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General metrics

14,830	2,279	116	9 min 6 sec	17 min 31 sec
characters	words	sentences	reading time	speaking time

Score

81

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Writing Issues

118	64	54
Issues left	Critical	Advanced

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Writing Issues

73	**Correctness**	
20	Determiner use (a/an/the/this, etc.)	
8	Faulty subject-verb agreement	
11	Mixed dialects of english	
9	Misspelled words	
3	Comma misuse within clauses	
4	Punctuation in compound/complex sentences	
1	Misplaced words or phrases	
6	Wrong or missing prepositions	
7	Incorrect noun number	
1	Faulty tense sequence	
2	Confused words	
1	Improper formatting	
41	**Clarity**	
21	Passive voice misuse	
9	Wordy sentences	
1	Hard-to-read text	
10	Unclear sentences	
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Unique Words

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rare words

Word Length

4.6

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Sentence Length

19.6

Measures average sentence length

words per sentence

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SUBSURFACE STRUCTURE OF BATURAGUNG ESCARPMENT REVEALED THROUGH THREE-DIMENSIONAL GRAVITY INVERSION

STRUKTUR BAWAH PERMUKAAN PEGUNUNGAN BATURAGUNG DITINJAU MENGGUNAKAN INVERSI 3D ANOMALI GRAVITASI

Abstract. Baturagung Escarpment is an essential tectonic element of the Java[1] Island because it represents a transition from the Southern Mountain Block to the Kendeng Basin. This study has succeeded in producing a three-dimensional model of the Baturagung Escarpment subsurface using gravity anomaly data. The data is distributed[2] along a regional scale transect, whose resolving capability has been tested[3] using a checkerboard test. Our proposed geophysical model can fit the observed data very well, with a 0.77% RMS error. This model exhibits the existence of[4] a structural depression bounded by high basement blocks below the Baturagung Escarpment, one of the basement block outcrops at Jiwo Hills. The maximum width of the depression is ~10 km, with a depth exceeding 3 km in some places. The depression might be formed[5] because of an extensional tectonic regime that prevailed during the Palaeogene, followed by volcanic arc loads' emplacement up to the early Miocene.

Abstrak. Pegunungan Baturagung adalah salah satu unsur tektonik penting di Pulau Jawa karena mewakili transisi dari Blok Pegunungan Selatan ke Cekungan Kendeng. Dalam penelitian ini, kami berhasil membuat suatu model geofisika tiga dimensi bawah permukaan Pegunungan Baturagung dengan menggunakan metode gravitasi. Data gravitasi yang kami gunakan dikumpulkan pada titik-titik yang tersebar pada lintasan pengukuran skala regional. Uji papan catur telah memastikan bahwa persebaran titik-titik kami mampu mencapai target penelitian, yaitu keberadaan struktur geologi di bawah Pegunungan Baturagung. Model geofisika yang kami usulkan dapat memberikan nilai anomali yang sesuai dengan data pengamatan (ralat RMS sebesar 0.77%). Model tersebut menunjukkan keberadaan cekungan yang berjurus Timur Laut – Barat Daya dengan lebar maksimal ~10 km di bawah Pegunungan Baturagung. Kedalaman maksimum dari cekungan ini > 3 km. Cekungan ini dibatasi oleh blok batuan dasar yang salah satu bagiannya tersingkap di Perbukitan Jiwo. Kami menginterpretasikan bahwa cekungan tersebut bisa terbentuk karena adanya tektonik ekstensi selama masa Paleogen diikuti dengan masuknya busur vulkanik hingga Miosen awal.

INTRODUCTION

In the study of[6] the tectonics of Java Island, the Baturagung Escarpment is of utmost importance because it represents the transition from the Southern Mountain Block to the Kendeng Basin (Smyth et al., 2008). Baturagung Escarpment is composed of Cenozoic sedimentary strata that sits[7] unconformably above a Mesozoic metamorphic basement (Fig. 1) that crops out as Jiwo Hills (Rahardjo et al., 1995; Smyth et al., 2008; Surono et al., 1992).[8]

Several theories have been proposed[9] for the formation of Baturagung Escarpments, such as thrusting of Southern Mountain Block (Hall et al., 2007), vertical block faulting (Rahardjo et al., 1995; Surono et al., 1992), or northward-dipping normal fault (van Bemmelen, 1949). However, such theories were developed[10] upon surficial geological examinations, which may deviate from the true[11] subsurface conditions. Inspection of subsurface geology requires interpretation of geophysical data using an objective mathematical technique, such as inverse modelling[12] (Milsom & Eriksen, 2011). In this study, we will investigate the subsurface features of the Baturagung Escarpment by constrained inversion of gravity anomaly data.[13] The inversion strategy applied here will follow that of Miller et al. (2017), supplemented with the application of a reference model to guide the inversion process.

