[Opinion]

A Proposal for a Standardized Fault Description Format to Study Active Intraplate Tectonics in the Korean Peninsula

Youngbeom Cheon, Jin-Hyuck Choi, Seung Ryeol Lee
Geology Division, Korea Institute of Geoscience and Mineral Resources
(Received: 3 December 2019, revised: 9 December 2019, accepted: 11 December 2019)
Corresponding author: cheonyb@kigam.re.kr

Abstract: Intraplate faulting and the resultant earthquakes are not well understood because of their complex distribution, long period of seismic recurrence, and poor exposure of surface rupture. Pre-existing weaknesses should be studied to understand intraplate faulting and earthquakes. We are developing a long-term project to understand Korean-type intraplate fault behavior and recurrence intervals. As the first step, we will establish an integrated system for production, analysis, and management of fault data related to active crustal deformation. Here we propose a new format for fault data description and management.
keywords: Intraplate faulting, earthquake, pre-existing weakness, fault data description and management

1. Introduction

Plate boundary faults, loaded by steady-state relative plate motion, quasi-periodically release strain energy causing concentration of earthquake along plate boundary (Liu et al., 2011). In contrast, intraplate faults with a high degree of complexity and connectivity tend to be selectively reactivated in response to far field stress (Liu et al., 2011). Therefore, earthquakes in intraplate region are spatiotemporally much less regular than those in interplate region (Liu et al., 2011). Although some of the most destructive earthquakes in the world have occurred in intraplate region (England and Jackson, 2011), potentially active seismogenic structures are unfortunately not well exposed at surface due to coverage by thick recent sediments. In addition, moderate earthquakes within intraplate region commonly accompanied with rupture propagation beneath the surface. Earthquake behavior of blind active faults could be underestimated, until the occurrence of damaging earthquakes (Yule and Sieh, 2003 and references therein).

Most intraplate earthquakes occur along pre-existing weaknesses (Wibberley et al., 2008 and references therein). Under a homogeneous stress field, preferential reactivation is controlled by (1) attitudes of pre-existing fractures to imposed stress, (2) presence of anomalously low-friction material along particular faults, (3) heterogeneous distribution of fluid overpressure, and (4) fault distribution complexity, such as fault segment, connectivity, and discontinuity (e.g. Barka and Kadinsky-Cade, 1988; Sibson, 1995; Kelly et al., 1999). We therefore need to study pre-existing weaknesses (e.g., basement faults) in detail to understand intraplate faulting and the resultant earthquakes. The Geology Division at the Korea Institute of Geoscience and Mineral Resources (KIGAM) is developing a long-term project to build a Korean-type intraplate fault behavior and recurrence model. This project, referred to as the

Intraplate Setting Active Fault behavior & Earthquake recurrence or IntraSAFE, will establish an integrated system for production, analysis, and management of highly reliable fault data. To do this, we need to compile already-published fault data using a standardized description format and then manage additional data to be produced in the same format.

We therefore propose a new simplified format for fault outcrop descriptions in the integrated system (Fig. 1). We also present an example (Fig. 2) of a re-written fault outcrop description in the suggested format, using the data from the main core of the northern Yangsan Fault, originally produced by Cheon et al. (2019).

2. Why Do We Need Integrated Fault Data?

The widely accepted conceptual definition of a fault is any surface or narrow zone with visible shear displacement along it (Fossen, 2010). Although the term fault covers both brittle and ductile slip discontinuities, many geologists implicitly restrict the term to refer only to slip discontinuities dominated by brittle behavior (Fossen, 2010). Generally, a brittle fault zone can be divided into a fault core of cataclastic rocks, where most of the displacement is accommodated, and a surrounding damage zone of subsidiary structures (e.g. Chester et al., 1993; Caine et al., 1996; Billi et al., 2003; Faulkner et al., 2010). Additionally, a physically-discrete mixed zone could develop between fault core and damage zone (e.g. Rawling and Goodwin, 2003, 2006). Materials and structural complexity within a fault zone play an important role in controlling its hydrological, mechanical, and seismological properties and behaviors (e.g. Rawling et al., 2001; Wibberley et al., 2008; Faulkner et al., 2010). Thus, detailed quantitative information on the complex internal structure of a fault zone is definitely required to understand its earthquake behavior. A collection of fault outcrop information could provide significant data to understand fault segmentation.
During the last several decades, many Korean researchers have studied the structure and evolutionary history of Quaternary and basement faults. Recently, the damage caused by two moderate earthquakes (2016 Gyeongju and 2017 Pohang earthquakes; e.g. Kim Y et al., 2016; Kim K-H et al., 2016, 2017; Choi et al., 2019) in the southeastern part of Korea have led to an increase in personal and national interest in fault activity. As a result, several research projects concerning faults and earthquakes are being conducted. However, there are still no standardized formats for fault outcrop description and data acquisition, and a large amount of information on faults in the Korean peninsula is still distributed. It is thus necessary to build a database in a unified format via standardization and systematization. The integration and advancement of fault-to-earthquake information will contribute to a reliable archive of crustal deformation information and can be used as concrete data for earthquake disaster assessment.

