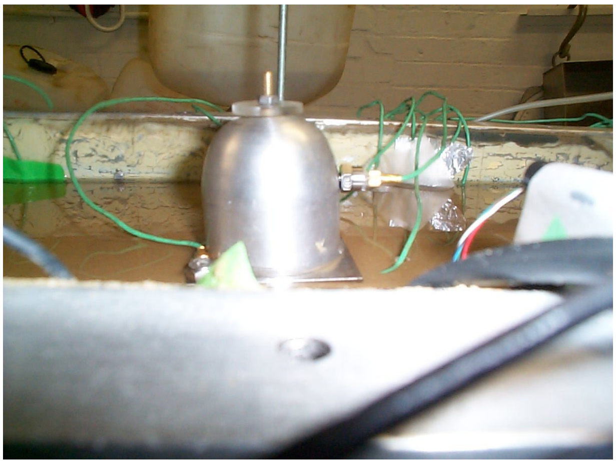
Time histories of the acceleration and the pore pressure for the centrifuge tests are shown in Figure 6 to 53. All the results are in model scale. This implies that the values of acceleration will be 50 times smaller in prototype scale following scaling laws. Figure 5 presents the post test visual observation after the tests have been performed. A brief outline of the results will be discussed here, further discussions can be found in Ghosh (2003).

BG-04 Approximate tilt angle 5°

BG-05, approximate tilt angle 6°



BG-07 Approximate tilt about 4°



BG-08, virtually no tilt

Figure 5: Post test observations in test BG-04, BG-05, BG-07 and BG-08.

5.1 Test BG-04

The results are plotted in Figure 6 to 20. Earthquakes were fired at different frequencies and magnitudes. At low frequency and strength of the earthquake, most of the base acceleration is transferred to the base of the rigid raft foundation without significant softening of the subsoil.

At higher strength earthquake, the sandwiched loose layer had liquefied as evident from the excess pore pressure measurement in the free field and had reduced the accelerations transmitted to the base of the raft foundation.

5.2 Test BG-05

The test results from this test are plotted in Figure 21 to 29.The pore pressure measurements underneath the raft foundation for higher magnitude earthquake shows the existence of a dilative zone underneath the raft foundation. The existence of the localised loose patch surprisingly leads to higher accelerations measured at the base of the raft foundation. This can be attributed to increased modes of vibration due to the presence of the soft patch.

5.3 Test BG-07

The results of this test are presented in Figure 30 to 41. A series of earthquakes were fired and it was seen that the acceleration recorded at the base of the structure was attenuated after a few cycles. This can be attributed to the effects of the isolation properties of the trapped liquefiable layer, which reduce the base accelerations.

5.4 Test BG-08

The test results from this series of test are plotted in Figure 42 to 53. The densified zone underneath the raft foundation retains its shear stiffness and strength throughout the sequence of earthquake and transmits higher accelerations to the base of the raft foundation. The overall settlement of the foundation is slightly lower in this case, than the case where the densified zone extended to 1.5 times the width of the raft foundation.

6. Conclusions

The test results indicate the profound influence of the soil layering in modifying the response of the structure and influencing the soil structure interaction in different ways. The excess pore pressures measured underneath the structure never reach the free field values. This is due to the presence of a static shear underneath the foundation which leads to the creation of a dilation zone underneath the foundation which inhibits the rise of excess pore pressures to the free field values.

7. Acknowledgements

I would like to acknowledge the help that I received from the technicians at the Schofield Centre in performing these tests. The advice from Dr. Stuart Haigh and Dr. Andrew Brennan is gratefully acknowledged.

8. References

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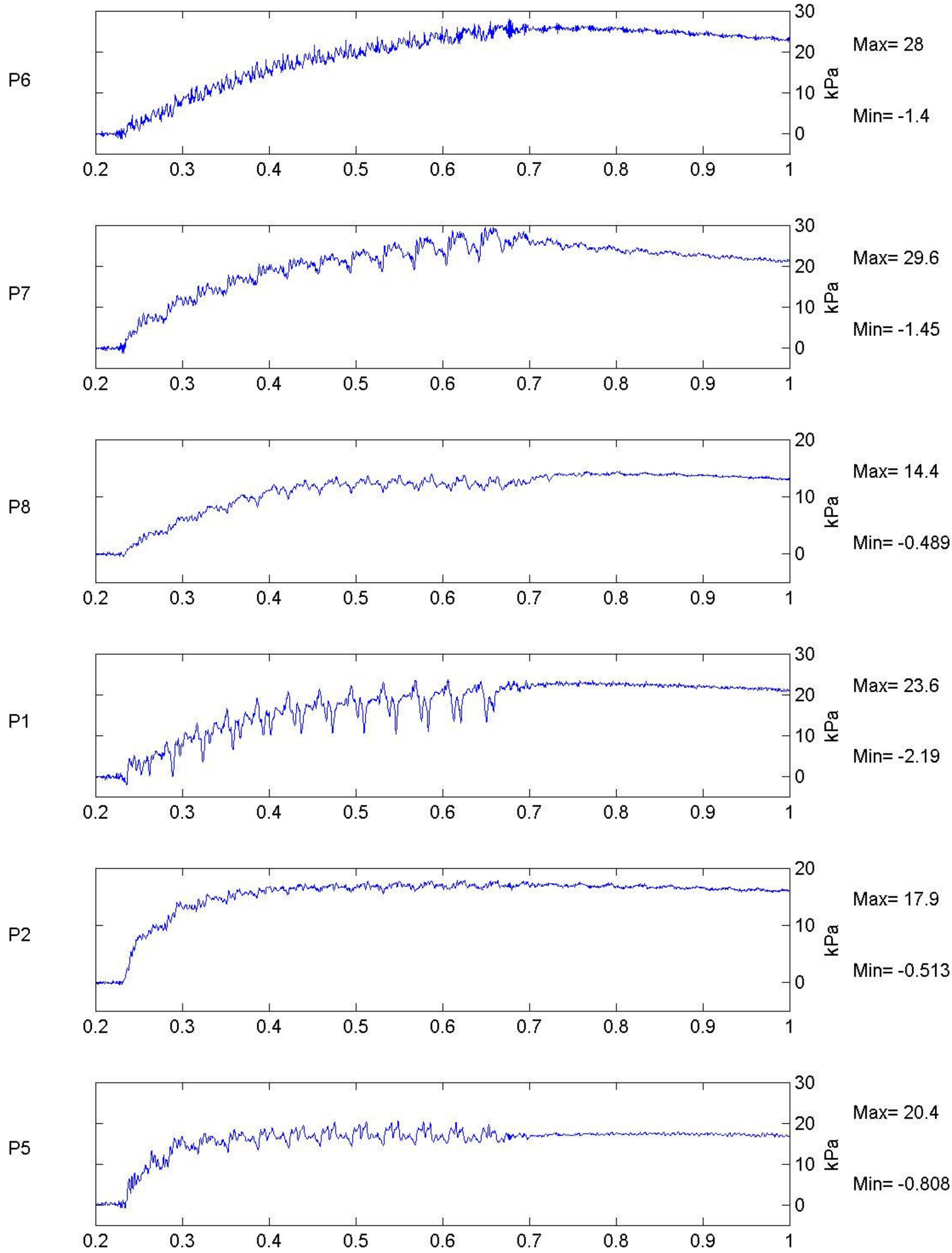
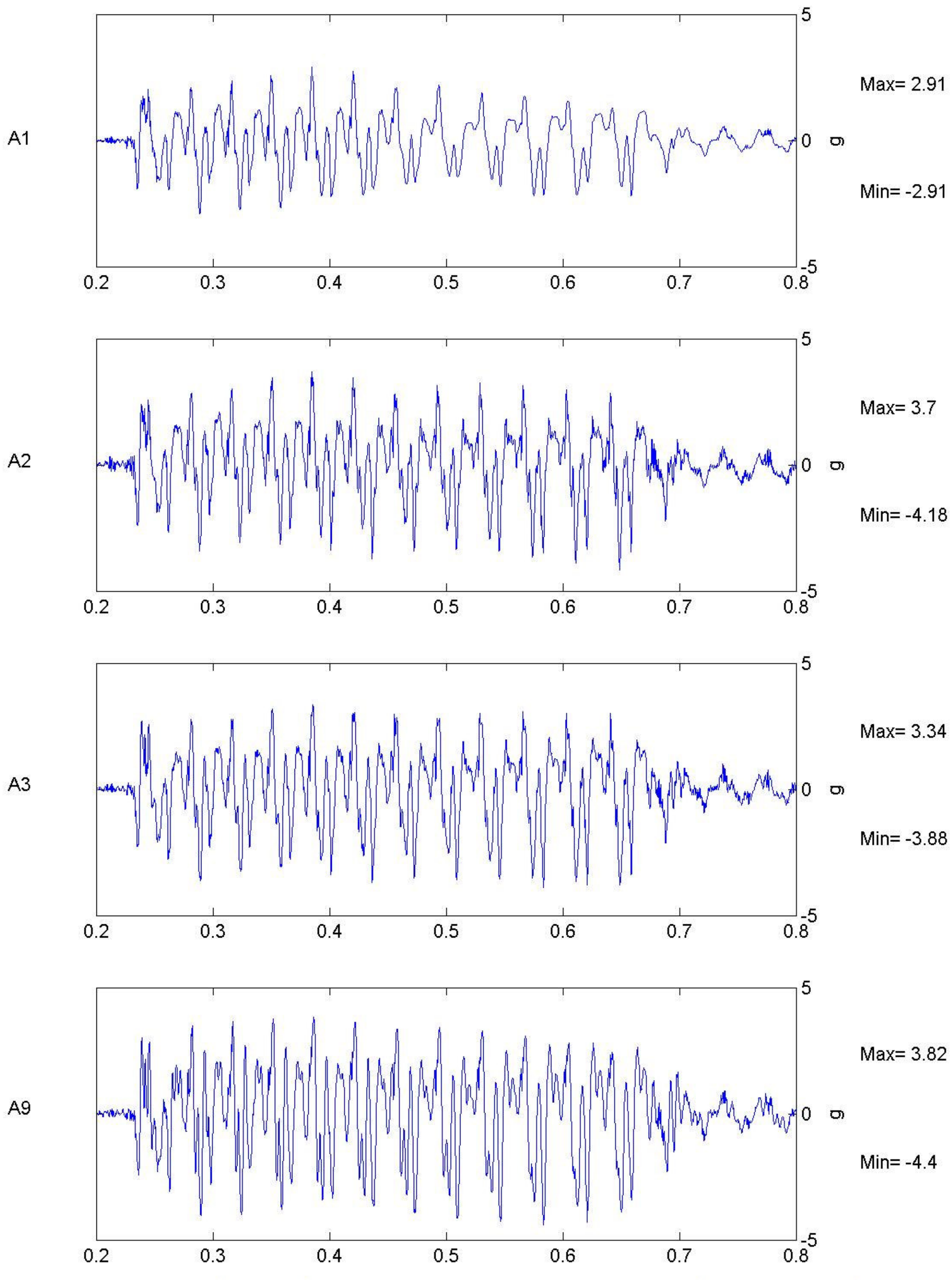


TEST BG-04	FREQ 30Hz	Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	1	6



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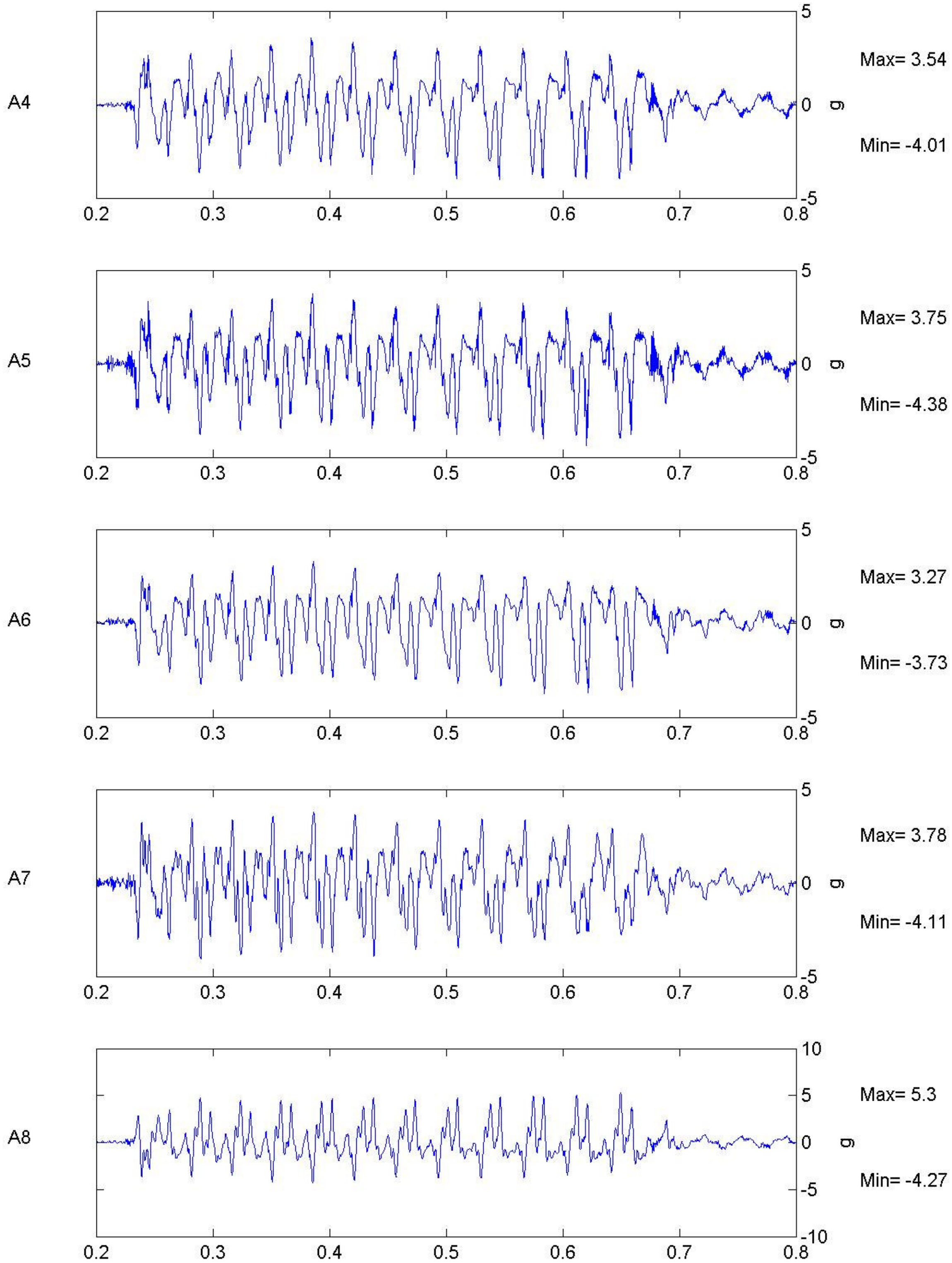
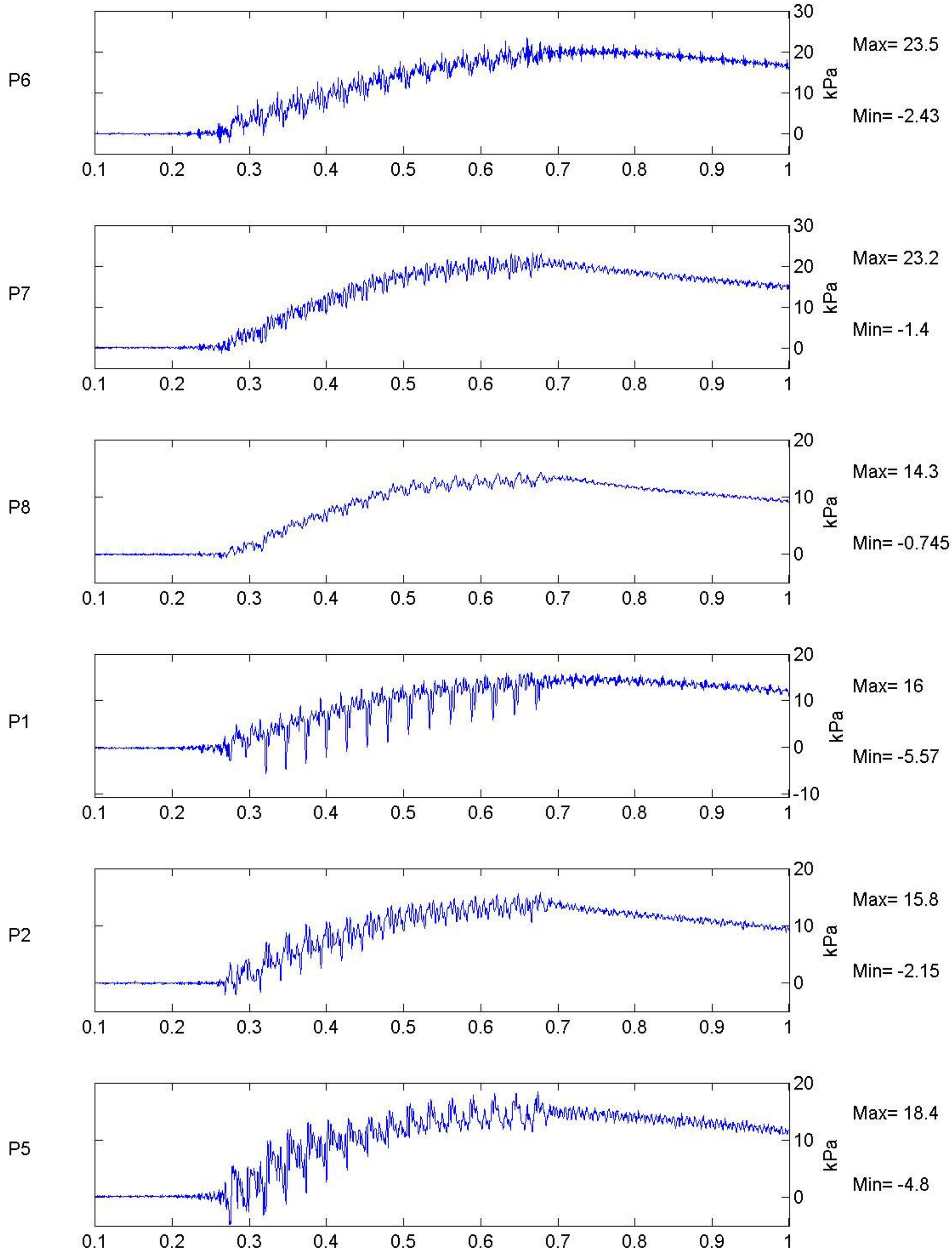
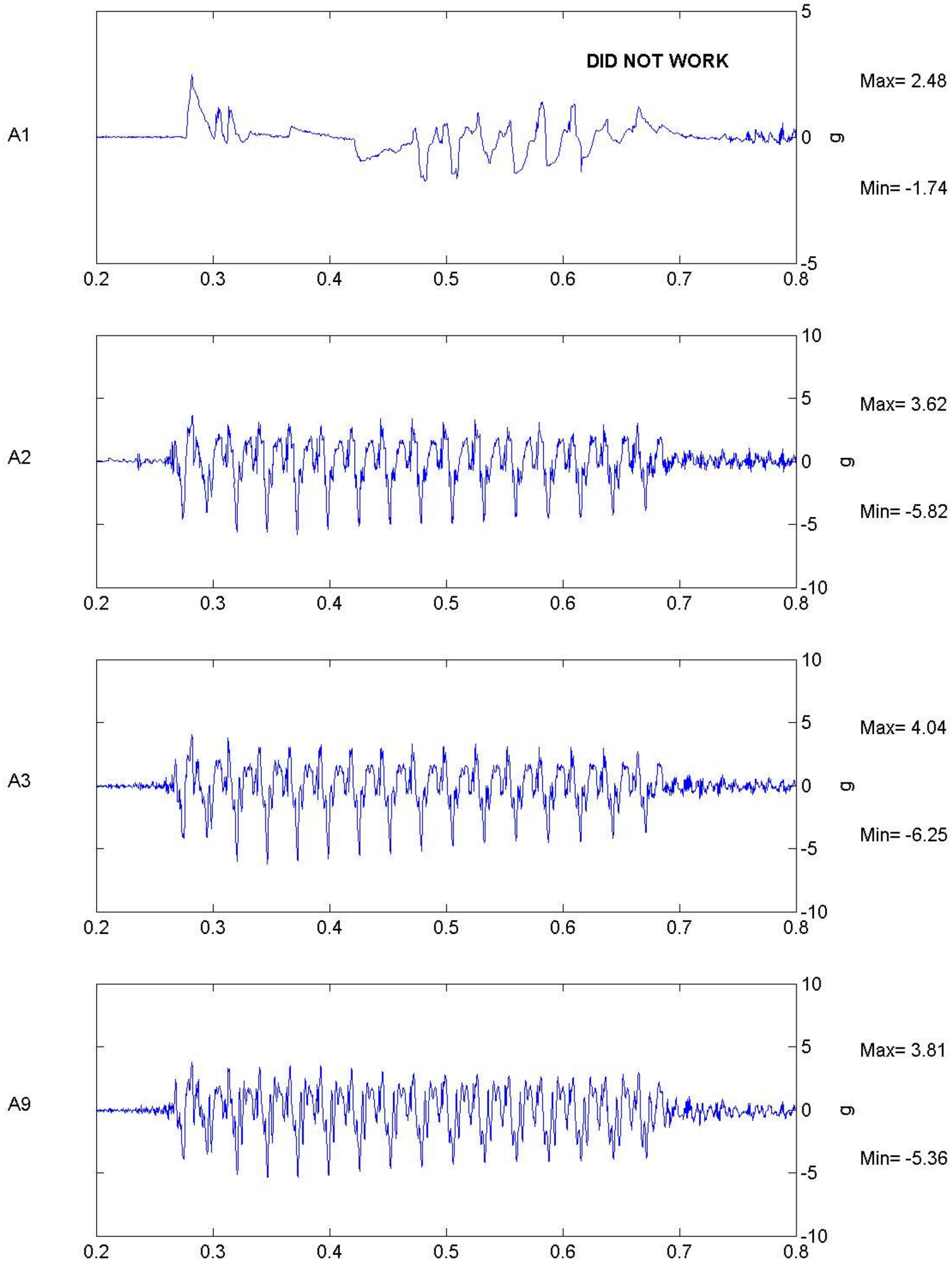
FLIGHT 1		Short-Term Time Records	1	7