PREVIOUS STUDIES

Regional scale[15] gravity anomaly mapping around the Baturagung Escarpment have[16] been conducted[17] by Sato and Untung (1978), Budiman (1991), Marzuki and Otong (1991), and Haryono et al. (1995). More recent gravity anomaly studies in the region have been targeting local-scale anomalies, e.g.[18] Arief et al. (2009) and Sihombing et al. (2015). However, all those studies were modelling[19] the anomaly using 2D or 2.5D source bodies.

In this study, we will model the gravity anomaly data using 3D volume elements (voxel). Theoretical[20] background of 3D gravity modelling[21] have[22] been explained in detail by Li and Oldenburg (1998). Three-dimensional gravity modelling[23] have[24] been applied[25] in Indonesia, e.g.[26] to resolve magmatic intrusion below Gunung Pandan (Wahyudi et al., 2019), hydrocarbon-producing anticline in Borneo (Christensen et al., 2018), and subsurface structures related to Sidoarjo Mudflow (Osorio et al., 2019).

METHODS

We use gravity anomaly data gathered over Baturagung Escarpment by an exploration group of Institut Teknologi Bandung (Fig. 1). The gravity data is then reviewed and processed into complete Bouguer anomaly using formulas presented in Hinze et al. (2005) and Hinze et al. (2013). The complete Bouguer anomaly is devoid of gravity effect from an ideal terrain above a vertical datum (Hinze et al., 2005), and to calculate the effect of topography above the WGS84 ellipsoid, we[27] build a MATLAB routine using Eq. 32 of Roussel et al. (2015). The value of rock density used for the data processing is 2.67 g/cm3. Because we are interested in the local-scale subsurface geology, we use the residual Bouguer anomaly to produce the density model. Calculation of the residual Bouguer anomaly Arx,y follows this formula (Hinze et al., 2013).

Arx,y=Ax,y-ARx,y

(1)

In the eq. (1), Ax,y denotes the complete Bouguer anomaly, and ARx,y symbolizes the regional Bouguer anomaly. To compute the regional Bouguer anomaly[28], this study uses a simple planar surface approximation of the form ARx,y=A+Bx+Cy (Draper & Smith, 1981). The simple planar surface approximation is chosen[29] to replicate the regional gravity effect given by the southwestern edge of the Merapi-Lawu Anomaly (Luehr et al., 2013).

To model the gravity data, we use the SimPEG package (Cockett et al., 2015). To run the modelling[30] process, SimPEG can use raw point data as its input and[31] no prior gridding is required (Cockett et al., 2015; Miller et al., 2017).[32] Thus, SimPEG is suitable for modelling[33] gravity data collected at unevenly spaced points on topographically challenging regions (Miller et al., 2017).

Modelling[34,35] process of SimPEG sought to minimize the objective function ϕm (Cockett et al., 2015).

ϕ(m) =ϕd(m) +βϕm(m)

(2)

An array of proposed model values is denoted[36] by m. In[37] the right hand[38] side of Eq. (2), β is a positive constant referred to as trade-off parameter, regression parameter, regularization parameter or[39] Tikhonov parameter (Tikhonov et al., 1995). Misfit between the observation data and modelled[40] values is denoted[41] by ϕd(m).

$\phi d(m) = 0.5 \cdot WdFm\text{-}dobs22$

(3)

In the Eq.[42] (3) above, Wd is a diagonal matrix whose diagonal elements are equal to 1ϵi, where ϵi equals to[43,44] the estimated value of standard[45] deviation of the ith data. The modelled[46] gravity values are symbolized by Fm, with F⋯ acts as an operator that calculates the gravity effect from the model m. Observed gravity data is denoted[47] by dobs (Cockett et al., 2015; Miller et al., 2017).