3. Summary Of The Fault Outcrop Description Form

The proposed description format contains a series of fault outcrop information, which is divided into basement fault information and Quaternary movement information. The items are as follows:

[Basement Fault Information]

(1) Investigation Name

: Describe name of fault outcrop.

(2) Researcher or Reference
: Describe researcher (or reference) who conducts fault investigation.
(3) Investigation Locality
(Administrative District, GPS coordinates)
: Describe the place where fault outcrop is situated.
(4) Photo
: Insert representative picture or photograph of fault outcrop.
(5) Fault Strike
: Describe fault strike, which is the direction of a line created by the intersection of a fault plane and a horizontal surface, 0° to 360° clockwise relative to North. All orientation data is described in azimuth notation.
(6) Fault Dip
: Describe dip of fault surface. It is angle of inclination measured from the horizontal.
(7) Fault Type
: Describe kinematics of fault. It is described as "RL (right-lateral (dextral) fault)", "LL (left-lateral (sinistral) fault)", "N (normal fault)", "R (reverse fault)", If it is oblique fault, it can be described as combination of lateral slip and dip slip, such as RL+N, RL+R, N+LL, R+RL, etc. If the fault has multiple movement kinematics, describe the dominant kinematics and then minor kinematics.
(8) Fault Striation
: Describe striation on fault surface. Striations are linear furrows, or linear marks on fault surface. It reveals the direction of movement along the fault. It can be described as "trend/plunge".
(9) Internal Structure
(Width, Kinematic Indicator, Deformation Characteristics)
: Describe characteristics of internal structure of fault zone (fault core, fault damage zone, mixed zone, fault rock type and material, alteration, microstructure, fault rock K-Ar age, and so on).
(10) Basement rocks Information
(Lithology, Stratigraphy, Radiometric Age)
: Describe information on basement rocks transected by fault.
[Quaternary Movement Information]
(11) Quaternary Movement Type
: Describe fault kinematics during the Quaternary.
(12) Quaternary offset Indicator
(Marker, Offset, Formation Age)
: Describe Quaternary displacement indicators. Markers of the Quaternary offset indicator are mainly geomorphic surface and/or sediment.
(13) Age of Last Movement
: Describe the latest movement of fault (ky BP) based on offset marker whose age can be estimated.

(14) Slip Rate
: Describe the slip rate (mm/yr) of fault during the Quaternary, determined from displacement and age of offset marker.

4. Acknowledgements

This research was supported by a grant (2018M3D7A1052897) from the Research on Geologic Hazard Assessment of Large Fault System Focusing on the Central Region of the Yangsan Fault from Basic Research Project of the Institute of Geoscience and Mineral Resources (KIGAM) funded by the National Research Foundation of Korea. We gratefully thank Prof. Park, S.I. and Prof. Cho. H. for valuable reviews.

5. References

Barka AA, Kadinsky-cade K (1988) Strike-slip fault geometry in Turkey and its Influence on earthquake activity. Tectonics, 7: 663-684.

Billi A, Salvini F, Storti F (2003) The damage zone-fault core transition in carbonate rocks: implications for fault growth, structure and permeability. J Struct Geol 25: 1779-1794.

Caine JS, Evans JP, Forster CB (1996) Fault zone architecture and permeability structure. Geology, 24, 1025-1028.

Cheon Y, Cho H, Ha S, Kang H-C, Kim J-S (2019) Tectonically controlled multiple stages of deformation along the Yangsan Fault Zone, SE Korea, since Late Cretaceous. J Asian Earth Sci 170: 188-207.

Chester FM, Evans JP, Biegel RL (1993) Internal structure and weakening mechanisms of the San Andreas Fault. J Geophys Res 98: 771-786.

Choi JH, Ko K, Gihm YS, Cho CS, Lee H, Song SG, Bang E-S, Lee H-J, Bae H-K, Kim SW, Choi S-J, Lee SS, Lee SR (2019) Surface deformations and rupture Processes associated with the 2017 M_w 5.4 Pohang, Korea, Earthquake. B Seismol Soc Am 109: 756-769.

England P, Jackson J (2011) Uncharted seismic risk. Nat Geosci 4: 348-349.