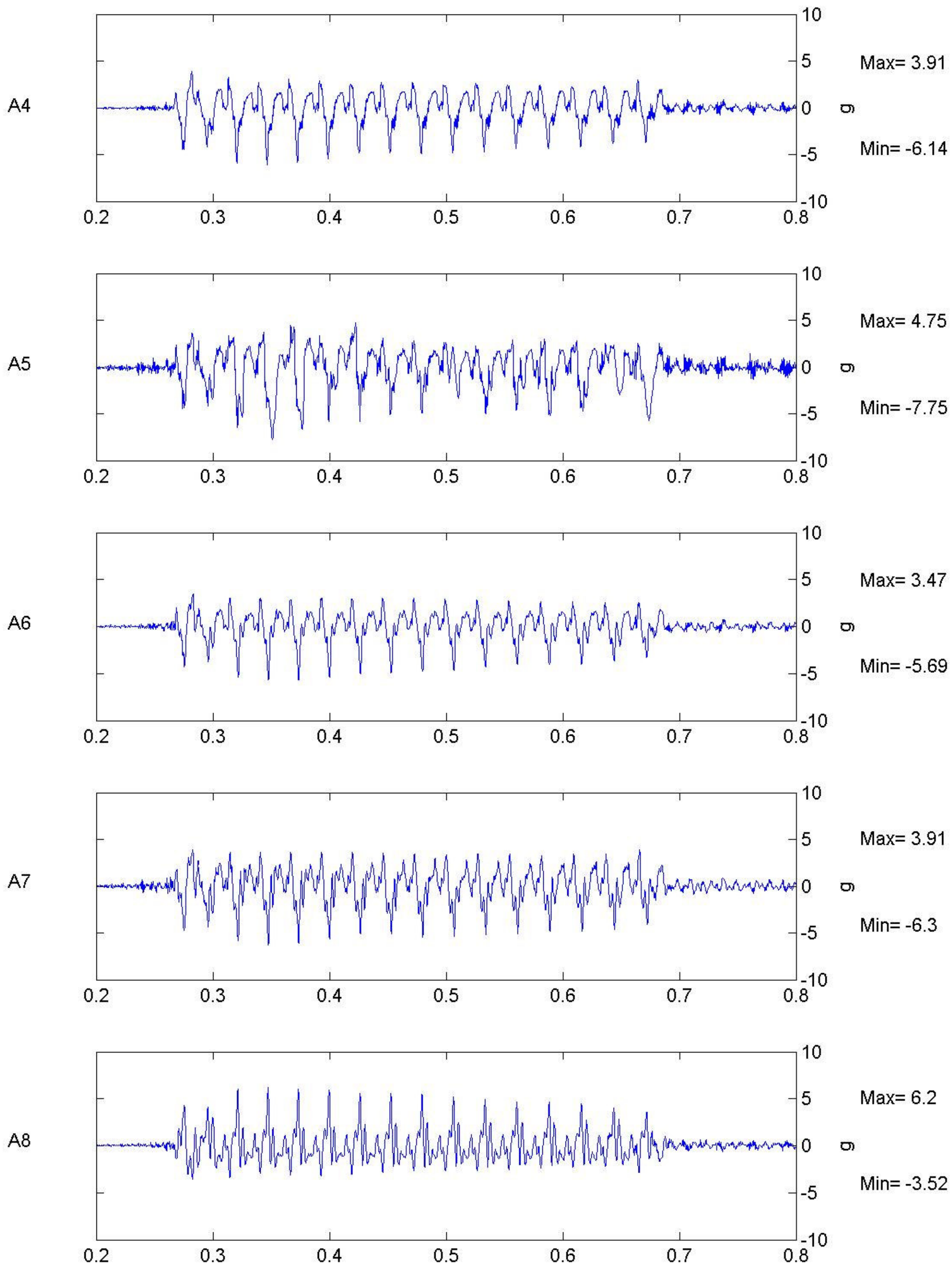
TEST BG-04 FLIGHT 1	FREQ 30 Hz	Scales: Model 8th order Butterworth Filter at 1000Hz Short-Term Time Records	Earthquake 1	Figure No. 8



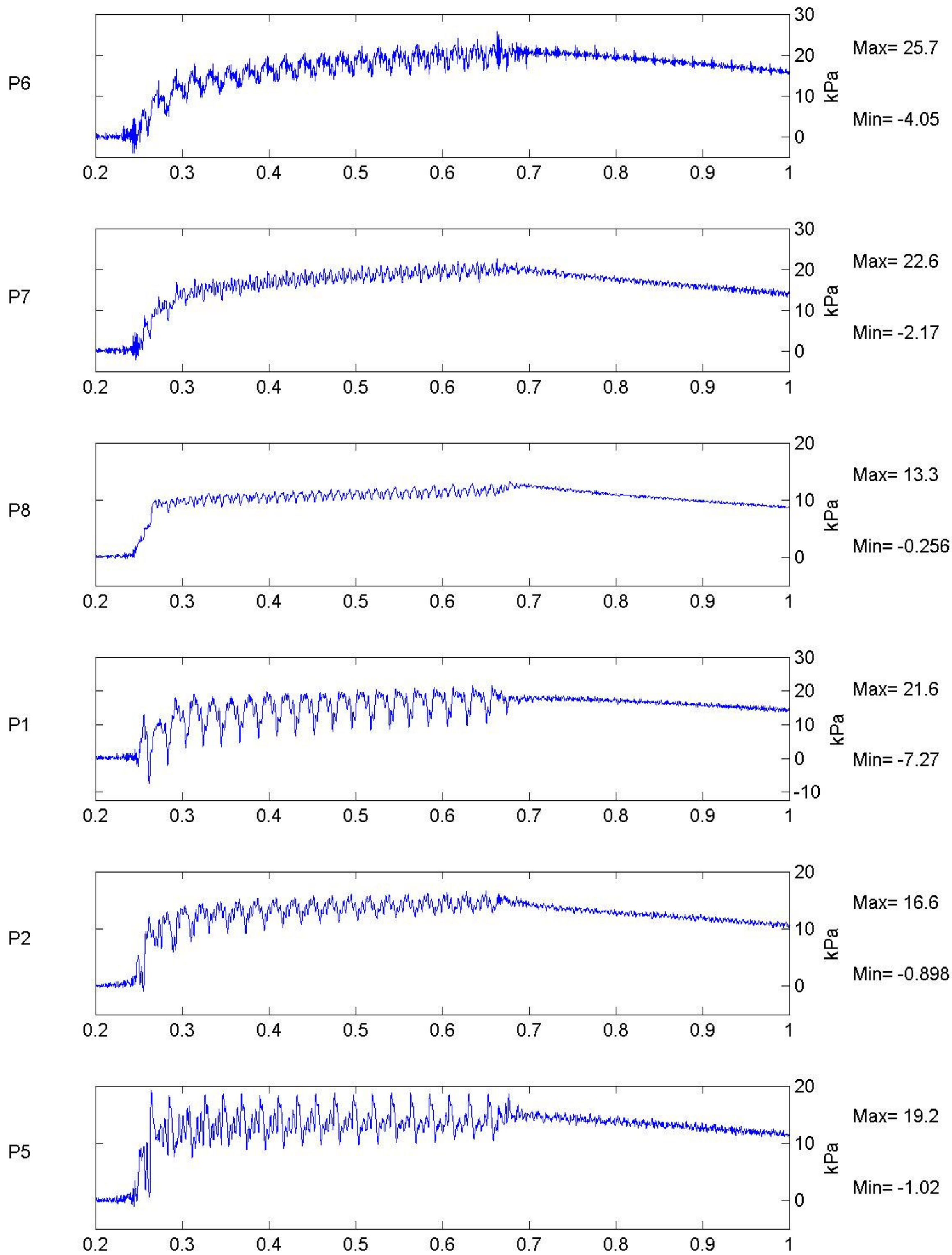
TEST BG-04 FLIGHT 1	FREQ 40 Hz	Scales: Model Unfiltered Data Short-Term Time Records	Earthquake 2	Figure No. 9



TEST BG-04 FLIGHT 1	**FREQ** **40 Hz**	Scales: Model Unfiltered Data Short-Term Time Records	Earthquake 2	Figure No. 10



TEST BG-04 FLIGHT 1	**FREQ** **40 Hz**	Scales: Model 8th order Butterworth Filter at 1000Hz Short-Term Time Records	Earthquake 2	Figure No. 11



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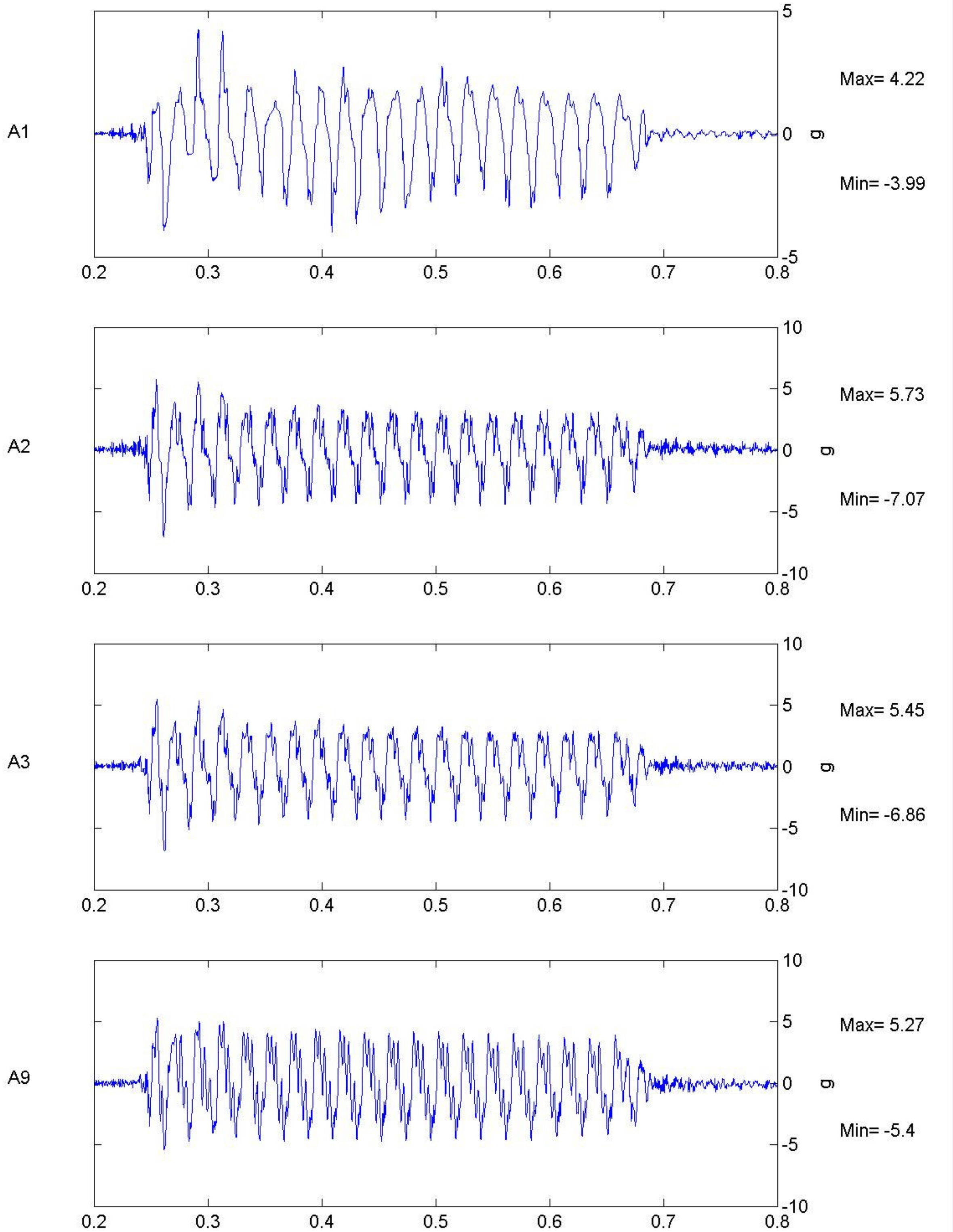
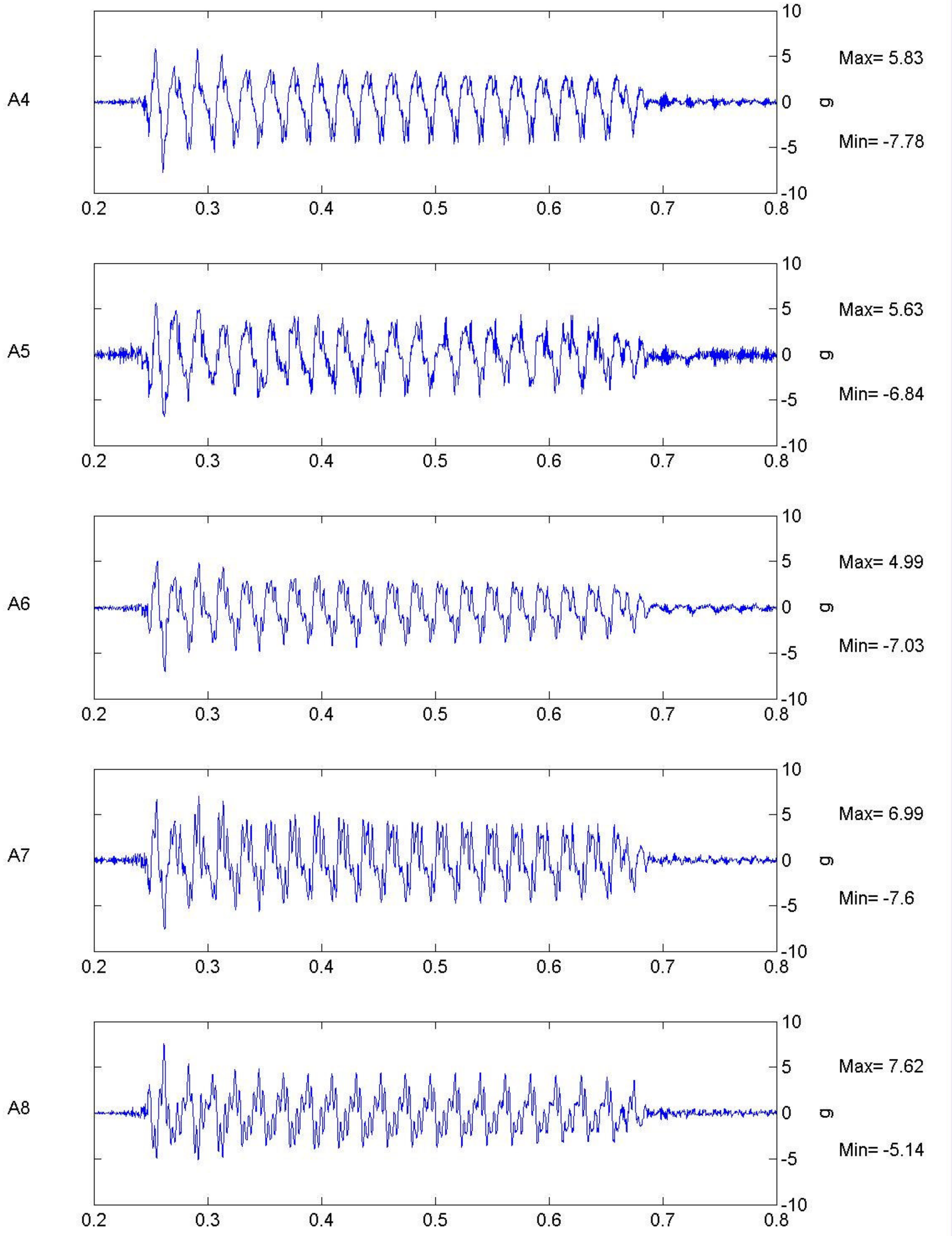
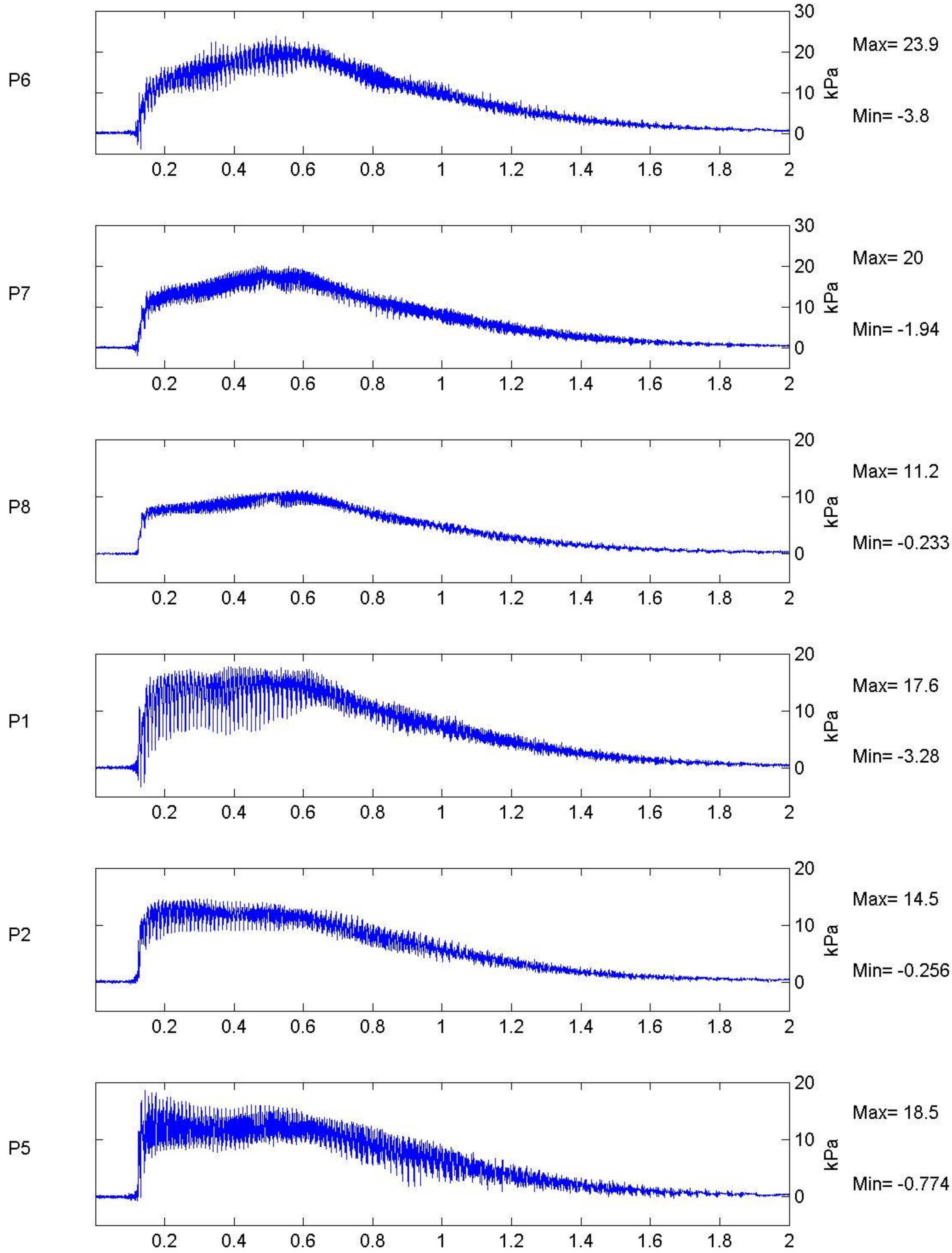


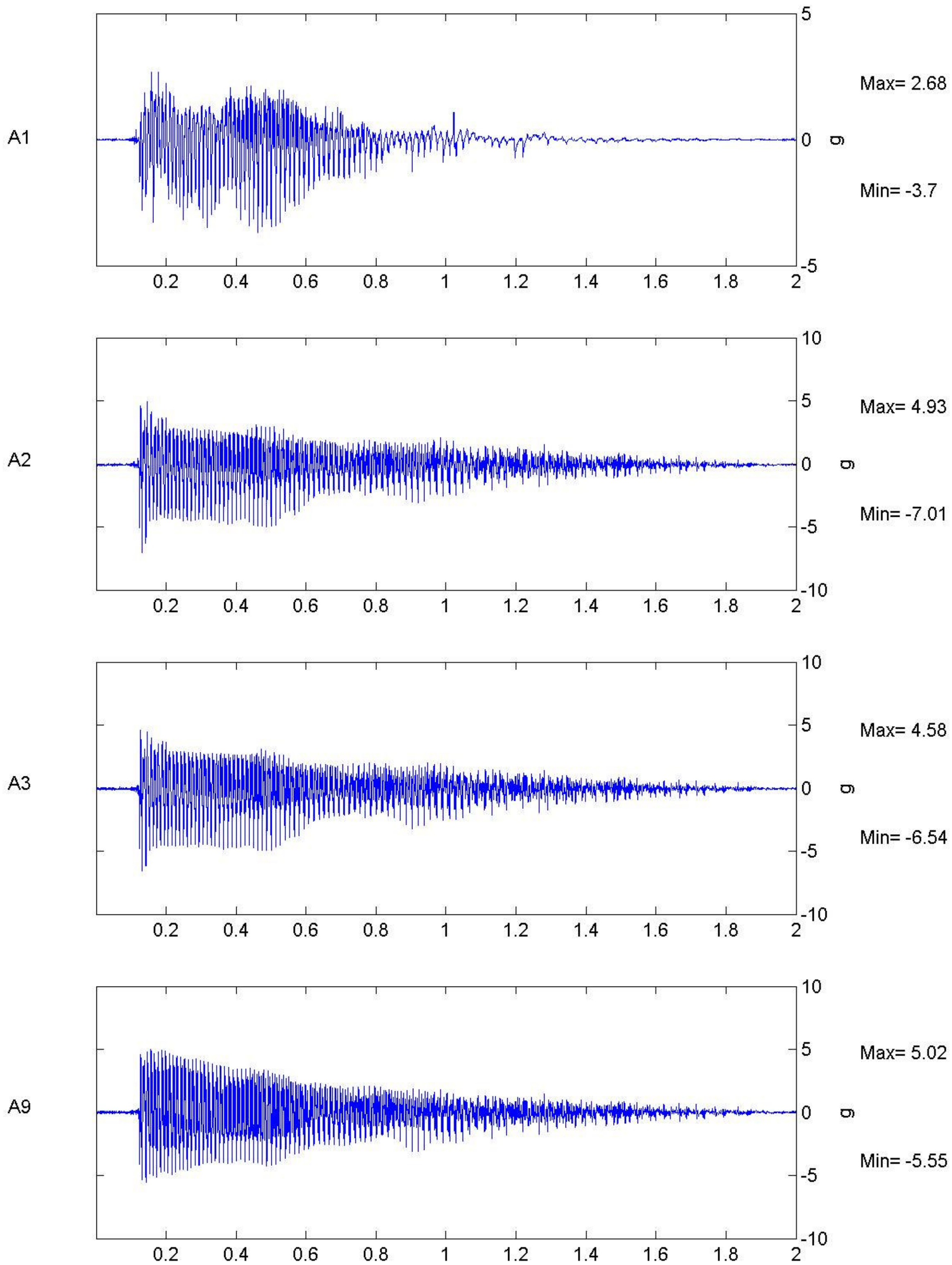
TEST BG-04 FLIGHT 1	**FREQ** **50 Hz**	Scales: Model 8th order Butterworth Filter at 1000Hz Short-Term Time Records	Earthquake 3	Figure No. 13



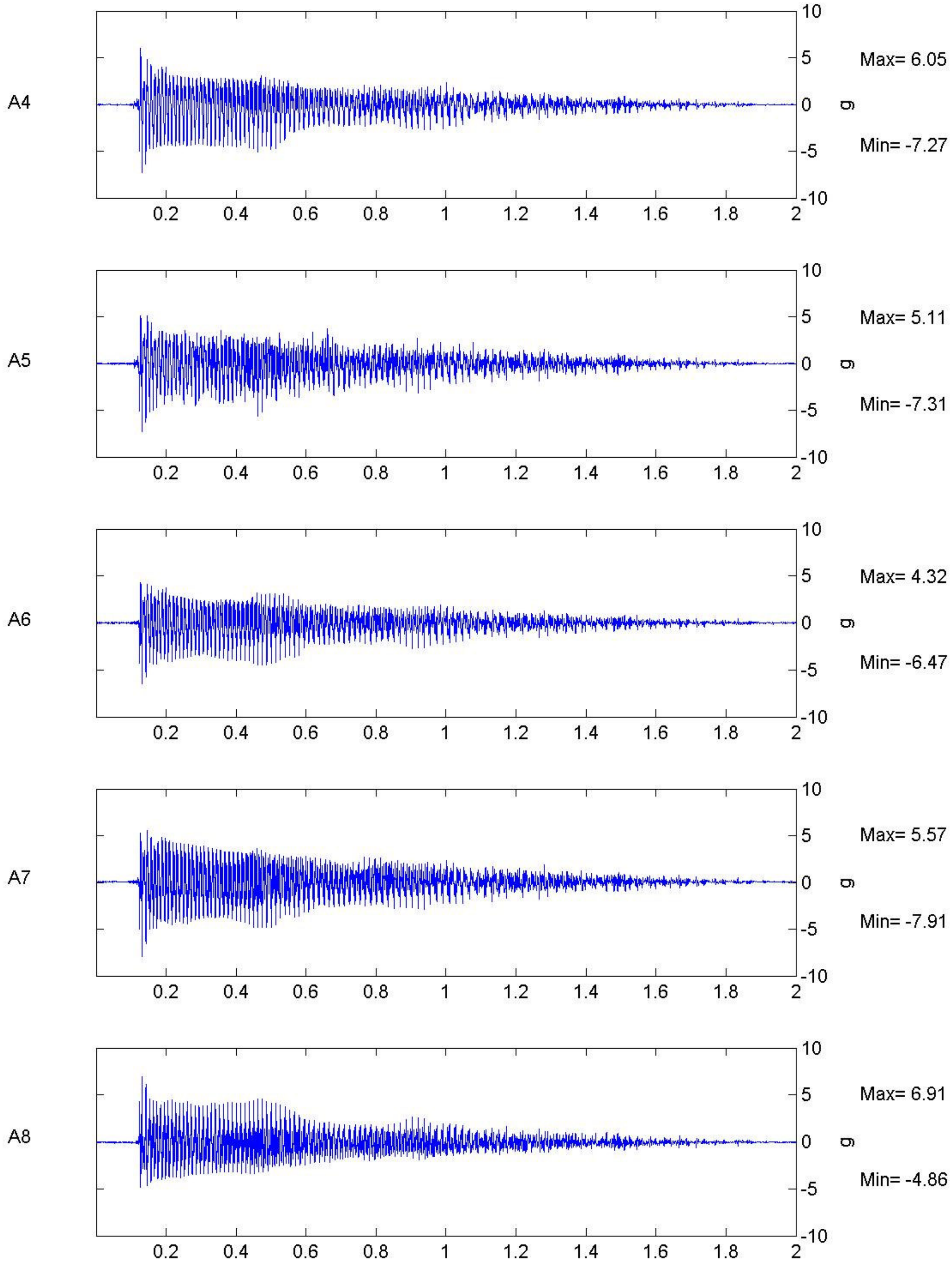
TEST BG-04 FLIGHT 1	**FREQ** **50Hz**	Scales: Model 8th order Butterworth Filter at 1000Hz Short-Term Time Records	Earthquake 3	Figure No. 14