On the other hand, ϕm(m) is calculated[48] using the following equation.

$\phi m(m) = 0.5 \cdot Wmm\text{-}mref22$

(4)

Eq. (4) above represents a measure of misfit between current model m and an a priori model mref[49]. This study uses a two-layered finite rectangular block model for mref[50], with upper[51] layer density of 2.3 g/cm3 and the lower[52] layer density of 3 g/cm3.

The difference between m and mref[53] is weighted[54] by Wm, a matrix whose elements are defined[55] by eq. (5) below.

$Wm = \alpha sI, \alpha xWxT, \alpha yWyT, \alpha zWzTT$

(5)

Both α* and W* controls the smoothness of the density model. Smaller values of α* and W* (minimum zero) will lead to a blocky density model, which is[56] suitable in areas with sharp density contrasts (Cockett et al., 2015; UBC-GIF, 2015a). In this study, we use these values for Wm.

Wm =2, 2,2,2T

(6)

Using Wm value described in eq. (6) will guarantee that the inversion process produces a model that is midway between smooth and blocky (UBC-GIF, 2015b). Our study also limits the inversion process to fill the density model with values ranging from 2 to 3 g/cm3. The lower search limit would indicate the bulk density of cavernous limestone, while the upper one would denote the bulk density of metamorphic and igneous basement (Jacoby & Smilde, 2009).

RESULTS AND DISCUSSION

Sensitivity Test

To demonstrate that our data point distribution is sufficient for resolving the subsurface structures below the Baturagung Escarpment, we did a sensitivity test.[57] In the test, we simulate a gravity anomaly measurement over a checkerboard density model below the Baturagung Escarpment topographic surface.[58] The location of measurement is equal to the position of our data points, and the gravity anomaly values at that point is[59] treated[60] as the observation data.[61] We then model the subsurface density using the observed gravity anomaly data, with parameters and reference model described in section (3). The results of our sensitivity test are presented[62] in Figure[63] 2 and 3. SimPEG inversion procedure successfully recovers the gravity anomaly produced by the checkerboard pattern measured on our data point. The amplitude of difference between the observed checkerboard anomaly (Fig. 2A) and the calculated anomaly (Fig. 2B) is no more than 0.03 mGal (Fig. 2C). The RMS error of the calculated anomaly is 0.01 mGal. In producing the three-dimensional density model, the inversion runs[64] for 35 iterations and converged after 30 iterations (Fig. 2D).

Three-dimensional[65] density model[66] calculated from the checkerboard gravity effect observed at our data points have patterns that matched the original checkerboard (Fig. 3). However, the original density values are not recovered well (Fig. 3B and 3D). In the calculated model, deeper voxels have lesser[67] density difference between the originally[68] negative and positive checkerboard density blocks. Another striking feature of the calculated density model (Fig. 3B and 3D) is[69] the presence of[70] fictitious circular high-density voxels surrounding data points located in the originally[71] negative density checkerboard blocks.

Baturagung Escarpment Gravity Anomaly

Figure (4) shows the residual gravity anomaly as measured over Baturagung Escarpment. A zone of gravity low is evident at the north eastern[72], central, western, and southern part[73] of the survey area (Fig. 4A). The inversion process converges after 20 iterations (Fig. 4D) and successfully reconstructed the observed anomaly (Fig. 4B) with RMS error 0.77 mGal (0.77% of data amplitude). Difference[74,75] between the calculated and observed anomaly are[76] mostly within 2[77] mGal (Fig. 4C). Large[78] difference[79] at the northwestern data points may hint at the insufficient data sampling over a concealed geologically complex region.

Modelling[80] of residual gravity anomaly data shows the presence of NW – SE trending, ~10 km-wide depression below the Baturagung Escarpment (Baturagung Depression, Fig. 5).[81] The depression is bounded[82] by fault associated to[83] Baturagung Escarpment (Fig. 5B). High density[84] basement block,[85] that outcrops at the northern part of survey[86] area (Fig. 1),[87] bounds the northern limit of sedimentary[88] basin (Fig. 5 and 6). Block faulting that bounds the northern limit of Baturagung[89] Depression (Fig. 6A and 6B) closely supports the geological cross section[90] proposed by Surono et al. (1992). In the deepest part of Baturagung[91] Depression, the contact between the low-density sediments and the basement might occur at a depth of more than 3 km (Fig. 6). Bodies of relatively higher density embedded in the sedimentary layer (Fig. 5A and 6) may reflect the presence of buried remnants of igneous masses related to the Late Oligocene – Early Miocene volcanoes around the Baturagung Depression (Hartono & Bronto, 2007; Smyth et al., 2011).