Faulkner DR, Jackson CAL, Lunn RJ, Schlische RW, Shipton ZK, Wibberley CAJ, Withjack, MO (2010) A review of recent developments concerning the structure, mechanics and fluid flow properties of fault zones. J Struct Geol 32: 1557-1575.

Fossen H, (2010) Structural Geology. Cambridge University Press, New York, 463 p.

Kim K-H, Kang T-S, Rhie J, Kim Y, Park Y, Kang SY, Han M, Kim J, Park J, Kim M, Kong C, Heo D, Lee H, Park E, Park H, Lee S-J, Cho S, Woo J-U, Lee S-H, Kim J (2016) The 12 September 2016 Gyeongju earthquakes: 2. Temporary seismic network for monitoring aftershocks. Geosci J 20: 753-757.

Kim K-H, Kim J, Han M, Kang SY, Son M, Kang T-S, Rhie J, Kim Y, Park Y, Kim H-J, You Q, Hao T (2017) Deep Fault Plane Revealed by High-Precision Locations of Early Aftershocks Following the 12 September 2016 ML 5.8 Gyeongju, Korea, Earthquake. B Seismol Soc Am 108: 517-523.

Kim Y, Rhie J, Kang T-S, Kim K-H, Kim M, Lee S-J (2016) The 12 September 2016 Gyeongju earthquakes: 1. Observation and remaining questions. Geosci J 20: 747-752.

Kelly PG, Peacock DCP, Sanderson DJ, McGurk AC (1999) Selective reverse-reactivation of normal faults, and deformation around reverse-reactivated faults in the Mesozoic of the Somerset coast. J Struct Geol 21: 496-509.

Liu M, Stein S, Wang H (2011) 2000 years of migrating earthquakes in North China: How earthquakes in midcontinents differ from those at plate boundaries. Geol Soc Am 3: 128-132.

Rawling GC, Goodwin LB (2003) Cataclasis and particulate flow in faulted, poorly lithified sediments. J Struct Geol 25, 317-331.

Rawling GC, Goodwin LB (2006) Structural record of the mechanical evolution of mixed zones in faulted poorly lithified sediments, Rio Grande rift, New Mexico, USA. J Struct Geol 28: 1623-1639.

Sibson RH (1995) Selective fault reactivation during basin inversion: potential for fluid redistribution through fault-valve action. Geol Soc Spec Publ 88: 3-19.

Wibberley CAJ, Yielding G, Toro GD (2008) On the structure and mechanical properties of large strike-slip faults. In: Wibberley CAJ, Kurz W, Imber J, Holdsworth RE, Collettini C (eds.) The internal structure of fault zones: Implications for mechanical and fluid flow properties. Geol Soc Spec Publ 299: 5-33.

Yule D, Sieh K (2003) Complexities of the San Andreas fault near San Gorgonio Pass: Implications for large earthquakes. J Geophys Res 108 B11: 2548.

Table. 1. Fault outcrop description format

Investigation Name(1)	Researcher or Reference(2)	Investigation Locality(3)		Photo(4)
		Administrative District	GPS coordinates	
			N○○°○○'○○"	
			E○○○°○○'○○"	

Fault Strike(5)	Fault Dip(6)	Fault Type(7)	Fault Striation(8)	Internal Structure(9)				
				Width (m)			Kinematic Indicator	Deformation Characteristics
		(major kinematics)		Fault Core			(movement sense indicator)	(fault rock material, fault rock K-Ar age, etc.)
		(minor kinematics)		Fault Damage zone	Hanging wall		(movement sense indicator)	(subsidiary fault, bedding, vein, etc.)
					Footwall			

Basement Rocks Information(10)					Remark
	Lithology	Stratigraphy	Radiometric Age (Ma)		(number of movement events, relative chronology of structures, reconstructed paleostresses etc.)
			Method	Age	
Hanging wall					
Footwall					

Quaternary Movement Information							
Quaternary Movement Type(11)	Quaternary offset Indicator(12)					Slip Rate(13) (mm/yr)	Age of Last Movement(14) (ky BP)
	Marker	offset (m)		Formation Age (ka)			
		Horizontal	Vertical	Method	Age		
Remark							
(number of Quaternary fault movement events, recurrent interval, fault rock ESR age, etc.)							
References							

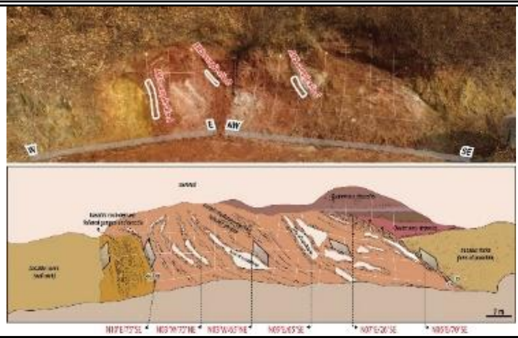
(5) and (6): All orientation data is described in azimuth notation.