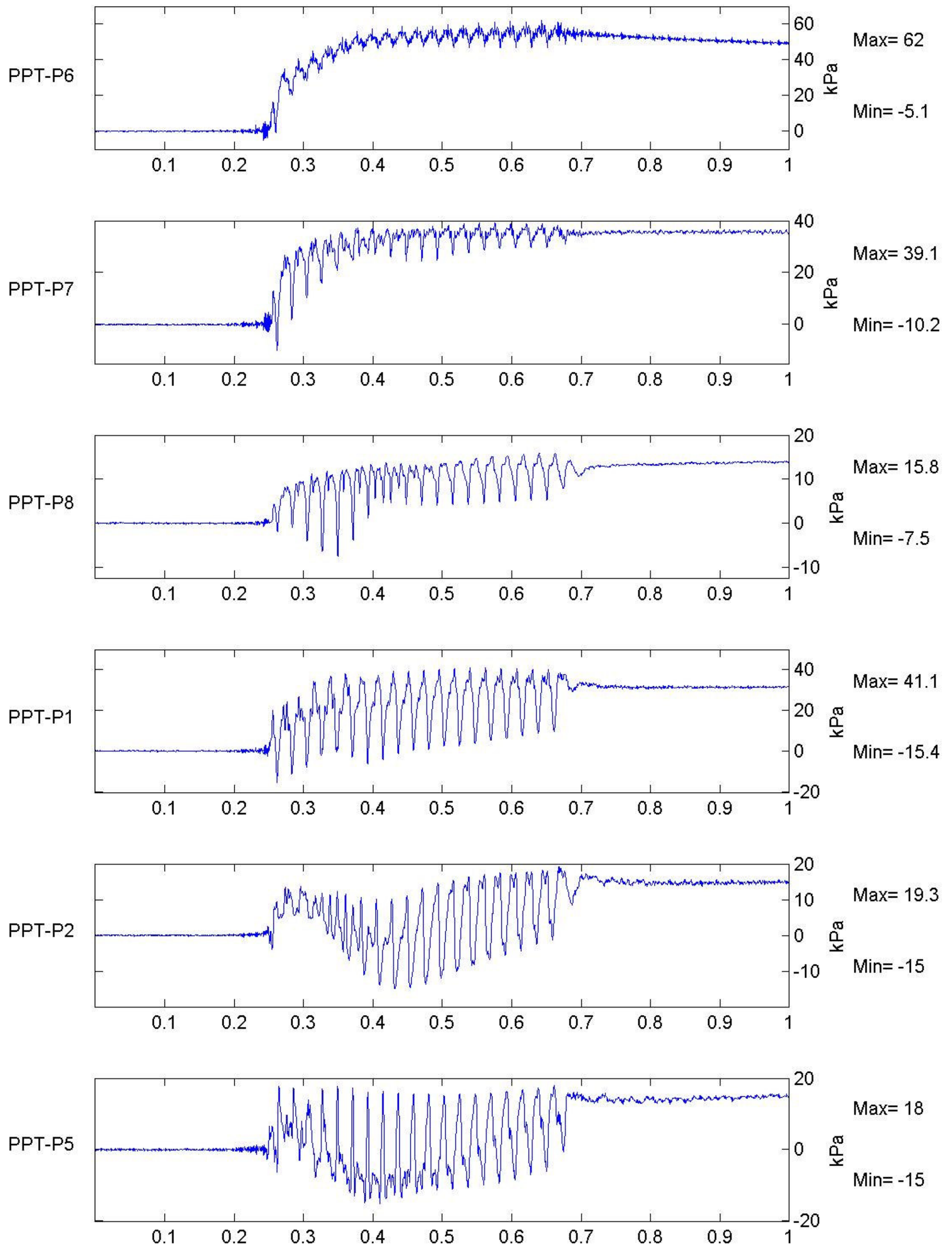
TEST BG-04 FLIGHT 1	SWEPT SINE WAVE	Scales: Model Unfiltered Data Short-Term Time Records	Earthquake 4	Figure No. 15



TEST BG-04 FLIGHT 1	SWEPT SINE WAVE	Scales: Model 8th order Butterworth Filter at 1000Hz Short-Term Time Records	Earthquake 4	Figure No. 16



TEST BG-04 FLIGHT 1	SWEPT SINE WAVE	Scales: Model 8th order Butterworth Filter at 1000Hz Short-Term Time Records	Earthquake 4	Figure No. 17



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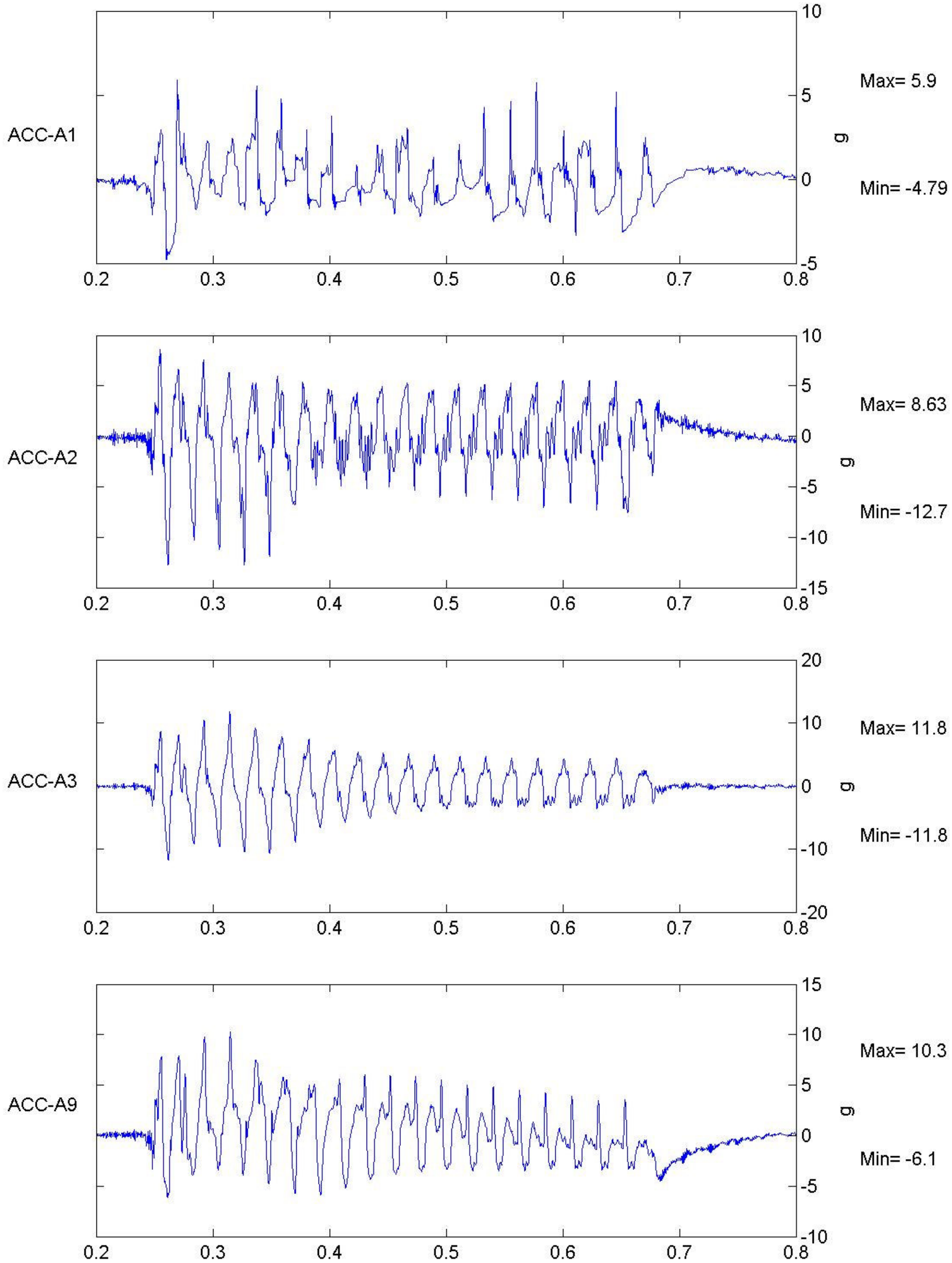
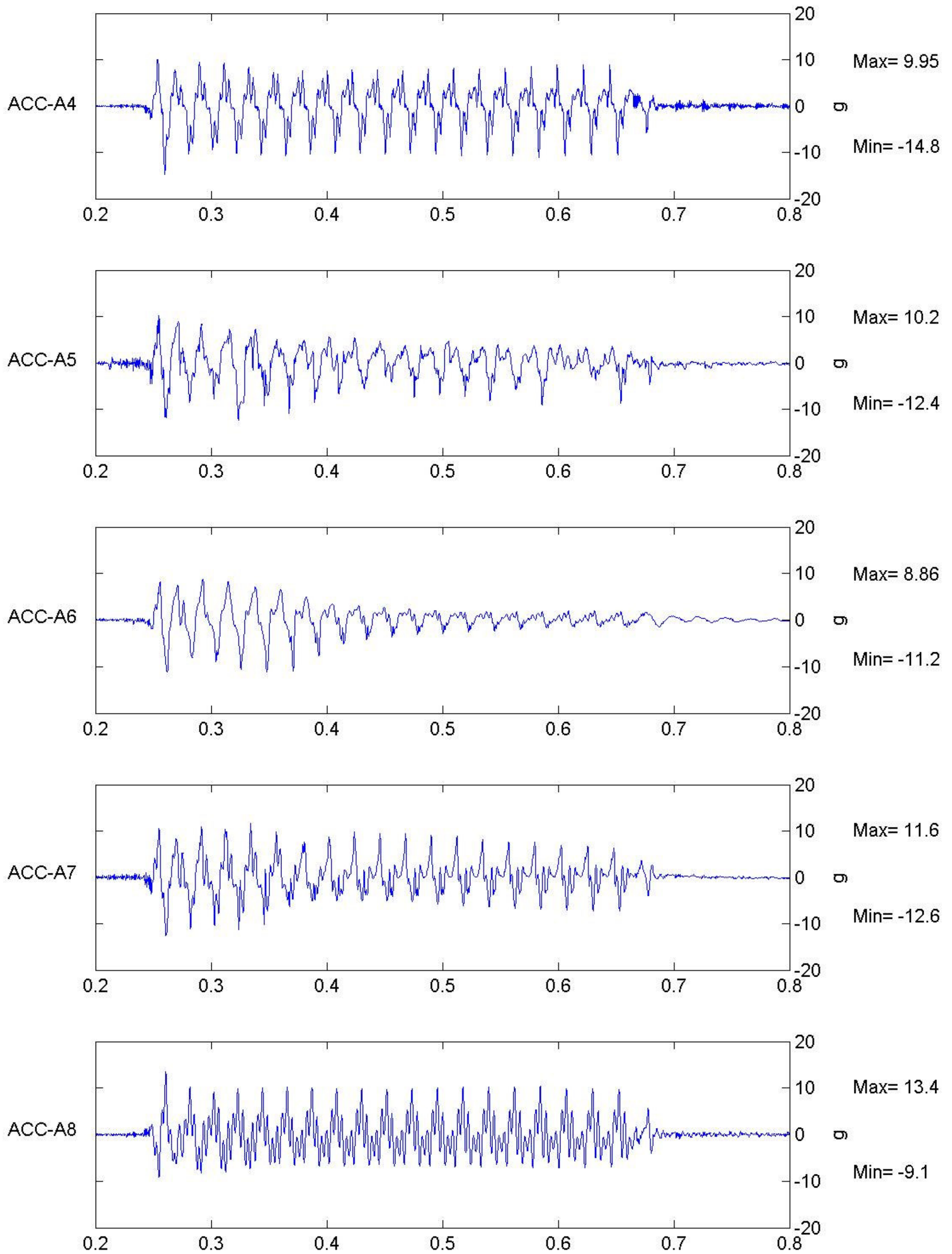


TEST BG-04	**FREQ 50 Hz**	Scales: Model 8th order Butterworth Filter at 1000Hz	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	5	19



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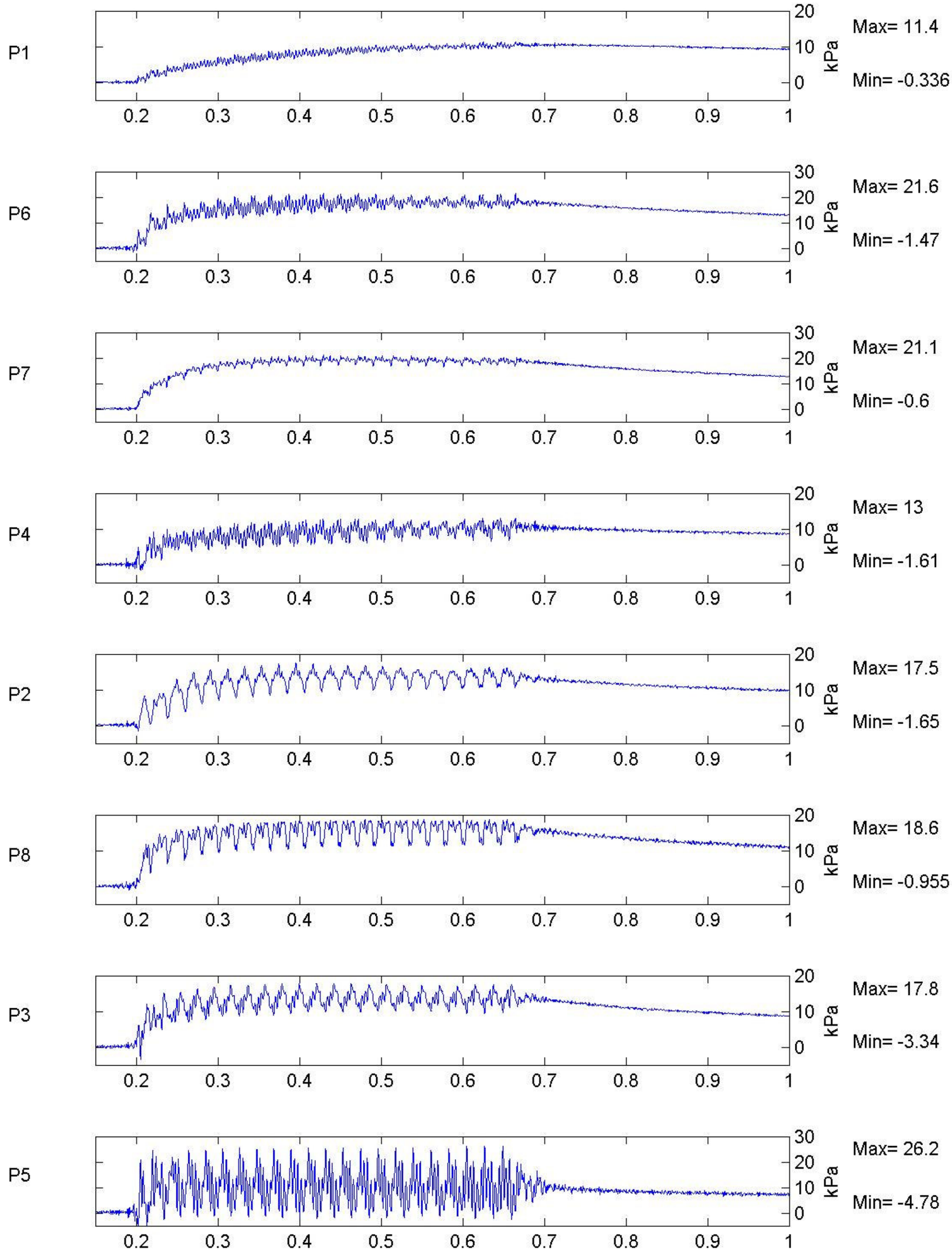
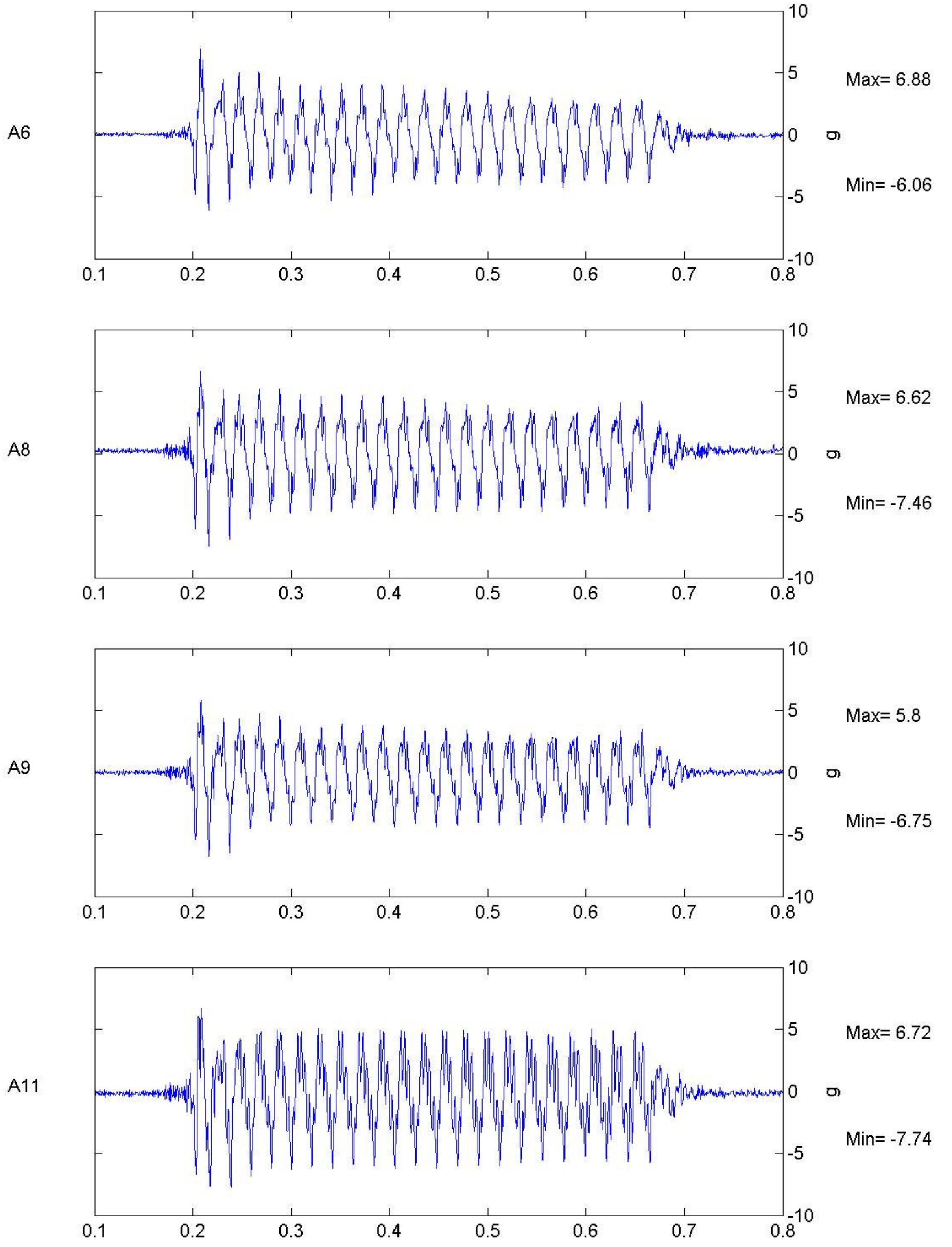


TEST BG-05 FLIGHT 1	**FREQ** **50 Hz**	Scales: Model Unfiltered Data Short-Term Time Records	Earthquake 1	Figure No. 21