In our model, the basement block that limits the southern side of Baturagung[92] Depression extends far beyond our survey area (Fig. 5 and 6). The northern basement block, however, is restricted by a fault that cuts the northern part of our survey area (Fig. 5 and 6B).[93] The fault, which trends from E to W, might have played an important[94] role in the tilting of Baturagung Escarpment and compressional tectonic features observed there[95] (cf. Husein et al., 2008; Purnomo & Purwoko, 1994).

Formation of Baturagung Depression

The presence of a geological depression beneath the Baturagung Escarpment is a novel idea for most geologists dealing with the tectonics of Javanese[96] Southern Mountains. Nevertheless, the presence of such feature in the Southern Mountains region have[97] been postulated[98] by Julias et al. (2017). The alignment of Baturagung[99] Depression is perpendicular to the Meratus Trend (Fig. 7, Subroto et al., 2007) that hosts several grabens that opened during the Paleogene (30 to 40 Ma, Mulyawan & Husein, 2014; Purnomo & Purwoko, 1994). The grabens are directed from NW to SE as a response[100] to the SSE-NNW directed[101] compressive stresses (Purnomo & Purwoko, 1994; Gultaf, 2014). The deepening process of Baturagung[102] Depression may continue well into the early Miocene (~20 Ma) due to the loads from the Southern Mountains Volcanic Arc mass (Smyth et al., 2008; Soeria-Atmadja et al., 1994; Waltham et al., 2008).

CONCLUSION AND FUTURE WORKS

We have successfully produced a new subsurface density model of the Baturagung Escarpment using gravity anomaly data. The data was collected[103] at distributed points that can objectively resolve large scale[104] regional geological structures in the region. Modelling[105] of the residual gravity anomaly revealed the presence of a concealed geological depression beneath the Baturagung Escarpment, which we called as Baturagung Depression.[106] Near the surface, the depression is at maximum[107] ~10 km wide, and it gets narrower with depth.[108] In the deepest part of the depression, the thickness of the sedimentary layer exceeds 3 km. Baturagung Depression might be formed[109] because of a prevailing extensional tectonic regime during the Paleogene (30 - 40 Ma) followed by the emplacement of volcanic arc loads up to the early Miocene (~20 Ma).

Future works in the Baturagung Escarpment should be directed[110] into refining our subsurface model by incorporating the available or acquiring new gravity data. It is also possible to improve our model using the available borehole and geological dataset from various sources. A better understanding of Baturagung Escarpment geology will improve our knowledge on[111] the tectonic processes that has[112] affected Java Island, especially during the Cenozoic.

ACKNOWLEDGEMENTS

The writer would be grateful to[113] the helps[114] and assistances[115] offered by various parties during the course of[116] fieldwork, data processing, analysis, and paper writing.[117] The first author would like to thank to[118] Institut Teknologi Sumatera for supporting this research.

1.	~~the~~ Java	Determiner use (a/an/the/this, etc.)	Correctness
2.	*is distributed*	Passive voice misuse	Clarity
3.	*been tested*	Passive voice misuse	Clarity
4.	~~the existence of~~	Wordy sentences	Clarity
5.	*be formed*	Passive voice misuse	Clarity
6.	~~the study of~~ → studying	Wordy sentences	Clarity
7.	~~sits~~ → sit	Faulty subject-verb agreement	Correctness
8.	*Baturagung Escarpment is composed of Cenozoic sedimentary strata that sits unconformably above a Mesozoic metamorphic basement (Fig. 1) that crops out as Jiwo Hills (Rahardjo et al., 1995; Smyth et al., 2008; Surono et al., 1992).*	Hard-to-read text	Clarity
9.	*been proposed*	Passive voice misuse	Clarity
10.	*were developed*	Passive voice misuse	Clarity
11.	~~true~~ → actual, proper, right, real	Word choice	Engagement
12.	~~modelling~~ → modeling	Mixed dialects of English	Correctness
13.	*In this study, we will investigate the subsurface features of the Baturagung Escarpment by constrained inversion of gravity anomaly data.*	Unclear sentences	Clarity
14.	~~the application of~~ → applying	Wordy sentences	Clarity
15.	~~Regional scale~~ → Regional-scale	Misspelled words	Correctness
16.	~~have~~ → has	Faulty subject-verb agreement	Correctness