(7) and (11): Fault type is described as RL (right-lateral (dextral) fault), LL (left-lateral (sinistral) fault), N (normal fault), or R (reverse fault), If it is an oblique fault, it can be described as combination of lateral slip and dip slip, such as RL+N, RL+R, N+LL, or R+RL.

(8): Fault striation is described in "trend/plunge".

(12): Markers of Quaternary offset indicators are mainly geomorphic surface and/or sediment

Table. 2. Example (data from Cheon et al. (2019))

<table>
<tr><th rowspan="2">Investigation Name[(1)]</th><th rowspan="2">Researcher or Reference[(2)]</th><th colspan="2">Investigation Locality[(3)]</th><th rowspan="2">Photo[(4)]</th></tr>
<tr><th>Administrative District</th><th>GPS coordinates</th></tr>
<tr><td rowspan="2">YF-1</td><td rowspan="2">Cheon et al. (2019)_Journal of Asian Earth Science</td><td rowspan="2">Chuksan-Myeon, Yeongdeok-Gun, Gyeongsangbuk-Do</td><td>N36°29′31.68″</td><td rowspan="2"></td></tr>
<tr><td>E129°24′35.03″</td></tr>
</table>

<table>
<tr><th rowspan="2">Fault Strike[(5)]</th><th rowspan="2">Fault Dip[(6)]</th><th rowspan="2">Fault Type[(7)]</th><th rowspan="2">Fault Striation[(8)]</th><th colspan="5">Internal Structure[(9)]</th></tr>
<tr><th colspan="3">Width (m)</th><th>Kinematic Indicator</th><th>Deformation Characteristics</th></tr>
<tr><td rowspan="3">010°</td><td rowspan="3">70°</td><td>RL</td><td>-</td><td rowspan="1">Fault Core</td><td colspan="2">22</td><td>- Dextral slip kinematics in sedimentary-rock-derived subzone based on magnetic fabric analysis
- Dextral transpressional kinematics in basaltic-rock-derived subzone based on striations</td><td>- Basaltic-rock-derived-subzone (western part): 2 m in width; composed of foliated fault gouge and breccia
- Purple-mudstone-derived-subzone (eastern part): 20 m in width; composed of purple gouge and breccia; a few to tens of cm-thick lenses derived from light gray sandstone (NNE-SSW to N-S alignment); approximately 5-m-thick basaltic lens
- Thin (~2 cm), highly polished band of gouge between basaltic-rock-derived-subzone and sedimentary-rock-derived-subzone</td></tr>
<tr><td rowspan="2">RL+R</td><td rowspan="2">073°/68°</td><td rowspan="2">Fault Damage zone</td><td>Hanging wall</td><td>Several tens of meters</td><td rowspan="2"></td><td rowspan="2">- Difficult to determine the width and characteristics of the damage zone due to its exposure condition</td></tr>
<tr><td>Footwall</td><td>Several tens of meters</td></tr>
</table>

<table>
<tr><th colspan="4">Basement Rocks Information[(10)]</th><th>Remark</th></tr>
<tr><td></td><td>Lithology</td><td>Stratigraphy</td><td>radiometric Age (Ma)</td><td></td></tr>
</table>

			Method	Age	
Hanging wall	Purple mudstone	Hayang Group Ullyeonsan Formatiom	U-Pb SHRIMP	< 108 Ma	- The Ullyeonsan Formation sandstone detrital zircon U-Pb SHRIMP age is < 108 Ma (Kang et al., 2018) - E–W maximum horizontal compression reconstructed by striations in basaltic-rock-derived-subzone
Footwall	basalt	Yucheon Group	-	-	

Quaternary Movement Information

Quaternary Movement Type[11]	Quaternary offset Indicator[12]					Slip Rate[13] (mm/yr)	Age of Last Movement[14] (ky BP)
	Marker	Offset (m)		Formation Age (ka)			
		Horizontal	Vertical	Method	Age		

Remark

References

Cheon, Y., Cho, H., Ha, S., Kang, H.-C., Kim, J.-S., Son, M., 2019, Tectonically controlled multiple stages of deformation along the Yangsan Fault Zone, SE Korea, since Late Cretaceous. Journal of Asian Earth Sciences, 170, 188-207.

Kang, H,-C., Cheon, Y., Ha, S., Seo, K., Kim, J.-S., Shin, H.C., Son, M., 2018, Geology and U-Pb Age in the Eastern Part of Yeongdeok-gun, Gyeongsangbuk-do, Korea. Journal of the Petrological Society of Korea, 27, 153-171 (in Korean with English abstract).