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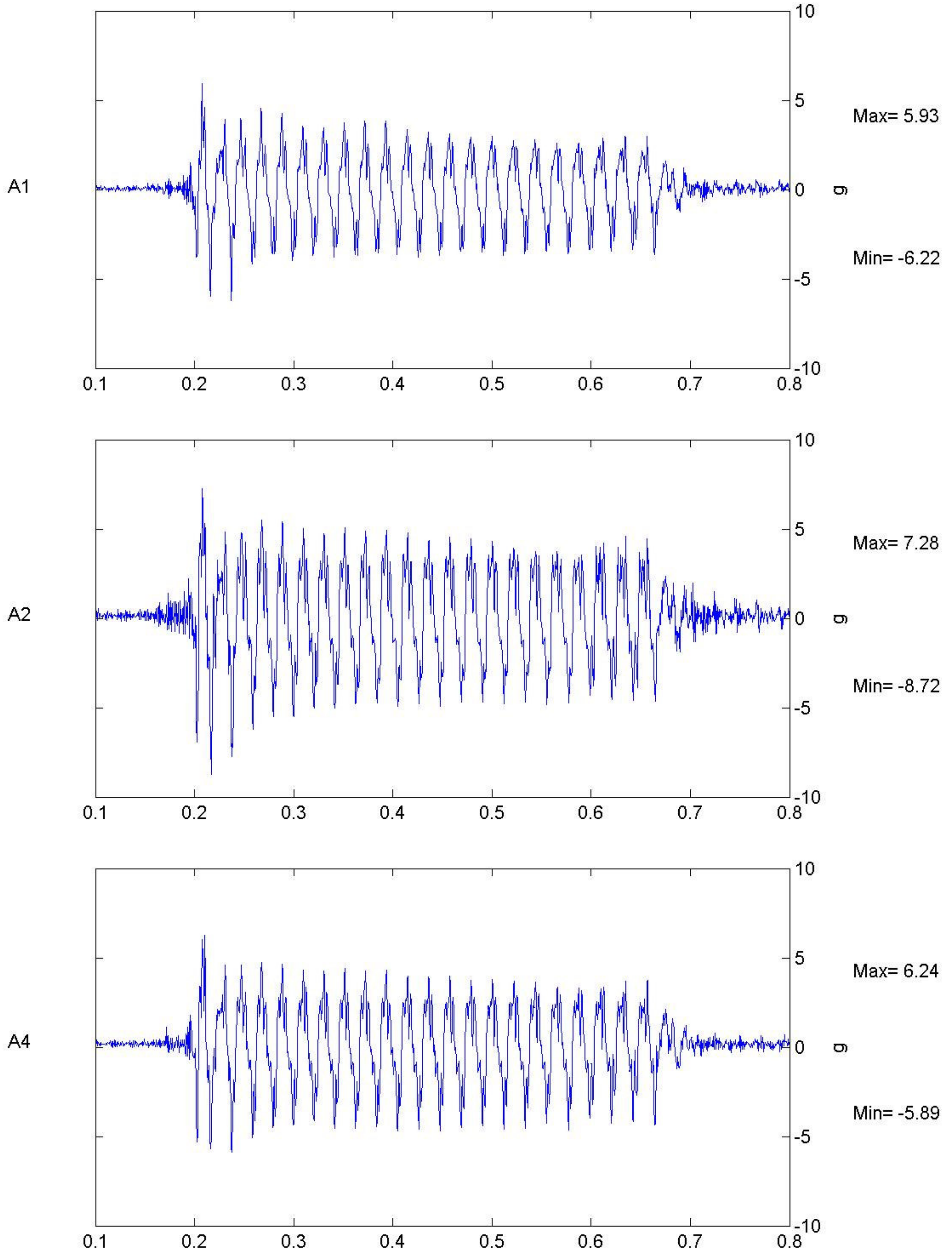
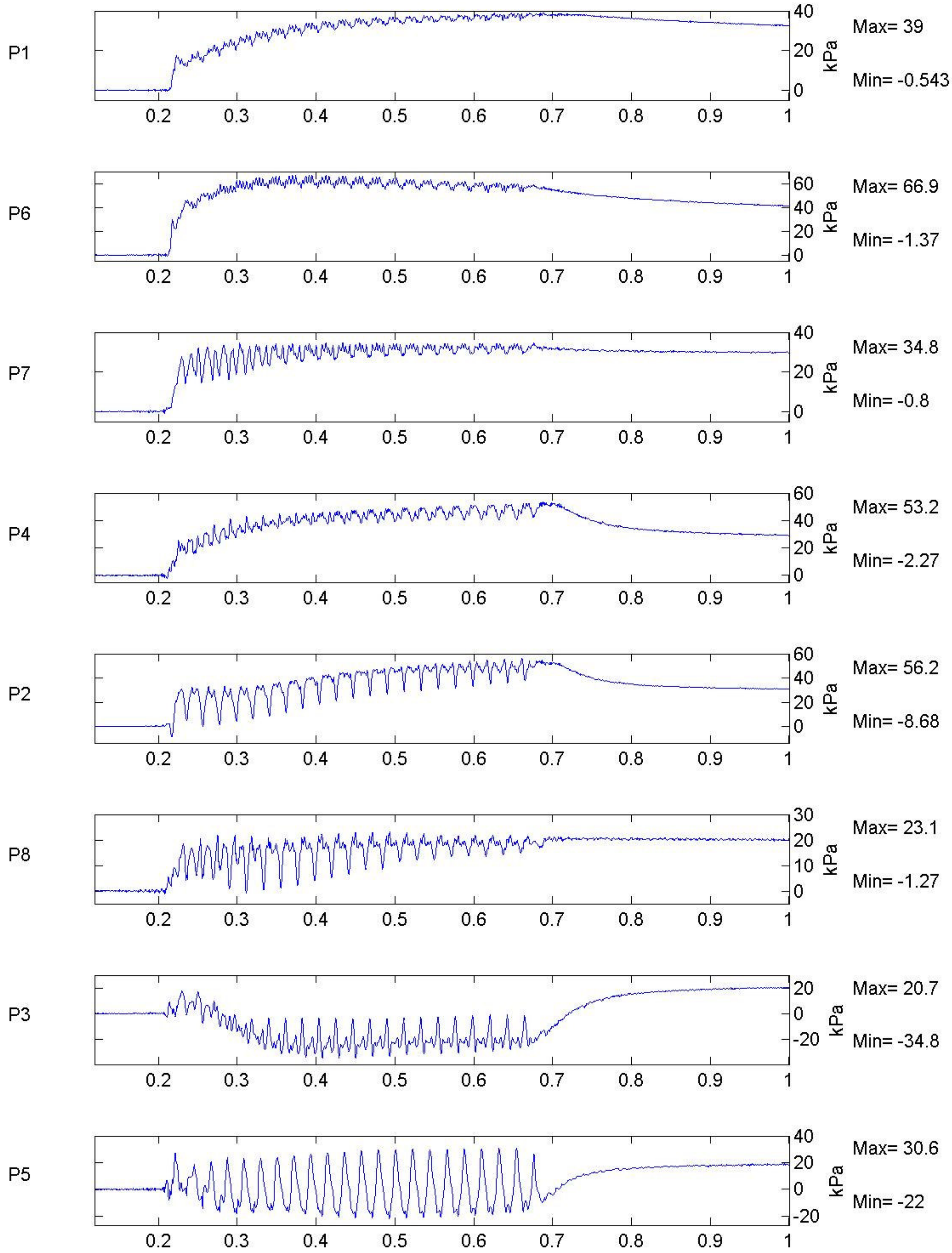
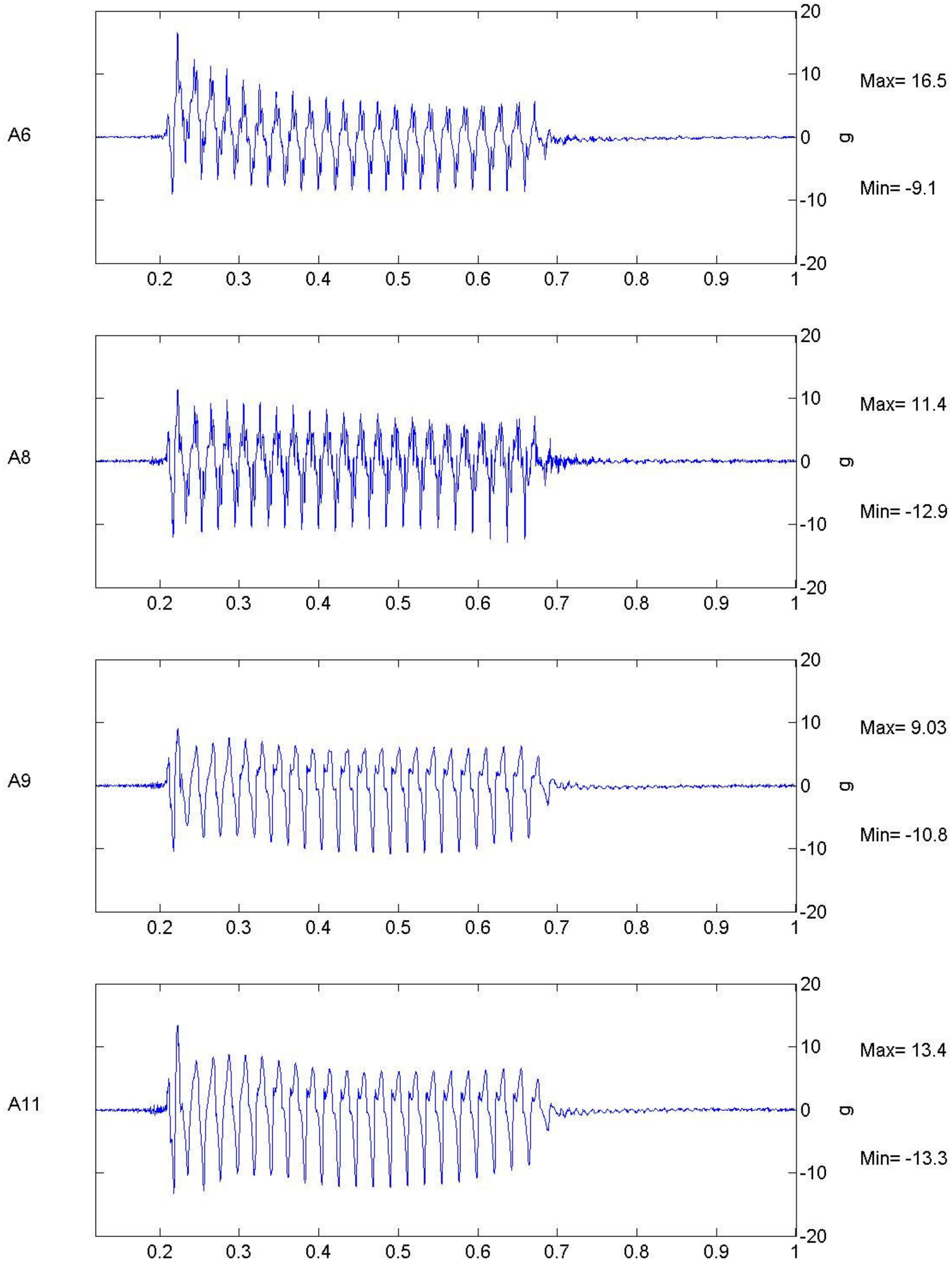


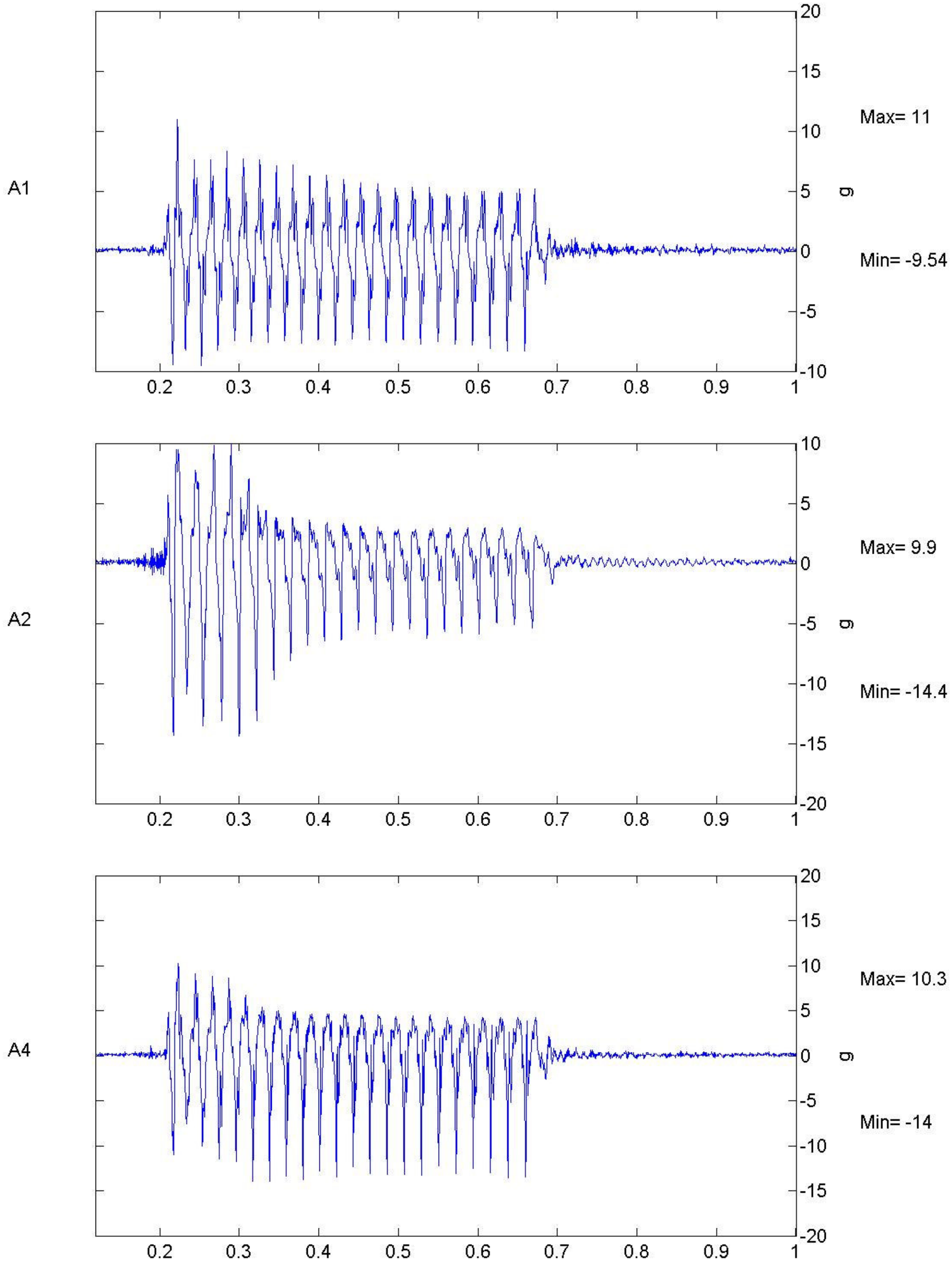
TEST BG-05 FLIGHT 1	**FREQ** **50 Hz**	Scales: Model 8th order Butterworth Filter at 750Hz Short-Term Time Records	Earthquake 1	Figure No. 23



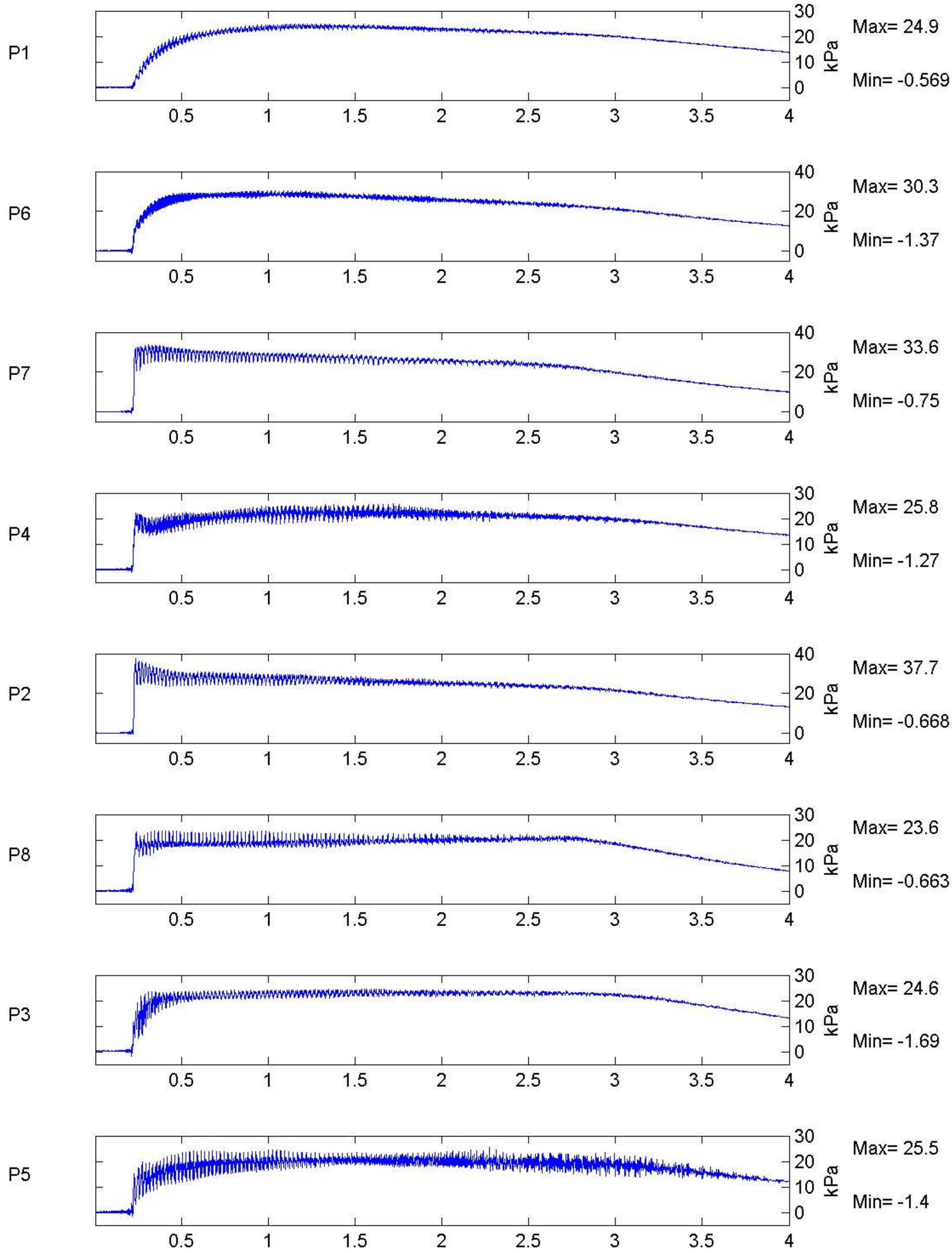
TEST BG-05 FLIGHT 1	**FREQ** **50 Hz**	Scales: Model Unfiltered Data Short-Term Time Records	Earthquake 2	Figure No. 24



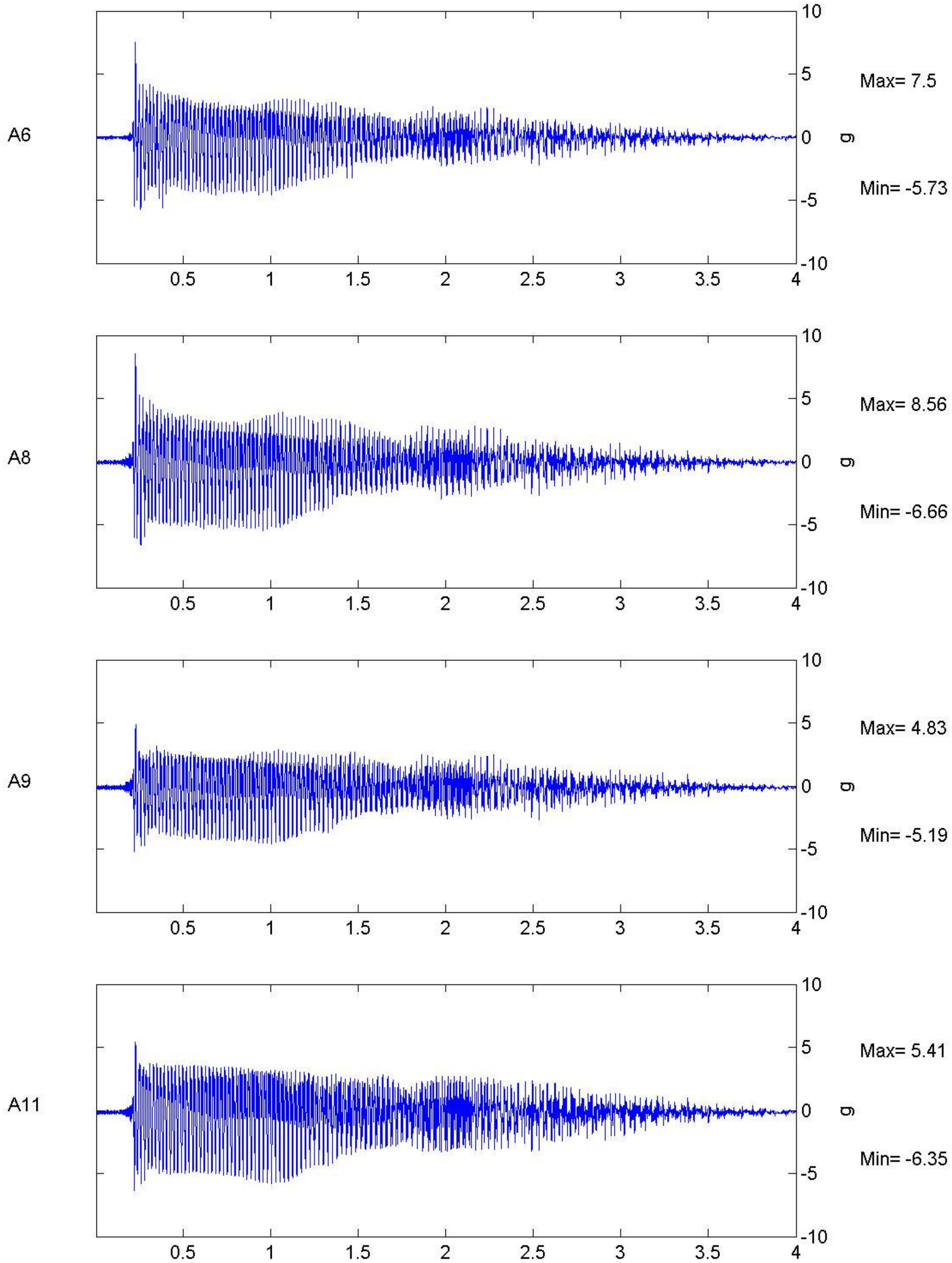
TEST BG-05 FLIGHT 1	**FREQ 50 Hz**	Scales: Model 8th order Butterworth Filter at 750Hz Short-Term Time Records	Earthquake 2	Figure No. 25



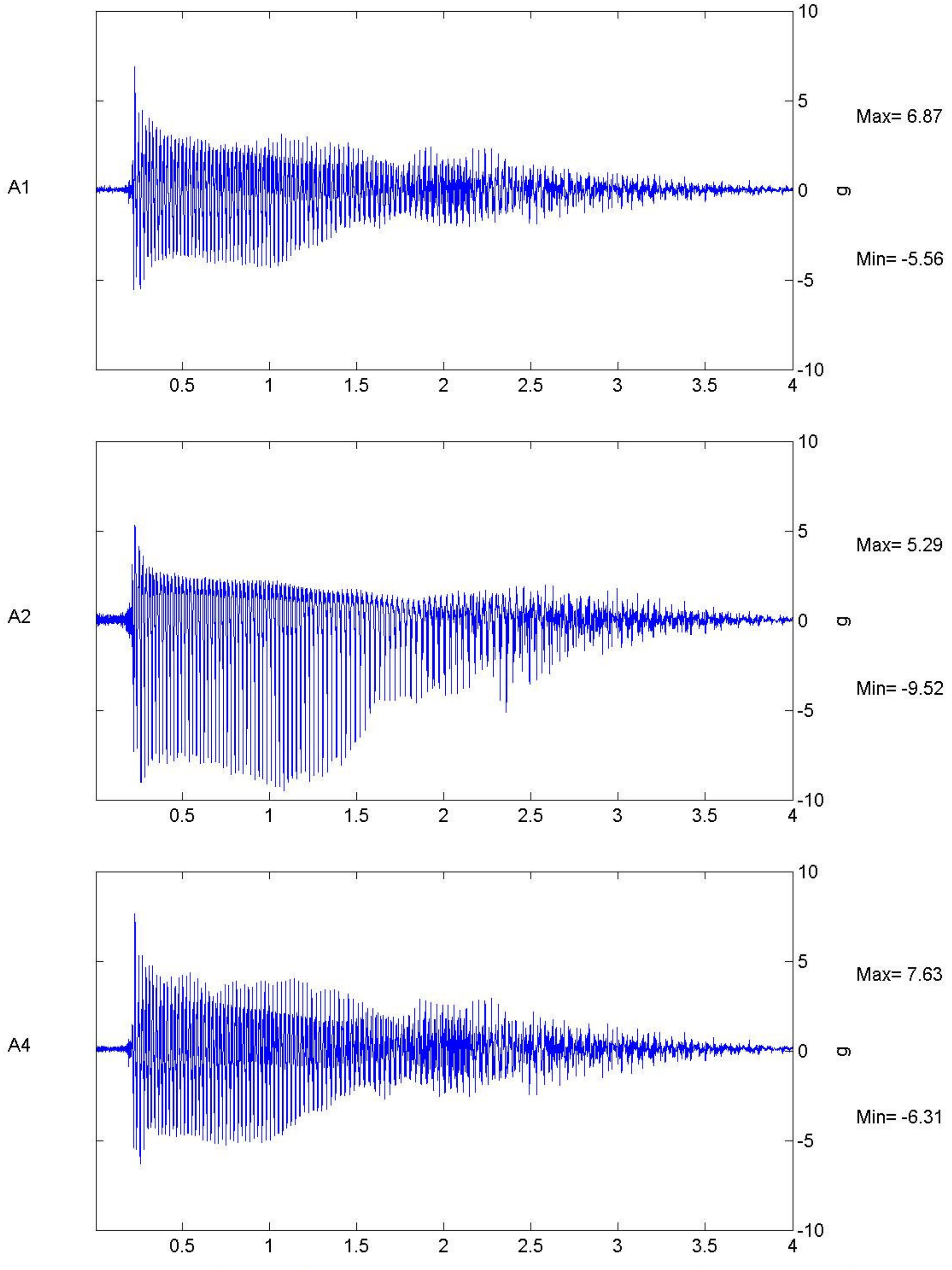
TEST BG-05	**FREQ 50 Hz**	Scales: Model 8th order Butterworth Filter at 750Hz	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	2	26