17.	*been conducted*	Passive voice misuse	Clarity
18.	e.g.,	Comma misuse within clauses	Correctness
19.	~~modelling~~ → modeling	Mixed dialects of English	Correctness
20.	The theoretical	Determiner use (a/an/the/this, etc.)	Correctness
21.	~~modelling~~ → modeling	Mixed dialects of English	Correctness
22.	~~have~~ → has	Faulty subject-verb agreement	Correctness
23.	~~modelling~~ → modeling	Mixed dialects of English	Correctness
24.	~~have~~ → has	Faulty subject-verb agreement	Correctness
25.	*been applied*	Passive voice misuse	Clarity
26.	e.g.,	Comma misuse within clauses	Correctness
27.	~~, we~~ → ; we, , and we, . We	Punctuation in compound/complex sentences	Correctness
28.	*To compute the regional Bouguer anomaly*	Misplaced words or phrases	Correctness
29.	*is chosen*	Passive voice misuse	Clarity
30.	~~modelling~~ → modeling	Mixed dialects of English	Correctness
31.	, and	Punctuation in compound/complex sentences	Correctness
32.	*To run the modelling process, SimPEG can use raw point data as its input and no prior gridding is required (Cockett et al., 2015; Miller et al., 2017).*	Unclear sentences	Clarity

33.	~~modelling~~ → modeling	Mixed dialects of English	Correctness
34.	The modelling	Determiner use (a/an/the/this, etc.)	Correctness
35.	~~Modelling~~ → Modeling	Mixed dialects of English	Correctness
36.	*is denoted*	Passive voice misuse	Clarity
37.	~~In~~ → On	Wrong or missing prepositions	Correctness
38.	~~right hand~~ → right-hand	Misspelled words	Correctness
39.	, or	Comma misuse within clauses	Correctness
40.	~~modelled~~ → modeled	Mixed dialects of English	Correctness
41.	*is denoted*	Passive voice misuse	Clarity
42.	~~the~~ Eq.	Determiner use (a/an/the/this, etc.)	Correctness
43.	~~to~~	Wrong or missing prepositions	Correctness
44.	~~to~~	Wordy sentences	Clarity
45.	the standard	Determiner use (a/an/the/this, etc.)	Correctness
46.	~~modelled~~ → modeled	Mixed dialects of English	Correctness
47.	*is denoted*	Passive voice misuse	Clarity
48.	*is calculated*	Passive voice misuse	Clarity
49.	~~mref~~ → ref, more, of	Misspelled words	Correctness
50.	~~mref~~ → more	Misspelled words	Correctness
51.	an upper	Determiner use (a/an/the/this, etc.)	Correctness

52.	~~the lower~~ → a lower	Determiner use (a/an/the/this, etc.)	Correctness
53.	~~mref~~ → more	Misspelled words	Correctness
54.	*is weighted*	Passive voice misuse	Clarity
55.	*are defined*	Passive voice misuse	Clarity
56.	~~, which is~~	Wordy sentences	Clarity
57.	*To demonstrate that our data point distribution is sufficient for resolving the subsurface structures below the Baturagung Escarpment, we did a sensitivity test.*	Unclear sentences	Clarity
58.	*In the test, we simulate a gravity anomaly measurement over a checkerboard density model below the Baturagung Escarpment topographic surface.*	Unclear sentences	Clarity
59.	~~is~~ → are	Faulty subject-verb agreement	Correctness
60.	*is treated*	Passive voice misuse	Clarity
61.	*The location of measurement is equal to the position of our data points, and the gravity anomaly values at that point is treated as the observation data.*	Unclear sentences	Clarity
62.	*are presented*	Passive voice misuse	Clarity
63.	~~Figure~~ → Figures	Incorrect noun number	Correctness
64.	~~runs~~ → ran	Faulty tense sequence	Correctness
65.	The three-dimensional	Determiner use (a/an/the/this, etc.)	Correctness
66.	~~model~~ → models	Incorrect noun number	Correctness
67.	a lesser	Determiner use	Correctness