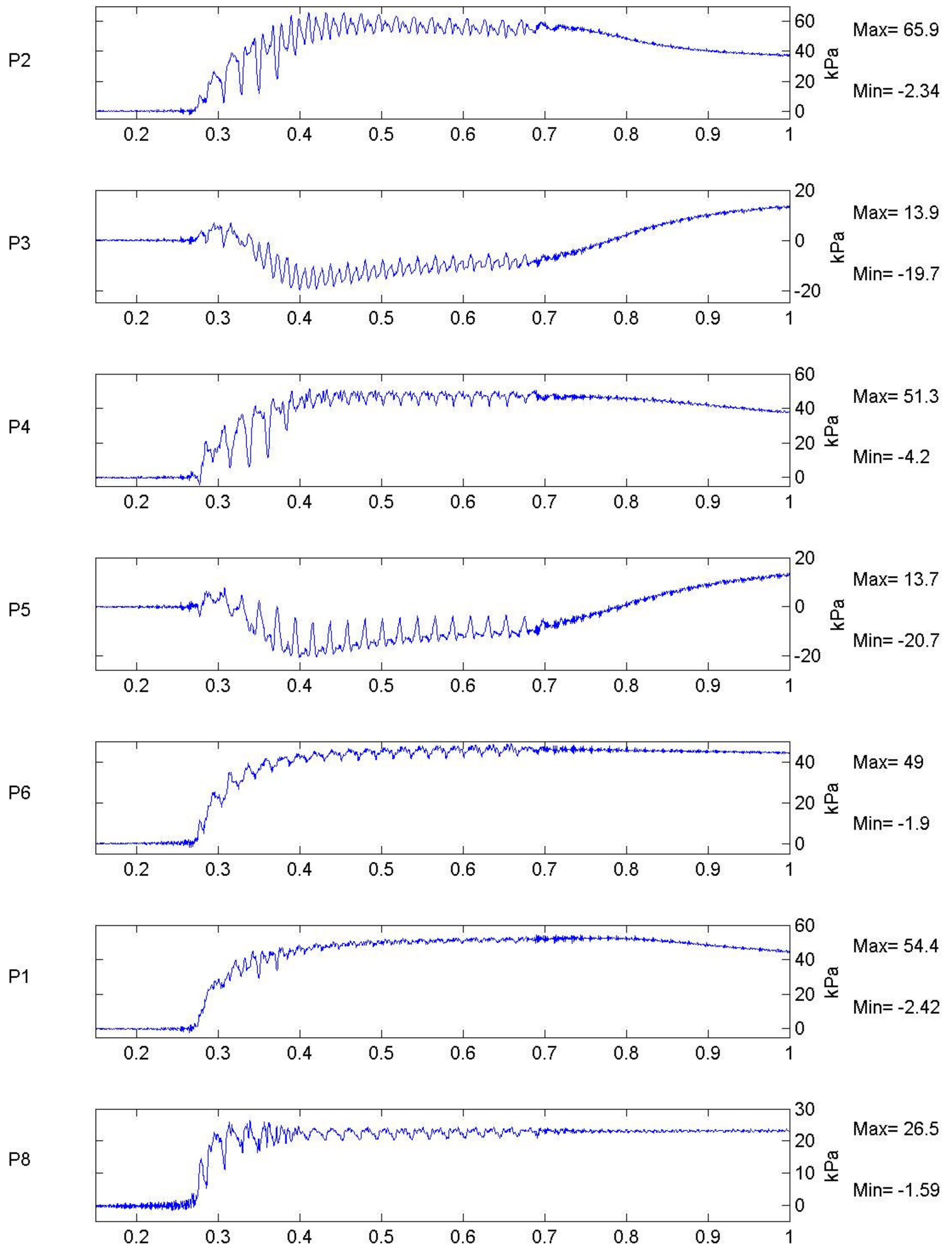
TEST BG-05 FLIGHT 1	SWEPT SINE	Scales: Model Unfiltered Data Long-Term Time Records	Earthquake 3	Figure No. 27



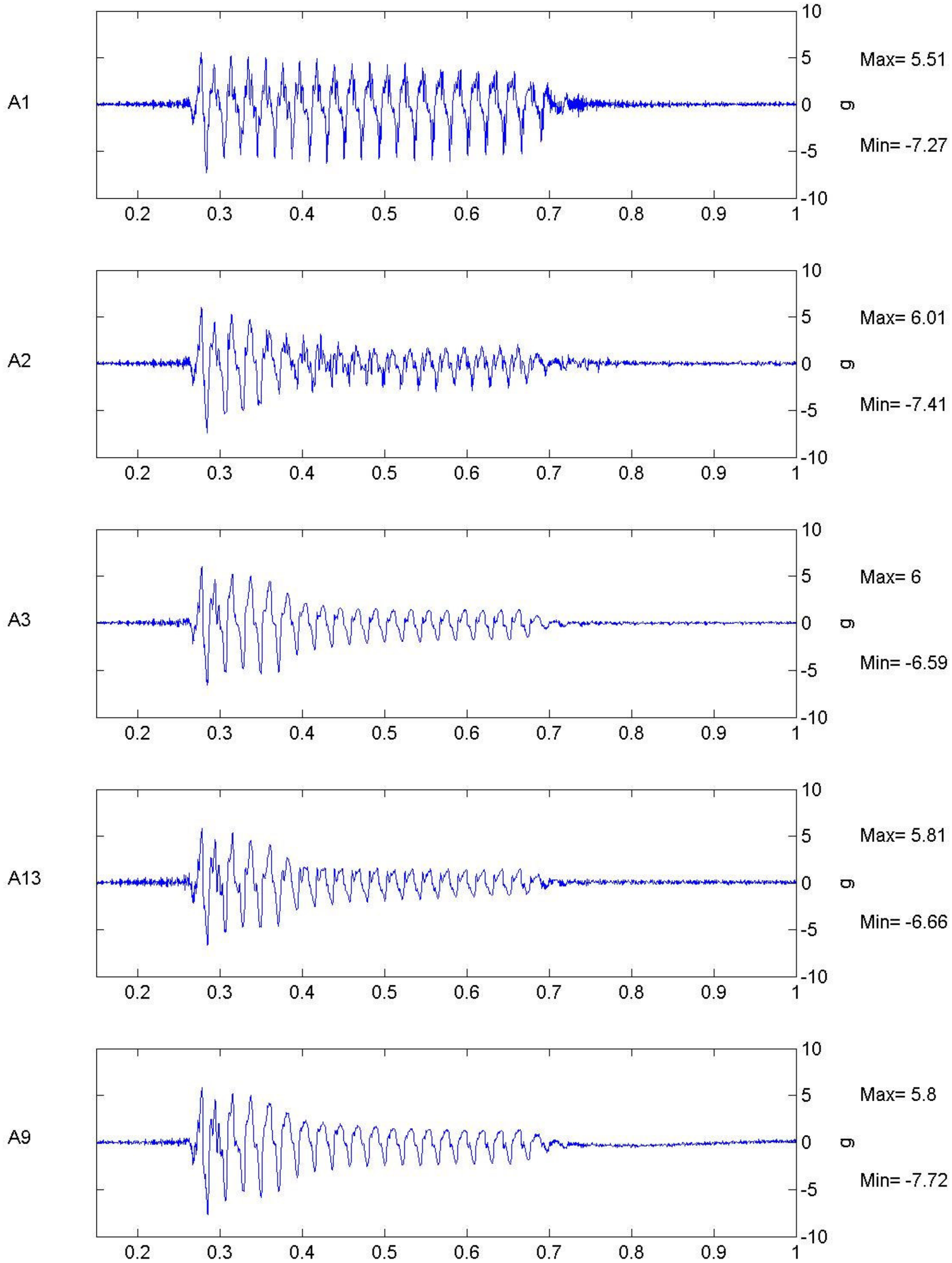
TEST BG-05 FLIGHT 1	SWEPT SINE	Scales: Model 8th order Butterworth Filter at 750Hz Long-Term Time Records	Earthquake 3	Figure No. 28



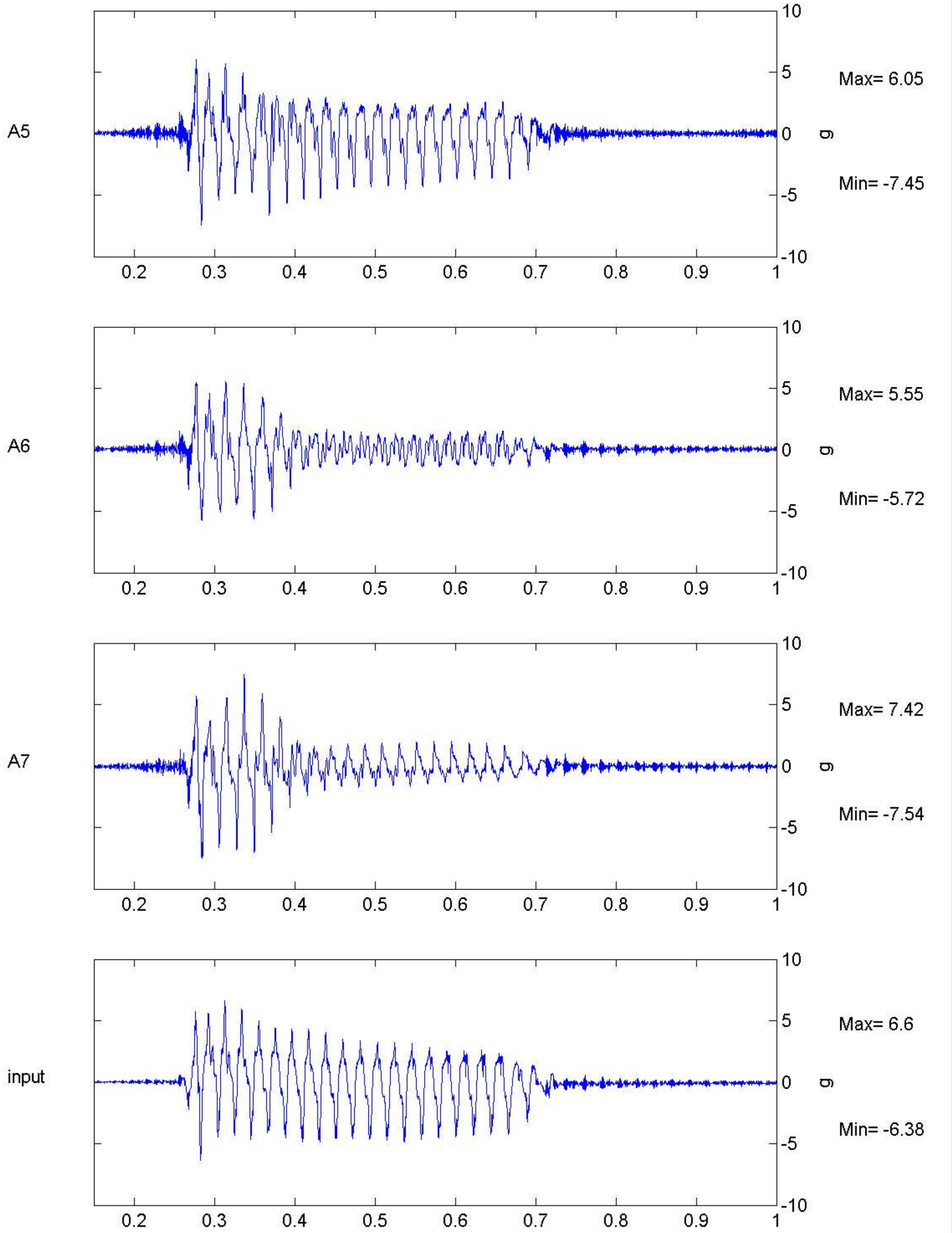
TEST BG-05 FLIGHT 1	**SWEPT SINE**	Scales: Model 8th order Butterworth Filter at 750Hz Long-Term Time Records	Earthquake 3	Figure No. 29



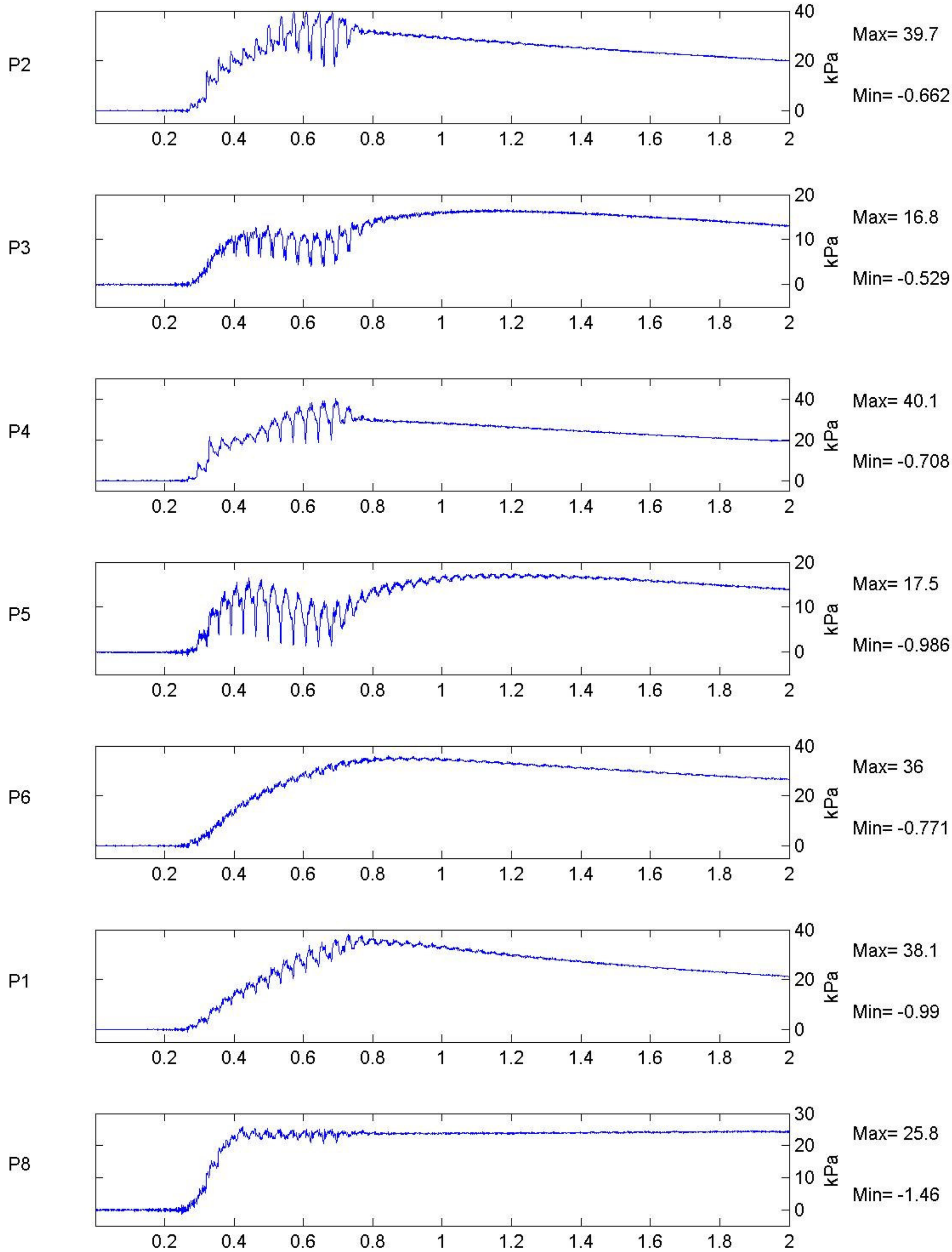
TEST BG-07 FLIGHT 1	**FREQ** **50 Hz**	Scales: Model Unfiltered Data Short-Term Time Records	Earthquake 1	Figure No. 30



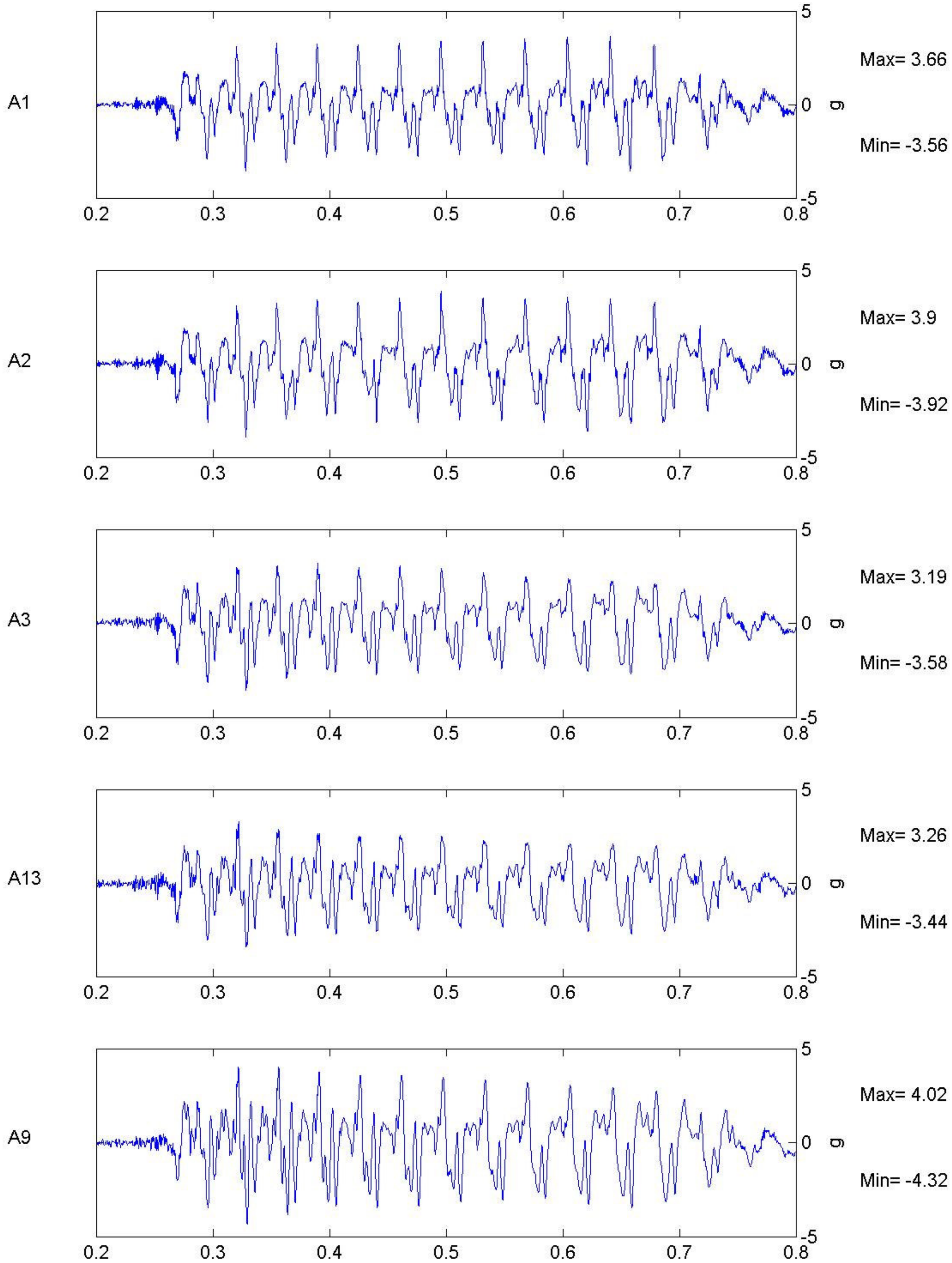
TEST BG-07	**FREQ 50 Hz**	Scales: Model 8th order Butterworth Filter at 1000Hz	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	1	31



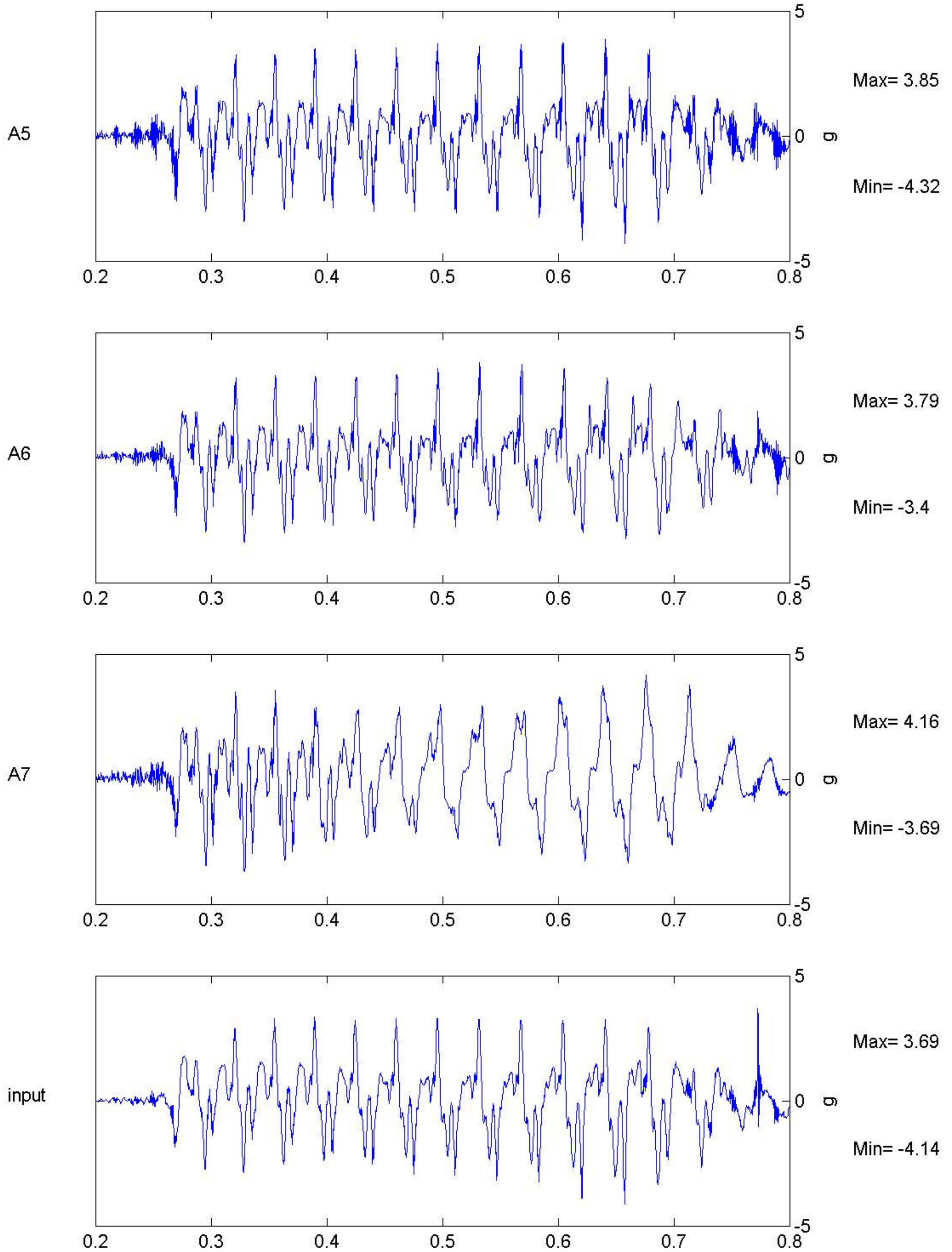
TEST BG-07 FLIGHT 1	**FREQ 50 Hz**	Scales: Model 8th order Butterworth Filter at 1000Hz Short-Term Time Records	Earthquake 1	Figure No. 32



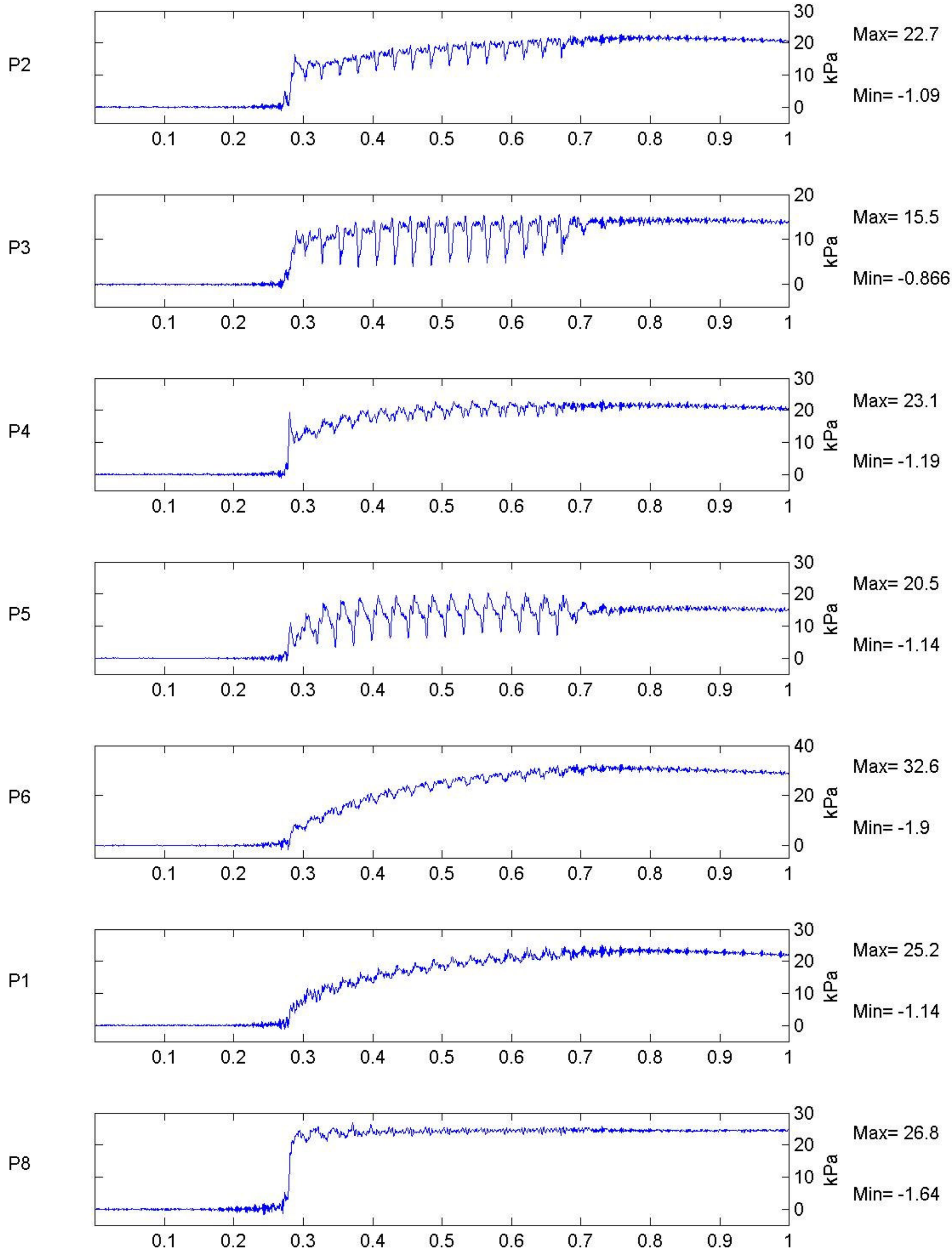
TEST BG-07 FLIGHT 1	**FREQ** **30 Hz**	Scales: Model Unfiltered Data Short-Term Time Records	Earthquake 2	Figure No. 33



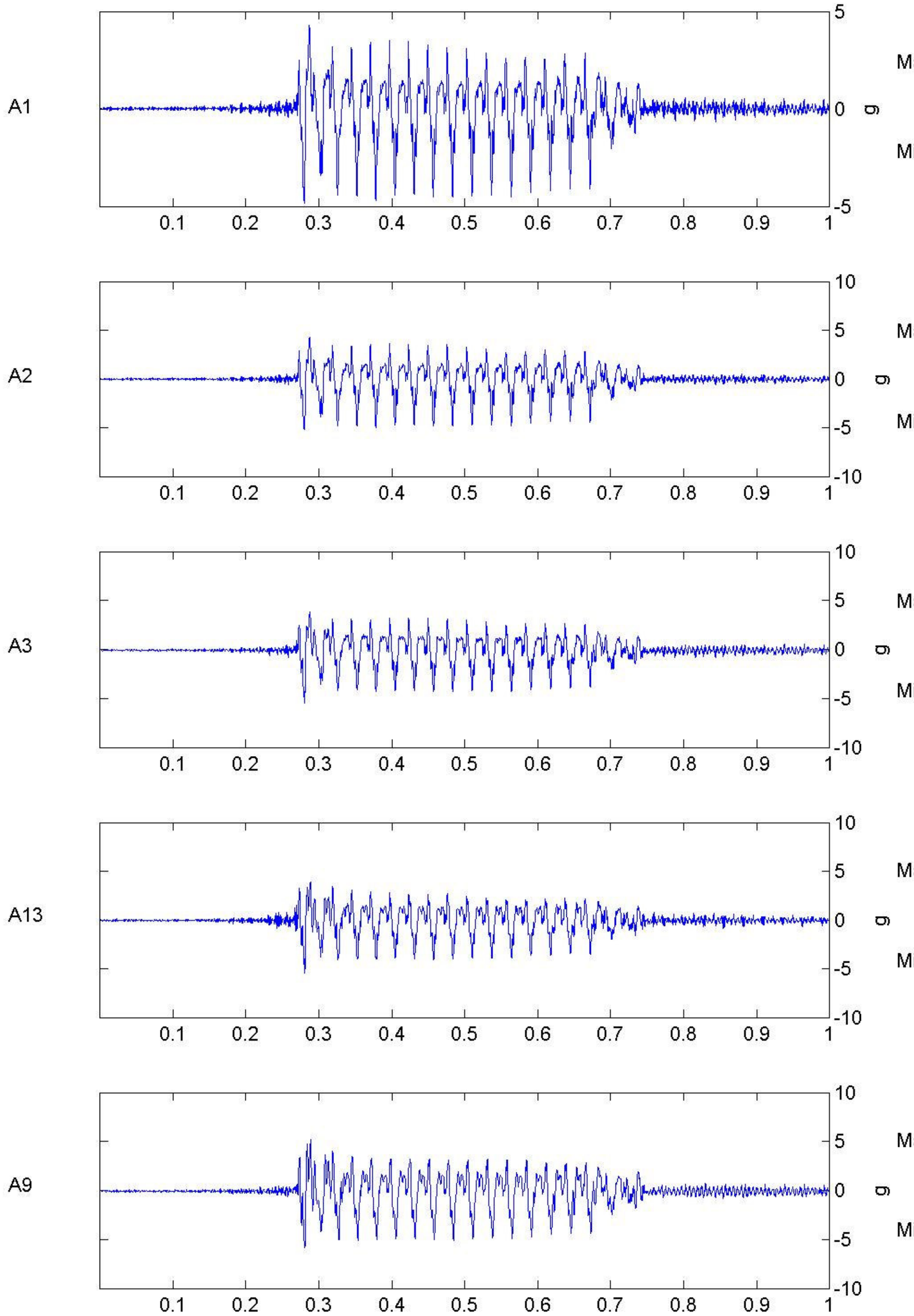
TEST BG-07 FLIGHT 1	**FREQ 30 Hz**	Scales: Model 8th order Butterworth Filter at 1000Hz Short-Term Time Records	Earthquake 2	Figure No. 34



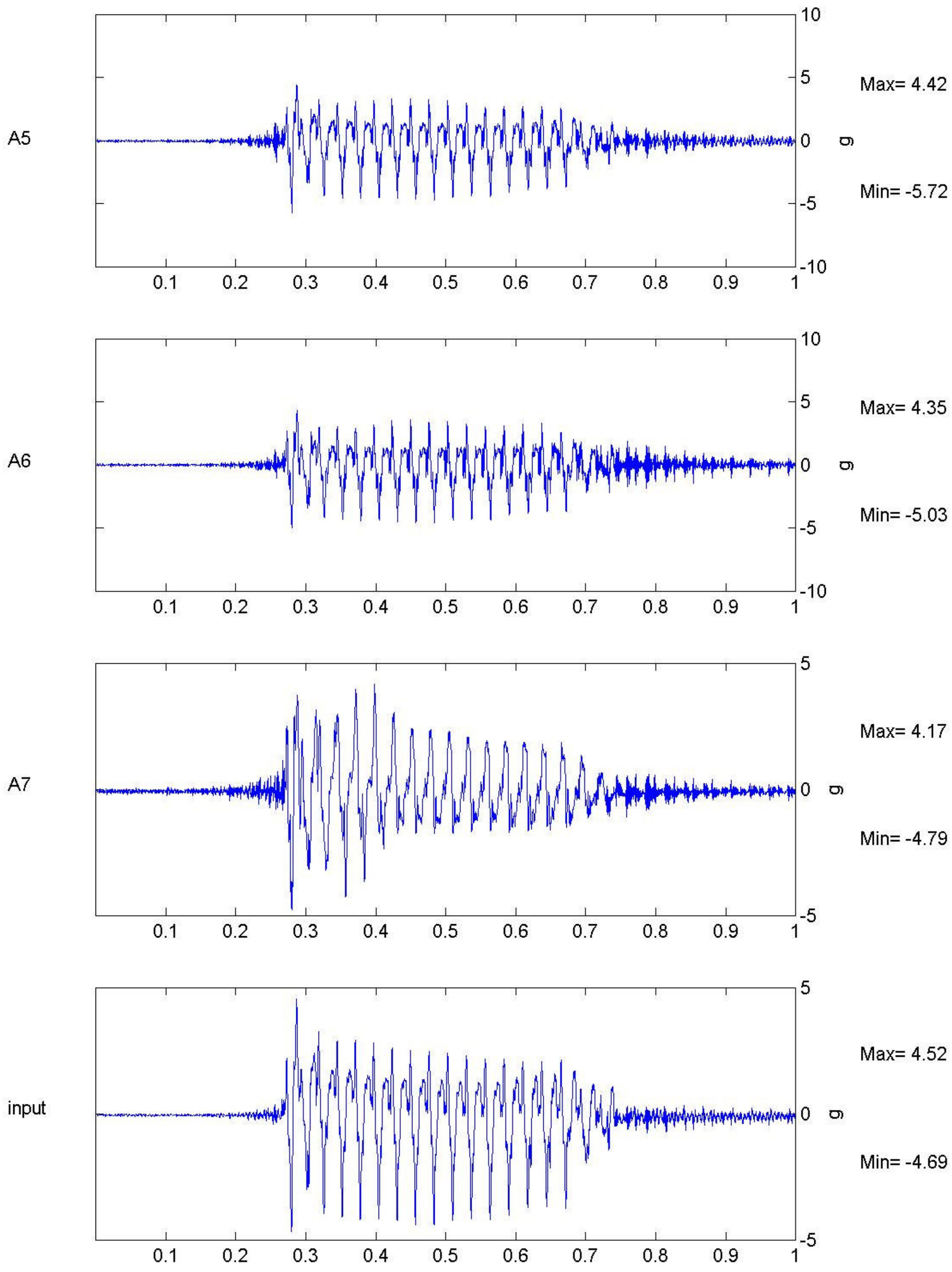
TEST BG-07 FLIGHT 1	**FREQ** **30 Hz**	Scales: Model 8th order Butterworth Filter at 1000Hz Short-Term Time Records	Earthquake 2	Figure No. 35



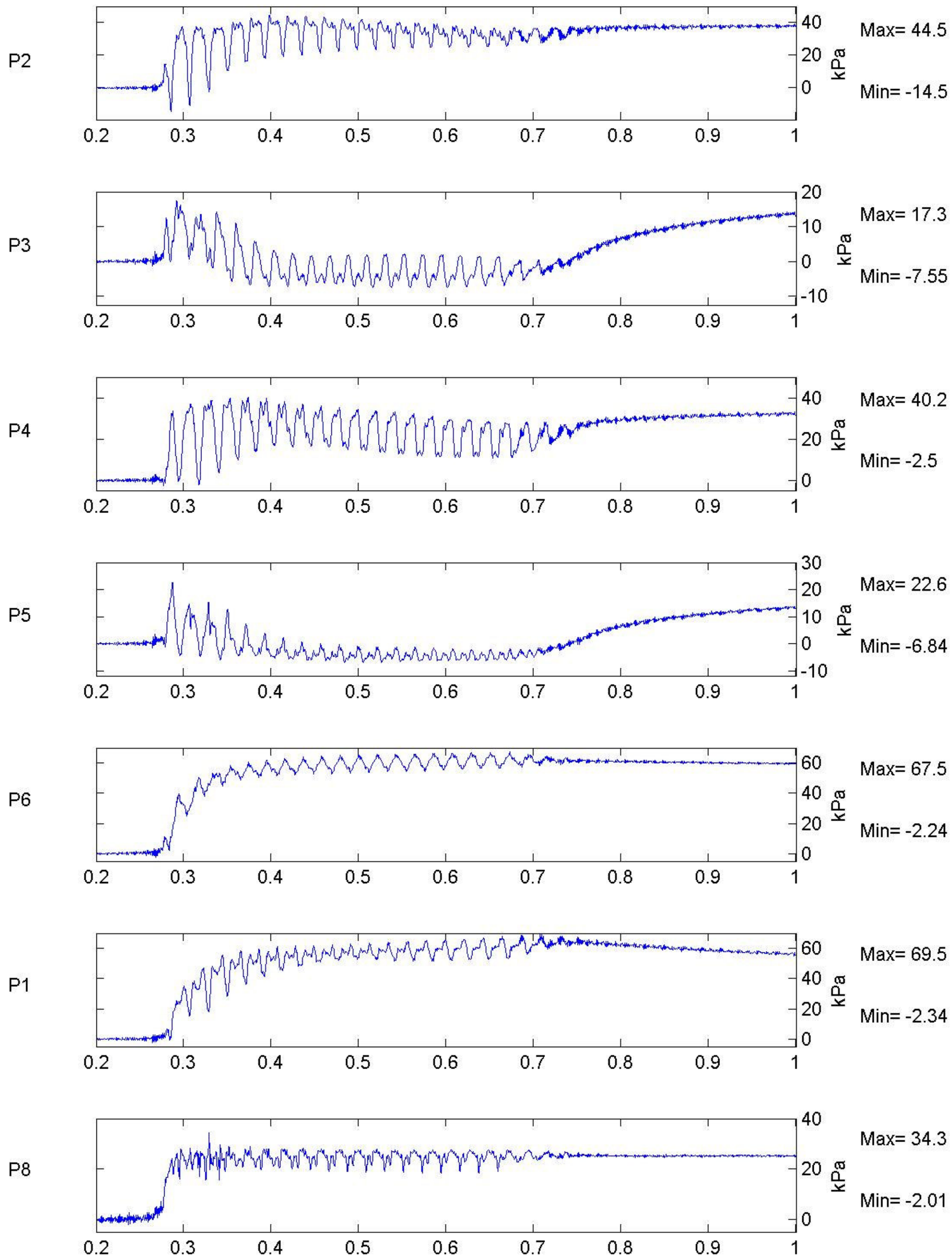
TEST BG-07 FLIGHT 1	**FREQ** **40 Hz**	Scales: Model Unfiltered Data Short-Term Time Records	Earthquake 3	Figure No. 36



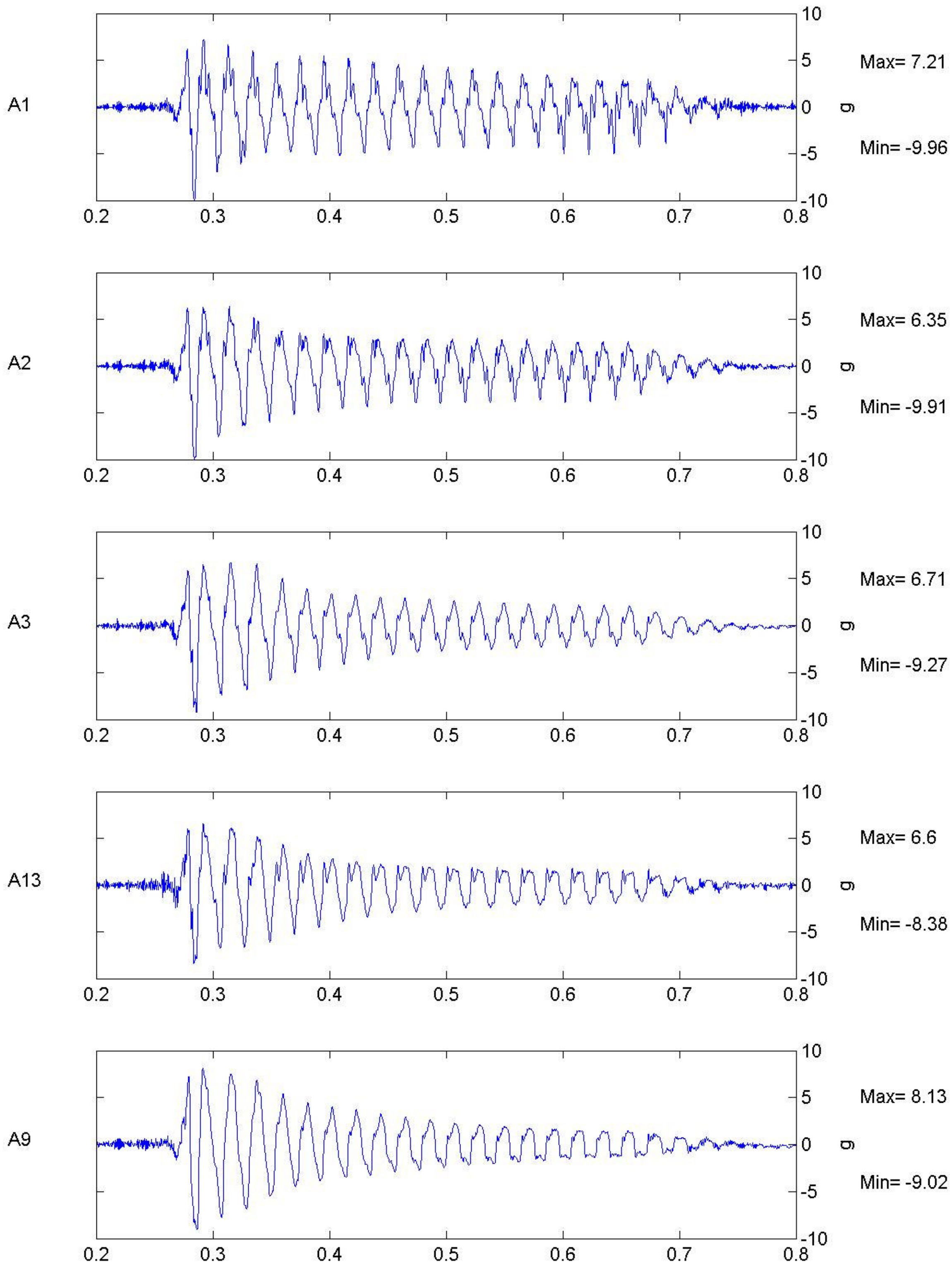
TEST BG-07 FLIGHT 1	**FREQ 40 Hz**	Scales: Model 8th order Butterworth Filter at 1000Hz Short-Term Time Records	Earthquake 3	Figure No. 37



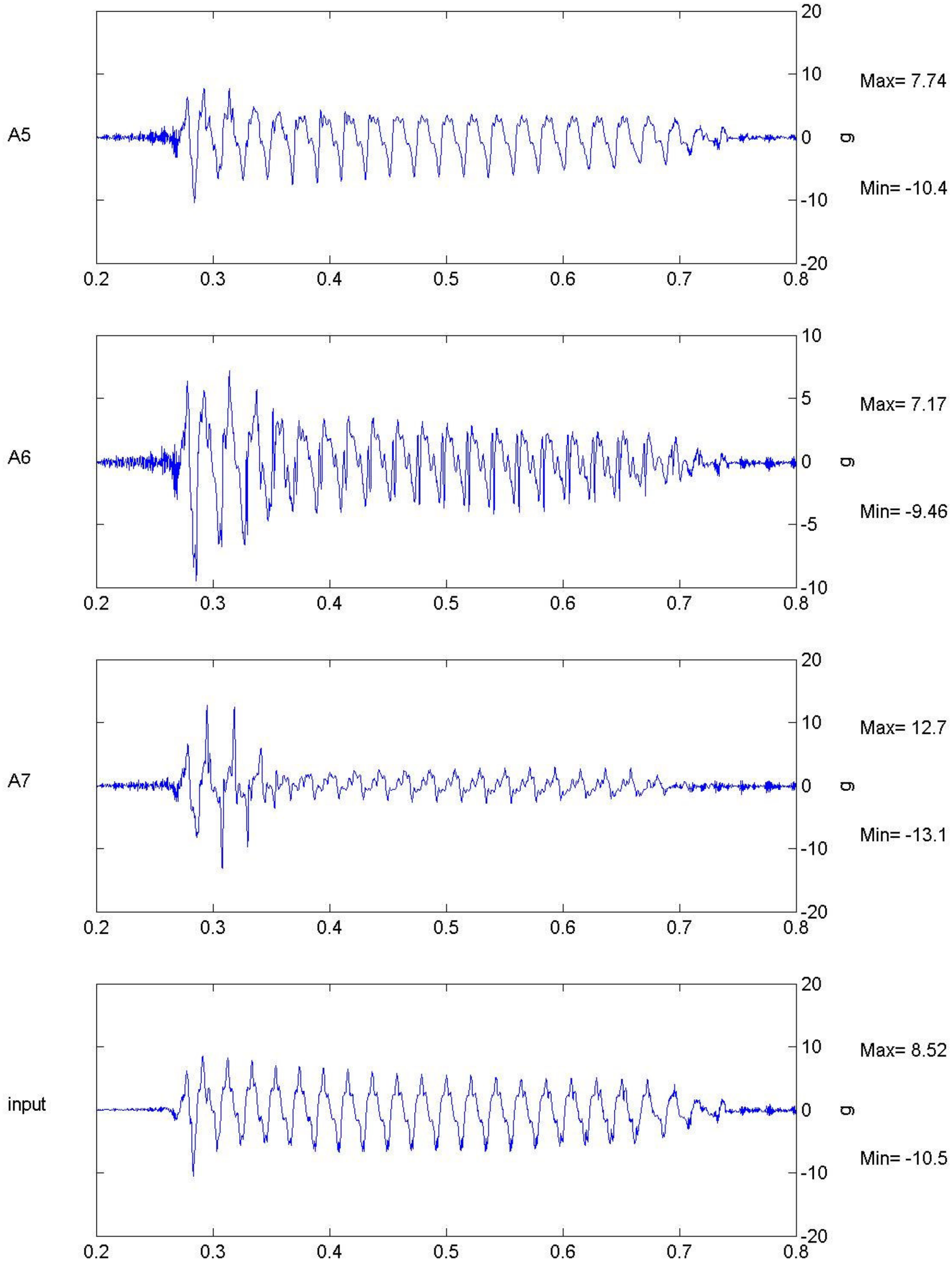
TEST BG-07 FLIGHT 1	**FREQ** **40 Hz**	Scales: Model 8th order Butterworth Filter at 1000Hz Short-Term Time Records	Earthquake 3	Figure No. 38