		(a/an/the/this, etc.)	
68.	~~originally~~ → initially	Word choice	Engagement
69.	~~is~~ → in	Confused words	Correctness
70.	~~the presence of~~	Wordy sentences	Clarity
71.	~~originally~~ → initially	Word choice	Engagement
72.	~~north eastern~~ → northeastern	Confused words	Correctness
73.	~~part~~ → parts	Incorrect noun number	Correctness
74.	The difference	Determiner use (a/an/the/this, etc.)	Correctness
75.	~~Difference~~ → Differences	Incorrect noun number	Correctness
76.	~~are~~ → is	Faulty subject-verb agreement	Correctness
77.	~~2~~ → two	Improper formatting	Correctness
78.	The large	Determiner use (a/an/the/this, etc.)	Correctness
79.	~~difference~~ → differences	Incorrect noun number	Correctness
80.	~~Modelling~~ → Modeling	Mixed dialects of English	Correctness
81.	*Modelling of residual gravity anomaly data shows the presence of NW – SE trending, ~10 km-wide depression below the Baturagung Escarpment (Baturagung Depression, Fig. 5).*	Unclear sentences	Clarity
82.	*is bounded*	Passive voice misuse	Clarity
83.	~~to~~ → with	Wrong or missing prepositions	Correctness
84.	~~High density~~ → High-density	Misspelled words	Correctness

85.	block,	Punctuation in compound/complex sentences	Correctness
86.	the survey	Determiner use (a/an/the/this, etc.)	Correctness
87.	),	Punctuation in compound/complex sentences	Correctness
88.	the sedimentary	Determiner use (a/an/the/this, etc.)	Correctness
89.	the Baturagung	Determiner use (a/an/the/this, etc.)	Correctness
90.	~~cross section~~ → cross-section	Misspelled words	Correctness
91.	the Baturagung	Determiner use (a/an/the/this, etc.)	Correctness
92.	the Baturagung	Determiner use (a/an/the/this, etc.)	Correctness
93.	*The northern basement block, however, is restricted by a fault that cuts the northern part of our survey area (Fig. 5 and 6B).*	Unclear sentences	Clarity
94.	~~important~~ → essential	Word choice	Engagement
95.	~~there~~	Wordy sentences	Clarity
96.	the Javanese	Determiner use (a/an/the/this, etc.)	Correctness
97.	~~have~~ → has	Faulty subject-verb agreement	Correctness
98.	*been postulated*	Passive voice misuse	Clarity
99.	the Baturagung	Determiner use (a/an/the/this, etc.)	Correctness

100.	~~as a response~~ → to respond	Wordy sentences	Clarity
101.	SSE-NNW-directed	Misspelled words	Correctness
102.	the Baturagung	Determiner use (a/an/the/this, etc.)	Correctness
103.	*was collected*	Passive voice misuse	Clarity
104.	~~large scale~~ → large-scale	Misspelled words	Correctness
105.	~~Modelling~~ → Modeling	Mixed dialects of English	Correctness
106.	*Modelling of the residual gravity anomaly revealed the presence of a concealed geological depression beneath the Baturagung Escarpment, which we called as Baturagung Depression.*	Unclear sentences	Clarity
107.	a maximum	Determiner use (a/an/the/this, etc.)	Correctness
108.	*Near the surface, the depression is at maximum ~10 km wide, and it gets narrower with depth.*	Unclear sentences	Clarity
109.	*be formed*	Passive voice misuse	Clarity
110.	*be directed*	Passive voice misuse	Clarity
111.	~~on~~ → of	Wrong or missing prepositions	Correctness
112.	~~has~~ → have	Faulty subject-verb agreement	Correctness
113.	~~to~~ → for	Wrong or missing prepositions	Correctness
114.	~~helps~~ → help, bits of help	Incorrect noun number	Correctness
115.	~~assistances~~ → assistance	Incorrect noun number	Correctness
116.	~~the course of~~	Wordy sentences	Clarity

117.	*The writer would be grateful to the helps and assistances offered by various parties during the course of fieldwork, data processing, analysis, and paper writing.*	Unclear sentences	Clarity
118.	~~to~~	Wrong or missing prepositions	Correctness