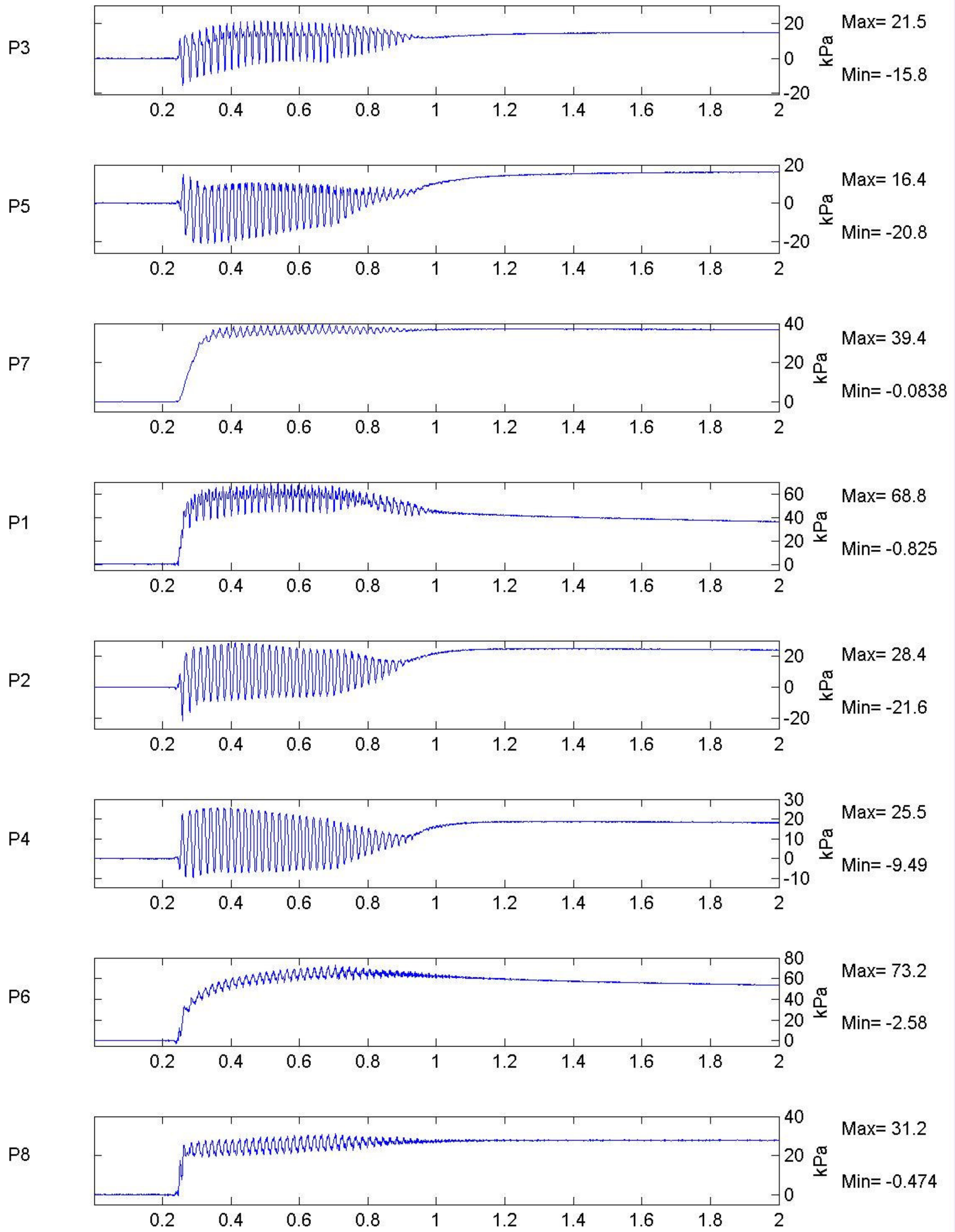
TEST BG-07 FLIGHT 1	**FREQ** **50 Hz**	Scales: Model Unfiltered Data Short-Term Time Records	Earthquake 4	Figure No. 39



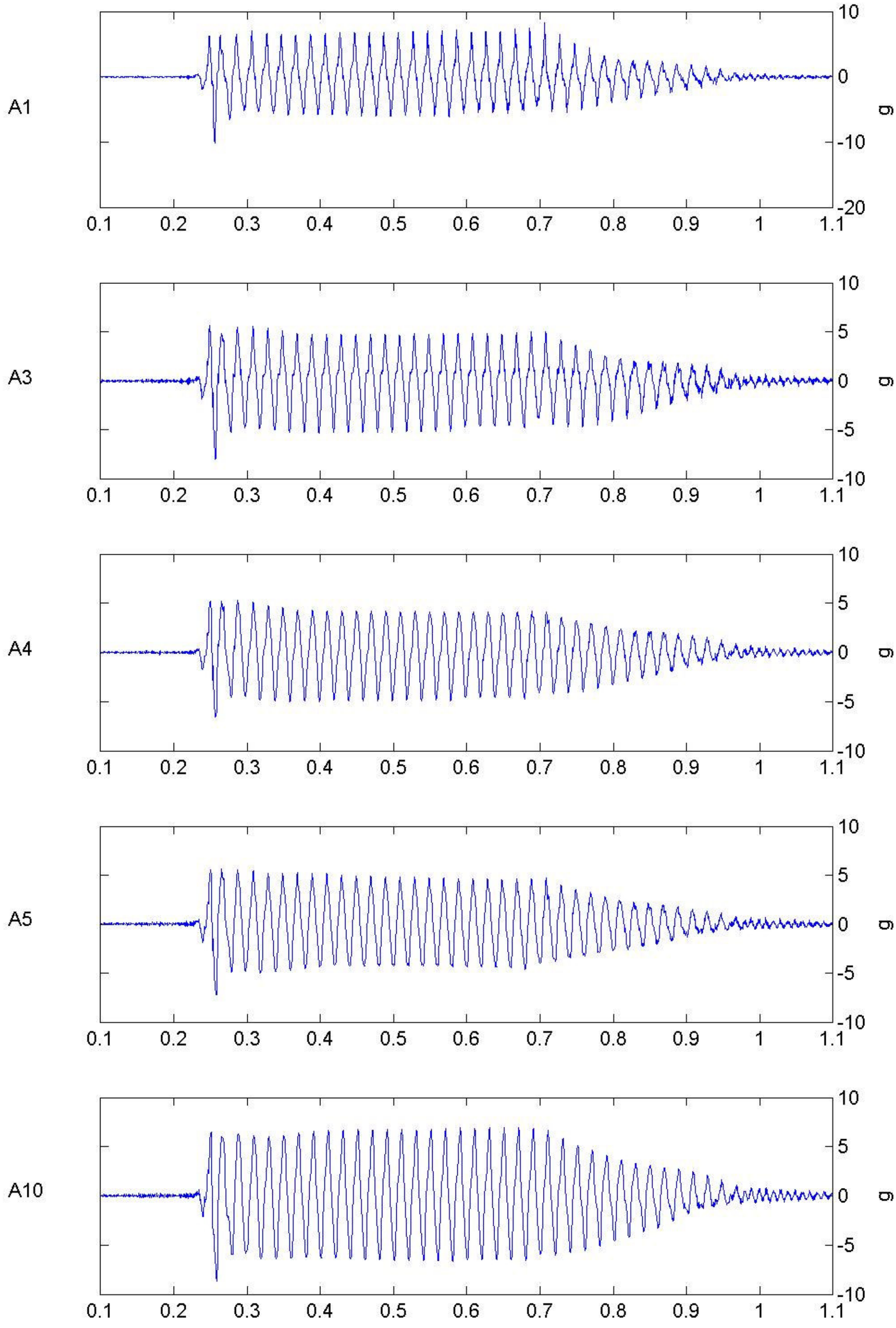
TEST BG-07 FLIGHT 1	**FREQ 50 Hz**	Scales: Model 8th order Butterworth Filter at 1000Hz Short-Term Time Records	Earthquake 4	Figure No. 40



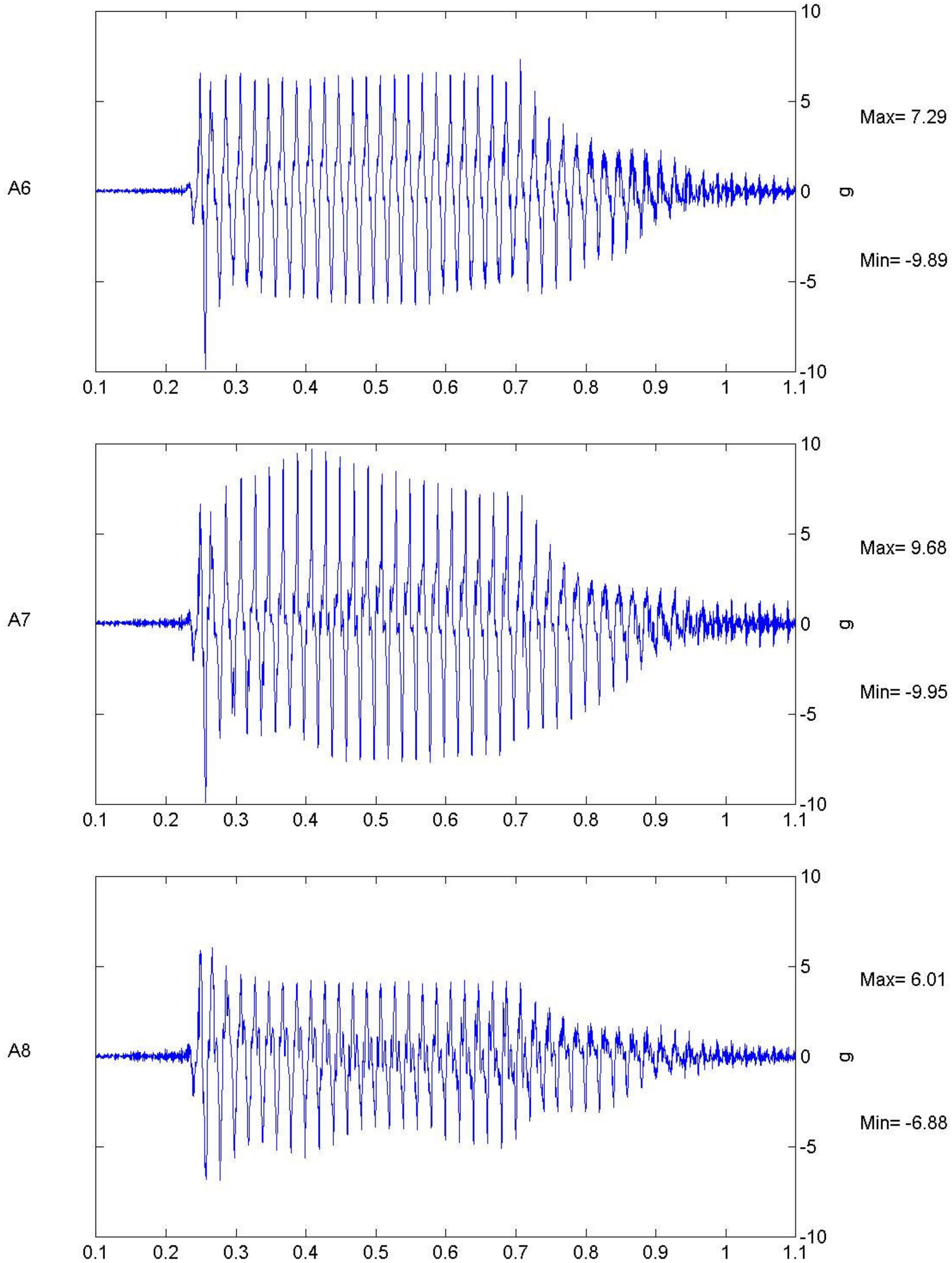
TEST BG-07 FLIGHT 1	FREQ 50 Hz	Scales: Model 8th order Butterworth Filter at 1000Hz Short-Term Time Records	Earthquake 4	Figure No. 41



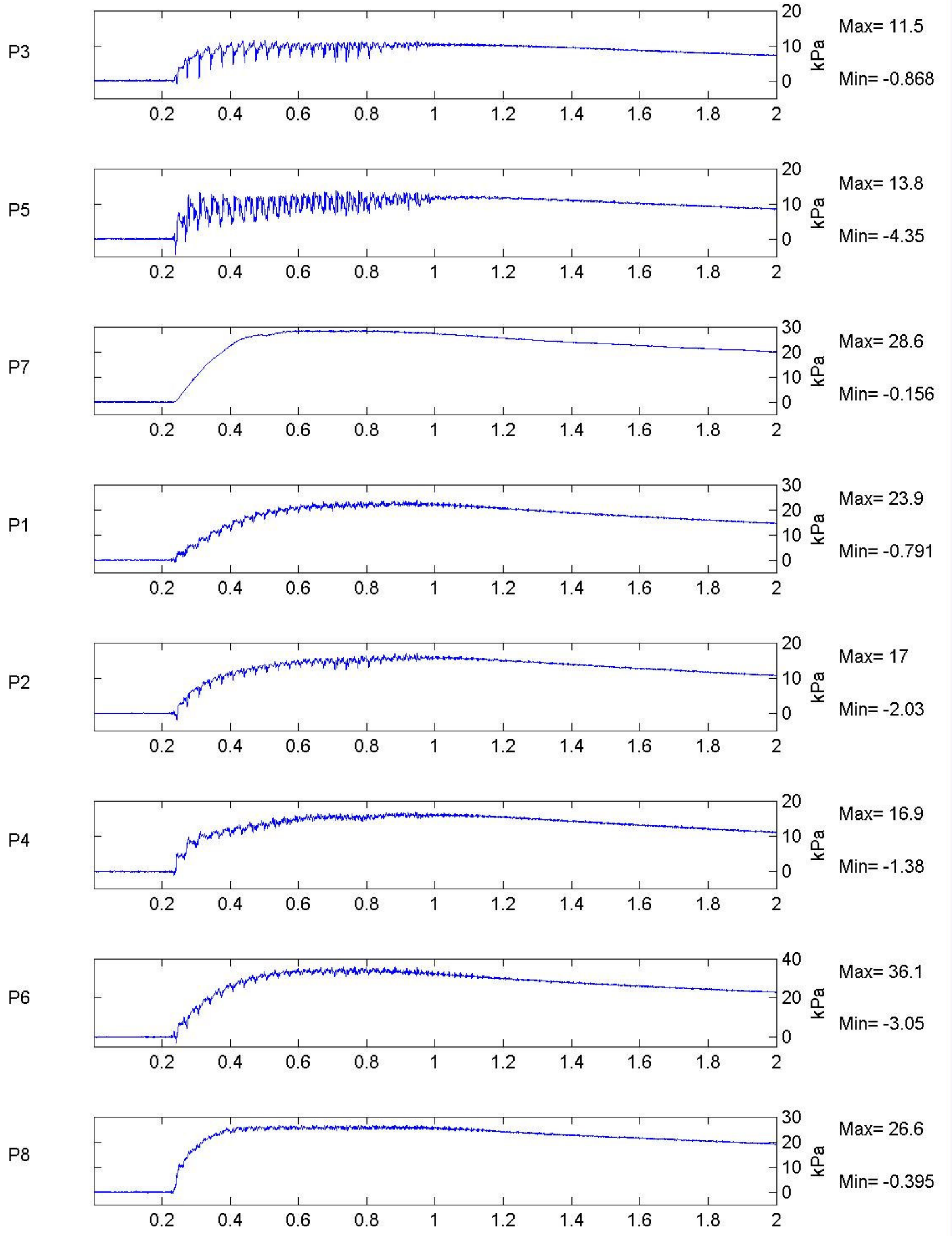
TEST BG-08 FLIGHT 1	**FREQ** **50 Hz**	Scales: Model Unfiltered Data Short-Term Time Records	Earthquake 1	Figure No. 42



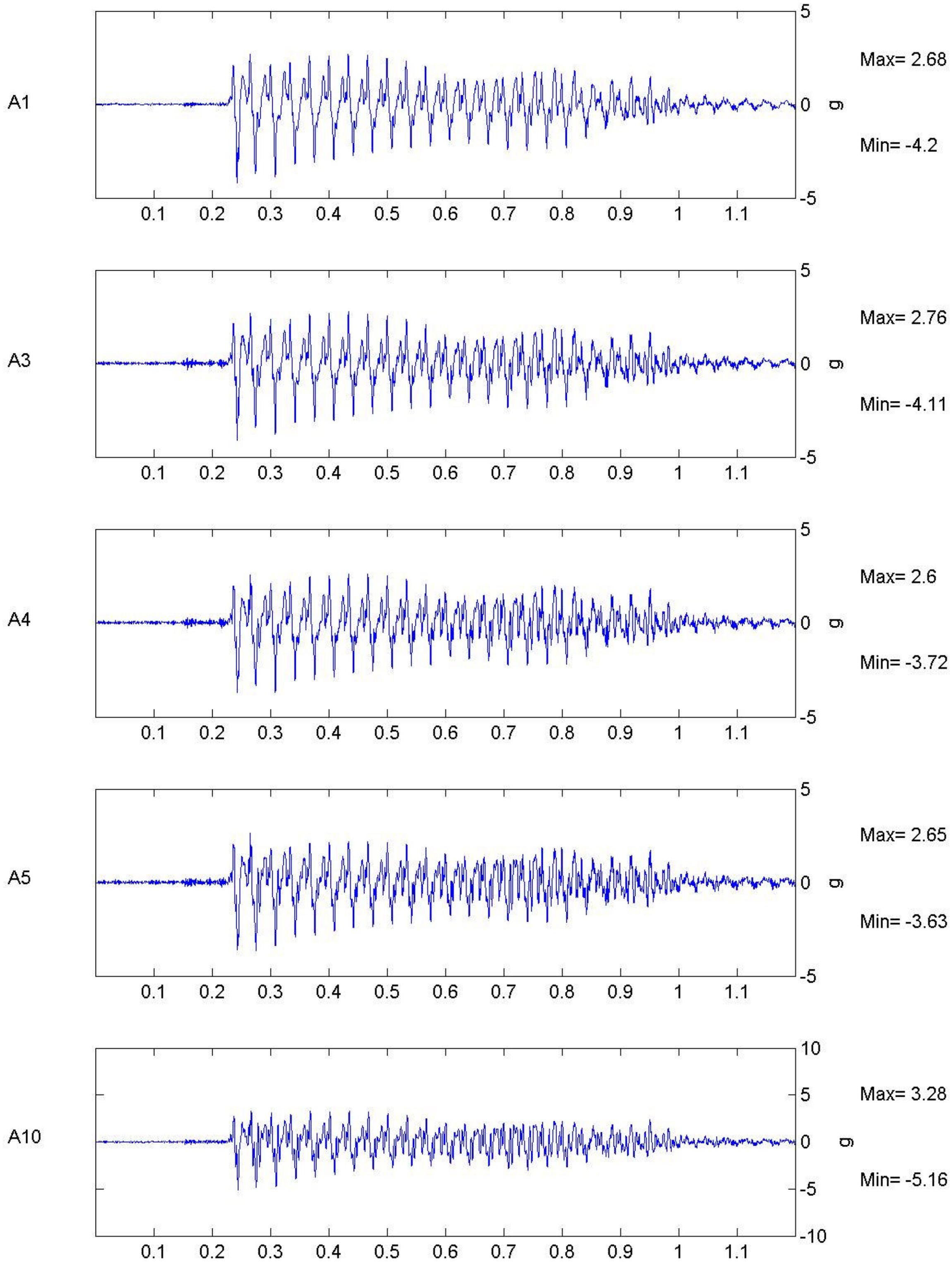
TEST BG-08 FLIGHT 1	**FREQ 50 Hz**	Scales: Model 8th order Butterworth Filter at 1000Hz Short-Term Time Records	Earthquake 1	Figure No. 43



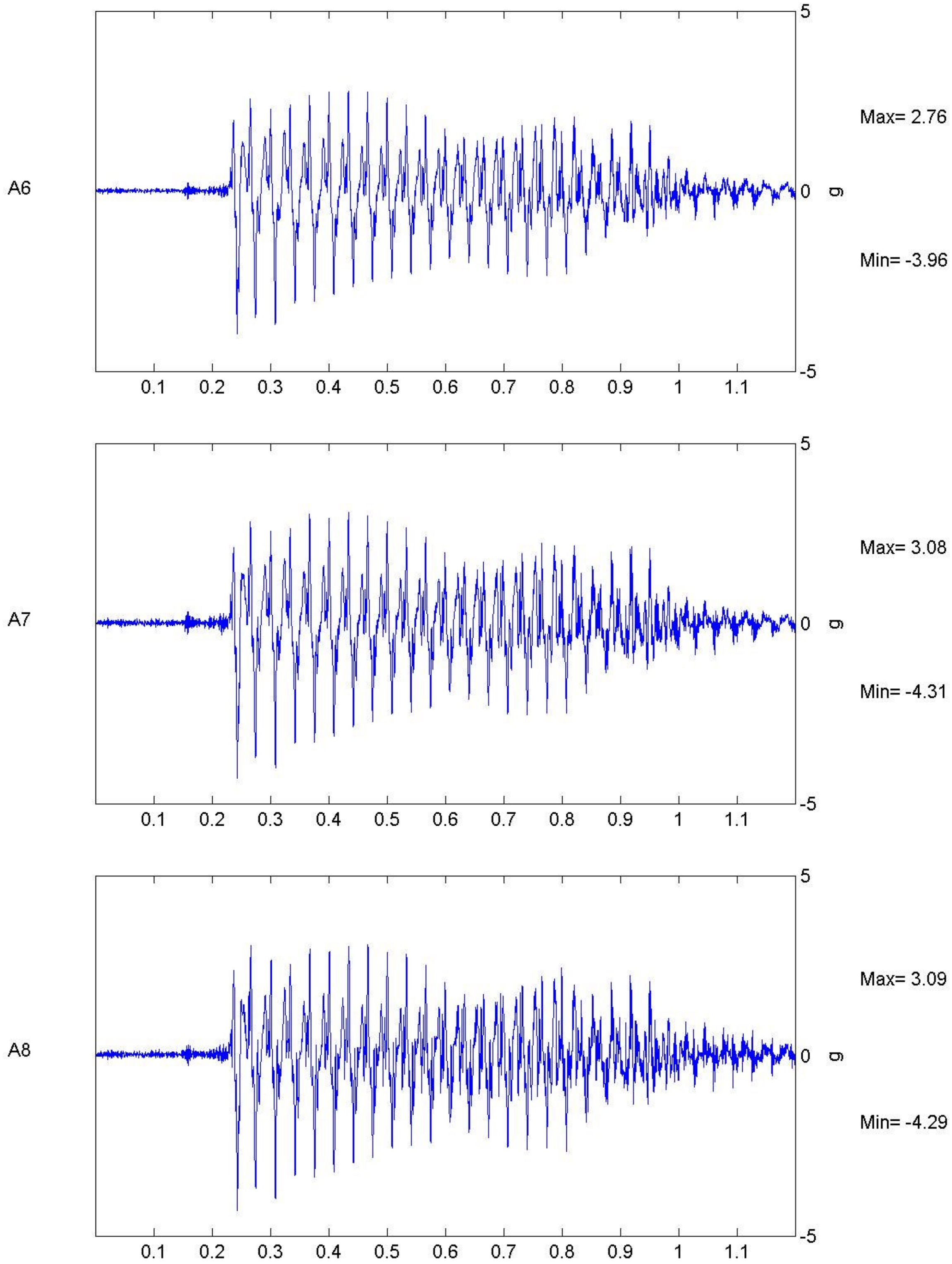
TEST BG-08	FREQ 50 Hz	Scales: Model 8th order Butterworth Filter at 1000Hz	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	1	44



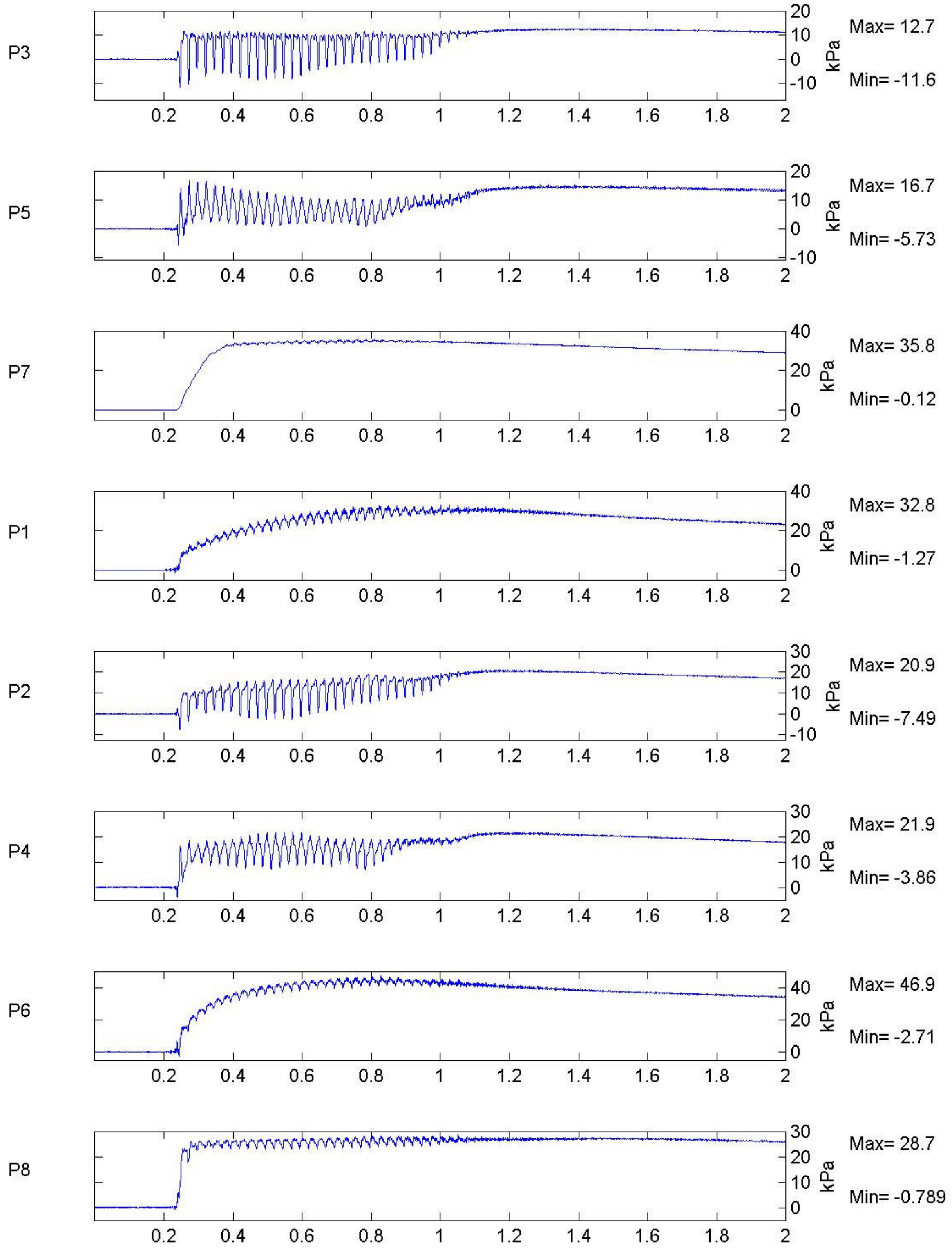
TEST BG-08 FLIGHT 1	**FREQ** **30 Hz**	Scales: Model Unfiltered Data Short-Term Time Records	Earthquake EQ2	Figure No. 45



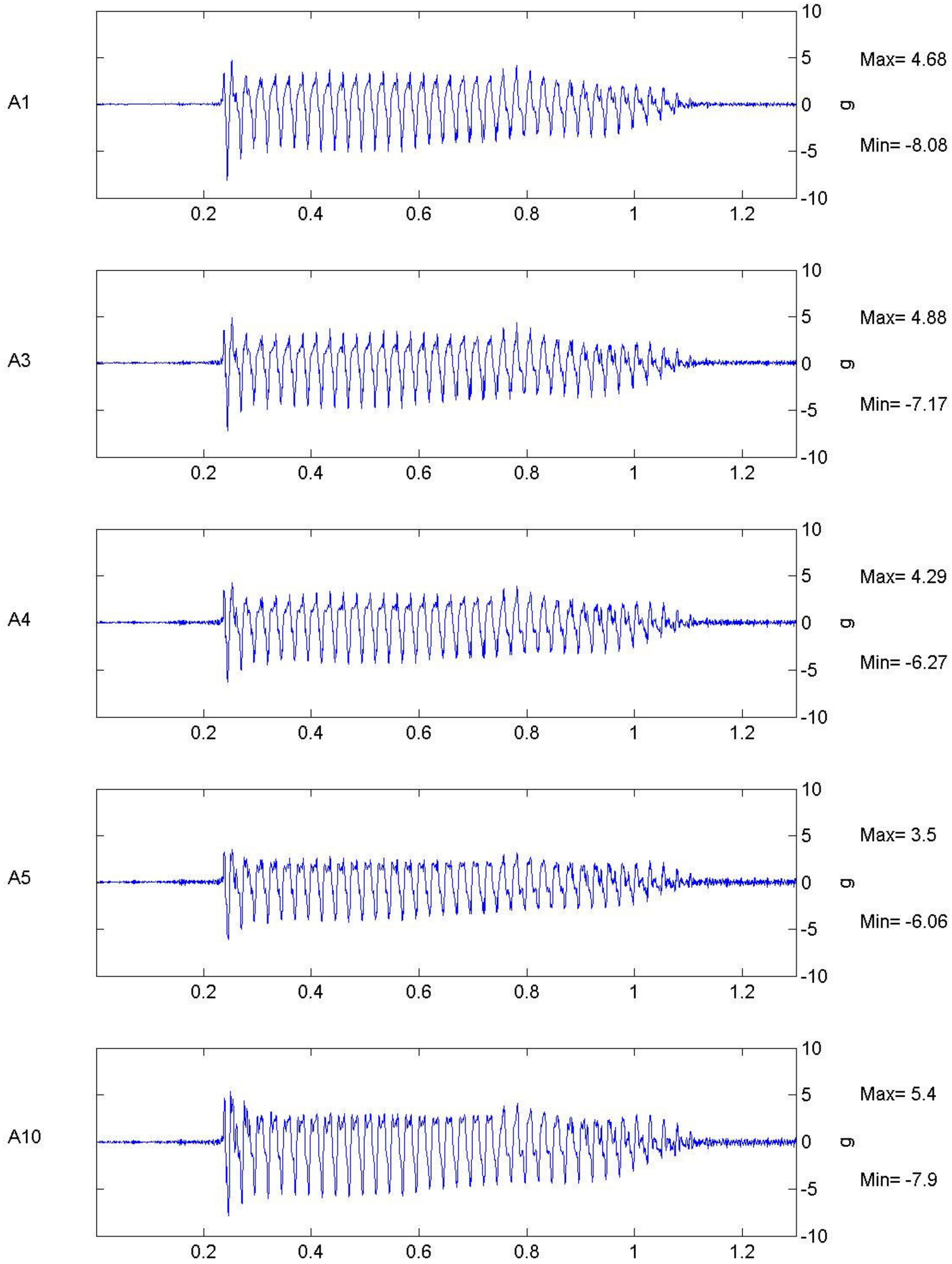
TEST BG-08 FLIGHT 1	**FREQ 30 Hz**	Scales: Model 8th order Butterworth Filter at 1000Hz Short-Term Time Records	Earthquake EQ2	Figure No. 46



TEST BG-08 FLIGHT 1	**FREQ** **30 Hz**	Scales: Model 8th order Butterworth Filter at 1000Hz Short-Term Time Records	Earthquake EQ2	Figure No. 47

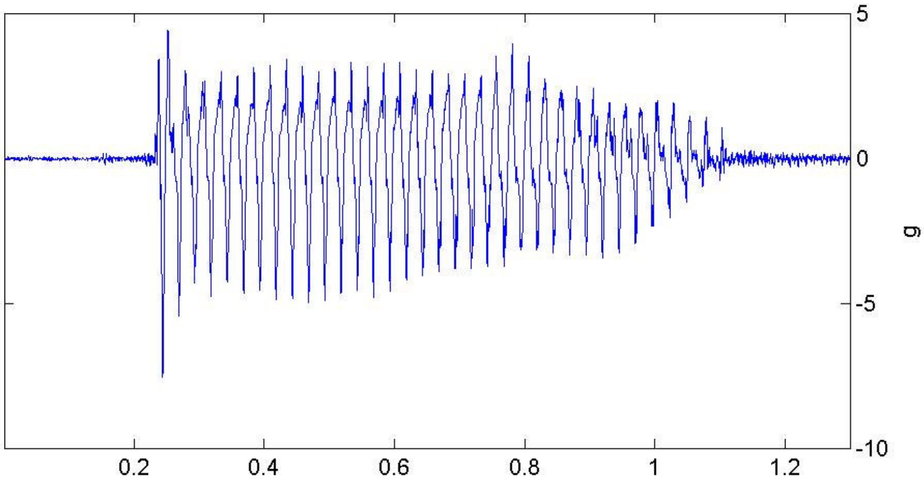


TEST BG-08 FLIGHT 1	**FREQ** **40 Hz**	Scales: Model Unfiltered Data Short-Term Time Records	Earthquake 1	Figure No. 48



TEST BG-08 FLIGHT 1	**FREQ 40 Hz**	Scales: Model 8th order Butterworth Filter at 750Hz Short-Term Time Records	Earthquake 1	Figure No. 49

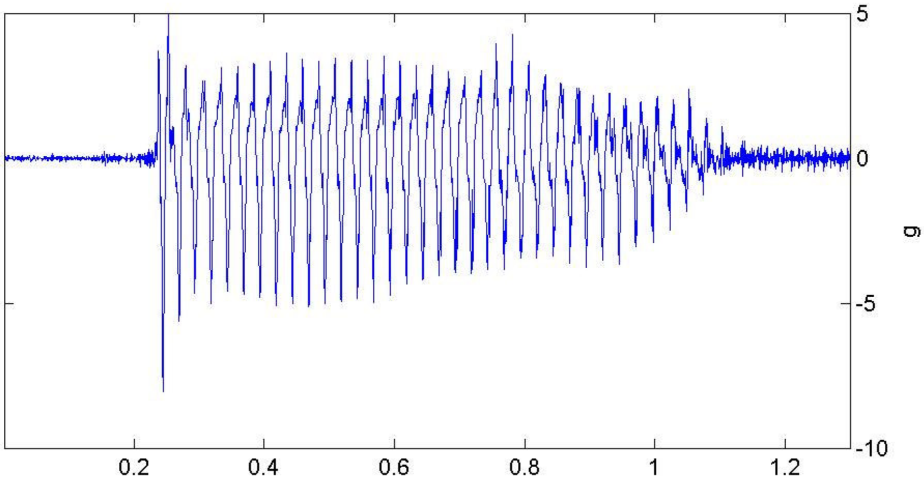
A6



Max= 4.41

Min= -7.54

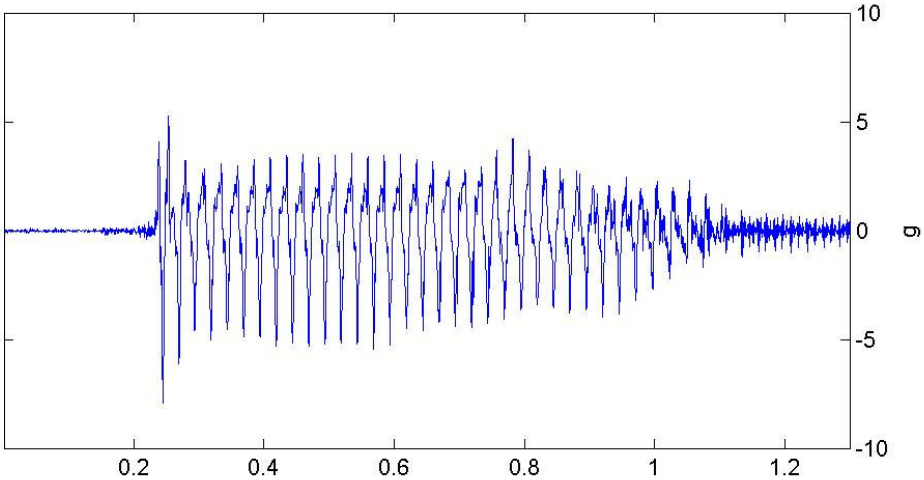
A7



Max= 4.96

Min= -8.07

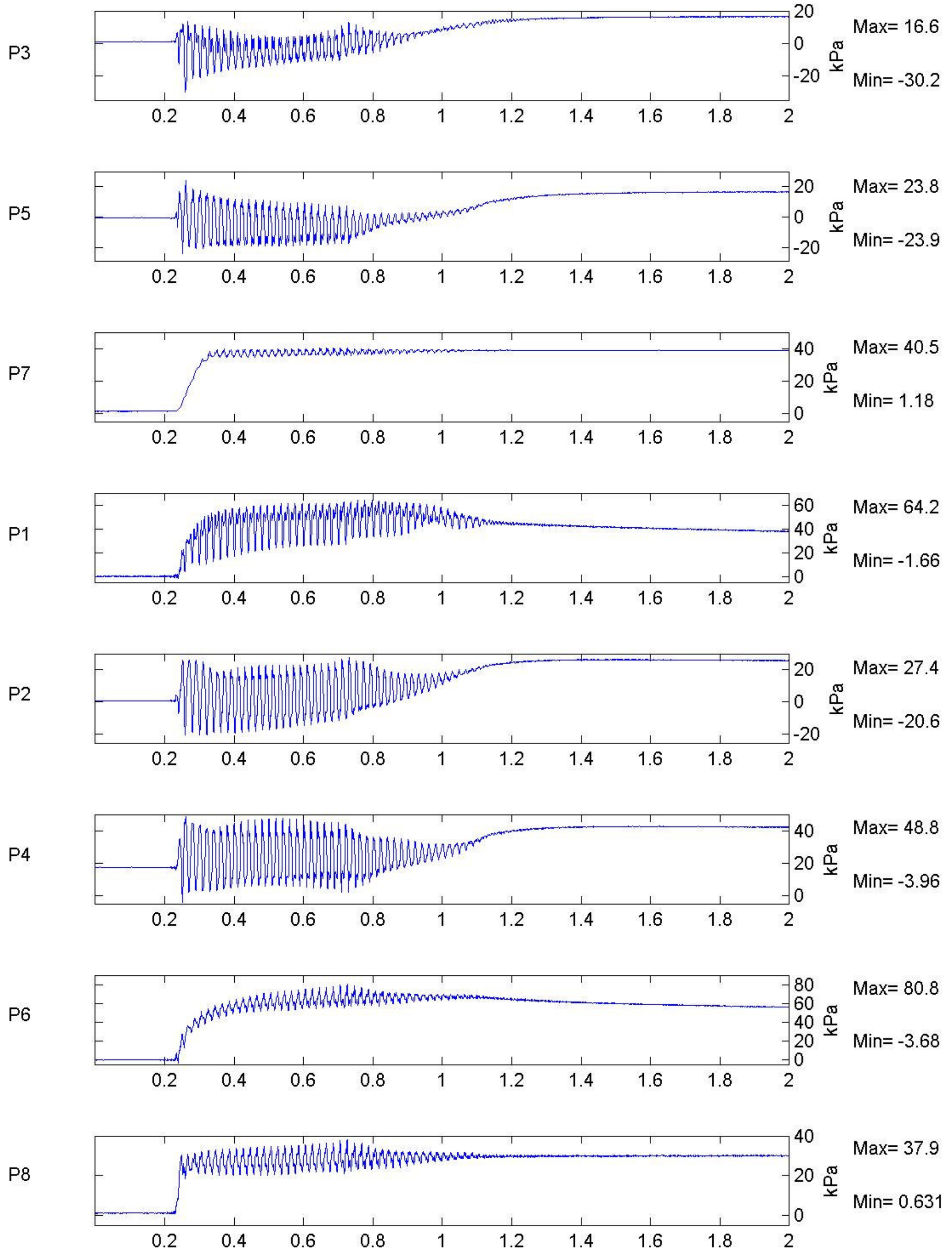
A8



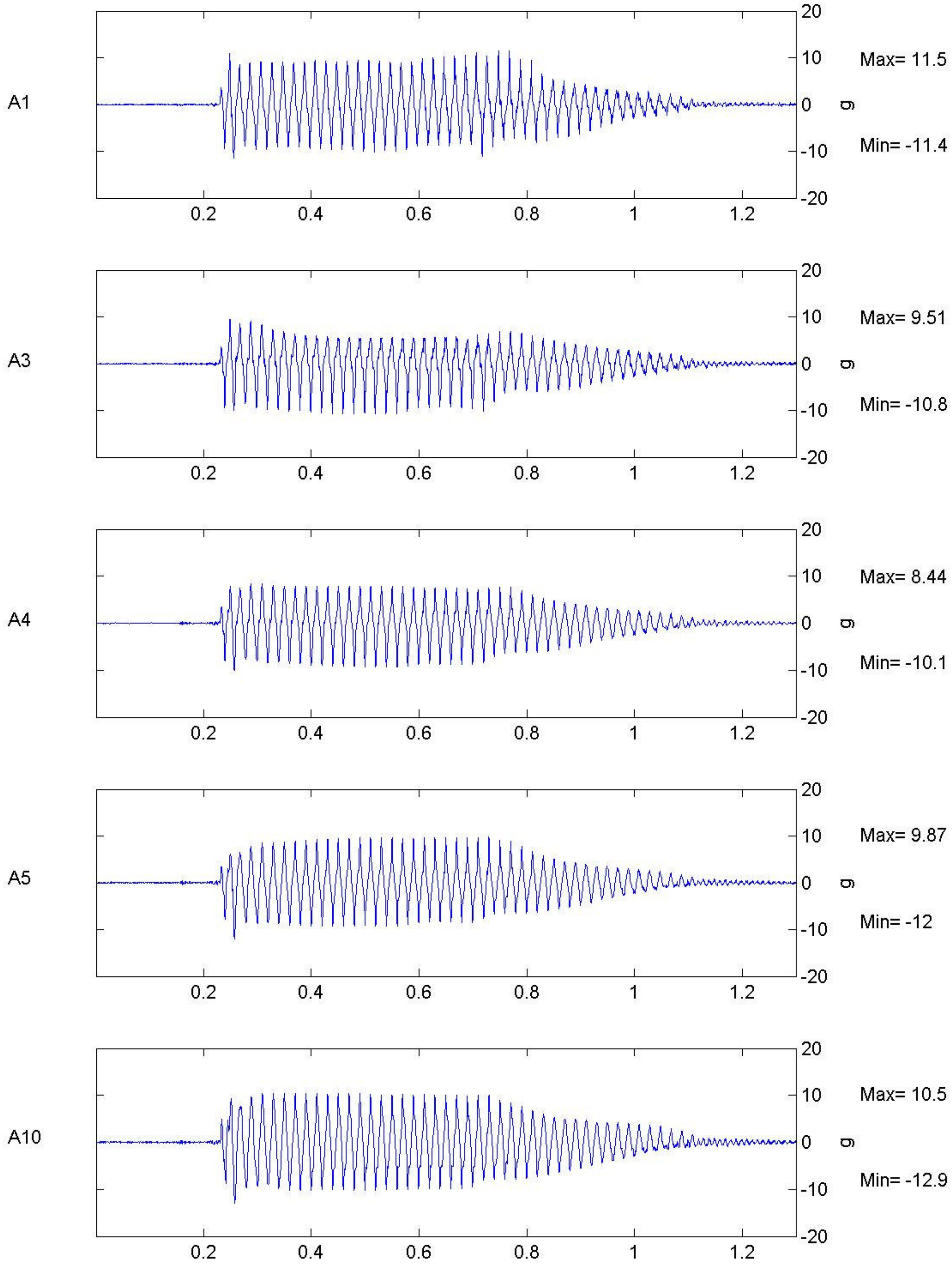
Max= 5.25

Min= -7.93

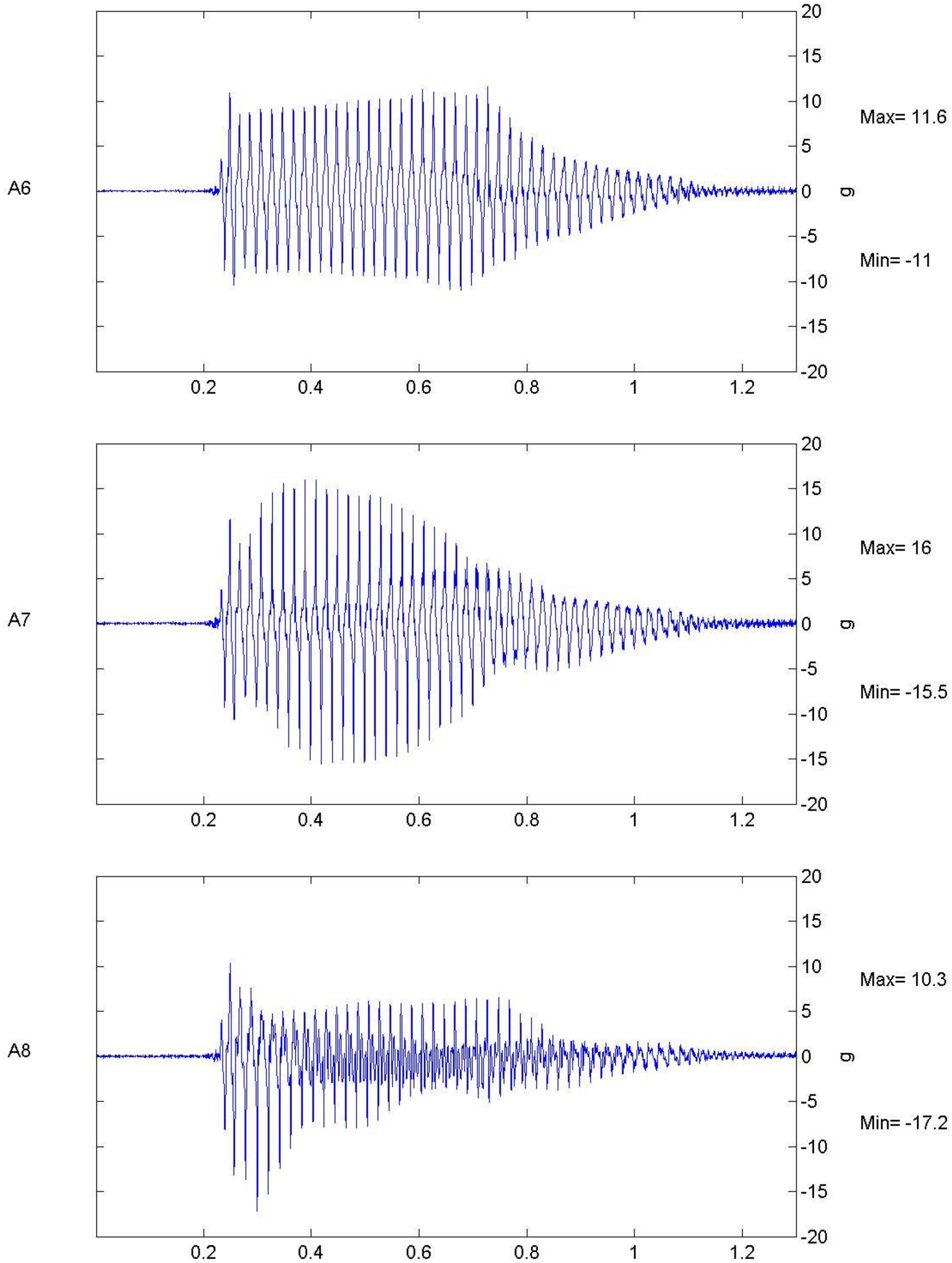
TEST BG-08	**FREQ 40 Hz**	Scales: Model 8th order Butterworth Filter at 750Hz	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	1	50



TEST BG-08 FLIGHT 1	**FREQ** **50 Hz**	Scales: Model Unfiltered Data Short-Term Time Records	Earthquake 4	Figure No. 51



TEST BG-08 FLIGHT 1	**FREQ 50 Hz**	Scales: Model 8th order Butterworth Filter at 750Hz Short-Term Time Records	Earthquake 4	Figure No. 52



TEST BG-08 FLIGHT 1	**FREQ** **50 Hz**	Scales: Model 8th order Butterworth Filter at 750Hz Short-Term Time Records	Earthquake 4	Figure No. 53