CHAPTER - I

INTRODUCTION

1.1 GENERAL

A nation’s wealth, progress and prosperity depend primarily upon the natural resources wealth, ecological status and its natural disaster vulnerability. These nature related prospects and problems greatly depend on the present day Earth system architecture which is the cumulative expression of palaeo, time transgressive and ongoing geological processes. For example, some of the mineral deposits might have been originated millions of years ago, but their precise inventory and the follow up exploitation strategies warrant information on such palaeo, time transgressive and ongoing geological processes, as the same only are controlling their present geo-positions and morphology.

On the contrary, resources like hydrocarbon or placer mineral deposits or groundwater systems are predominantly controlled by the recent geological processes. But the natural disasters like earthquakes, tsunamis, landslides, floods, etc. are completely controlled by the recent geological processes viz: Neo–Active tectonics, riverine processes, coastal processes, volcanic processes, glacial processes etc. Hence in general, understanding the geological processes are vital, whether it is for mineral exploration or for ecosystem mapping or for natural disaster mapping / mitigation. But at the same time evaluation of geological processes and their changing pattern over the years are difficult as it involves large amount of multifaceted spatial information and their integration.

In this context, the recently born Remote Sensing technology has proved its credentials in precise mapping and monitoring the dynamic changes that are taking place on the Earth’s surface owing to its synoptivity, multi-spectral photo-captivity and repetitivy; whereas the Geospatial technology (GIS) has advanced virtues in storing, manipulating, modeling, visualizing and integrating the huge amount of geospatial databases. Hence, by duly realizing their potentials, the present research study was taken up to develop some newer concepts on Neo–Active tectonic mapping. The topic of Neo–Active tectonic mapping was taken up because it involves the detection and mapping of large amount of geological / hydrological / geophysical anomalies; generation of
geospatial digital maps and the integration of all. In addition, such Neo–Active tectonics which is the index in understanding the seismic vulnerability do not have fool-proof and comprehensive concepts or methods owing to the involvement of such huge geospatial data sets. Again, the natural disasters in general and earthquakes in particular which are crippling the development and sustainability of many nations are beyond scientific prediction; hence, all over the world these disasters are causing greater loss to the man and his properties. Though there may not be any possibilities for predicting the seismicities, but in contrast, the identification of earthquake prone areas will greatly save the humanity and their various developmental programmes, as once these zones are precisely told, the man may not in go for any huge infrastructure developments. If at all any compulsions are there to go in for any developments in such disaster prone zones, the planners will take adequate protection strategies / measures. Analogous to earthquakes, tsunamis, floods, landslide, etc. are also unpredictable. Hence, once such new methodologies imbibing strong S&T are developed, it can be replicated to other areas for Neo–Active tectonic mapping and other similar hazards too.

With this urge in mind, the present study was undertaken for parts of South India, because this region has all along been thought as tectonically stable and inert to younger earth movements and seismicities / earthquakes, as this is a shield area. But at the same time, atleast during the last 200 years, over 250 earthquakes of low to high magnitude (2.5 – 6 in Richter scale) seem to have occurred in this region. Further, in the recent years, not only the frequency of seismicities has increased but their magnitude also appears to be on the rise. On the other hand, the disastrous earthquakes occurred with magnitude of ≥6 since 18th Century at Mahabaleshwar (1764), Jabalpur (1846, 1997), Coimbatore (1900), Koyna (1967), Killari (1993) and Bhuj (2001), in different parts of the Indian Peninsular shield, have given signals to the Geoscientists that the Peninsular India too warrants detailed studies for its seismic vulnerability. So this present study was taken up for the development of concepts / methods in identifying and mapping the Neo–Active tectonic zones by using the high resolution satellite and ground based data sets for culling out the

- Tectonic, riverine and coastal geomorphic anomalies
- Geophysical resistivity anomalies and 3D GIS based visualizations
Groundwater anomalies from the historical groundwater data and visualizing their modifications using GIS

GIS based integration of all these anomalies and detection of Neo–Active tectonic zones and

Visualization of Neo-Active tectonic model and its validation.

In the process of developing newer concepts on Neo-Active tectonic mapping for hard rock terrain using remote sensing and GIS, certain newer findings have also been made on the control of such tectonic movements over the environmental systems of the study area.

1.2 PREVIOUS WORK

Before embarking into this research programme, all the available earlier studies were browsed both in India as well as around the world. While browsing so, special attention was given on how the earlier workers have used lineament anomalies, fluvial and coastal geomorphic anomalies, geophysical anomalies, etc. towards understanding the recent tectonics of their study area.

1.2.1 International

1.2.1.1 Lineament Anomalies and Neo–Active Tectonics

Hobbs (1904) was the first person to coin the word “lineament”. He has studied the lineaments of Atlantic border region and defined such lineaments as rectilinear and curvilinear topographical features and explained that these are the reflections of crustal tectonic features.

Vening Meinze (1947) has interpreted some shear lineaments and attributed them to global stress pattern.

On the basis of the studies carried out in parts of Canadian Shield, Wilson (1948) inferred the lineaments as features associated with epirogenic upliftments.

Kupsh and Wild (1955) have observed that the lineaments of Avonlea area of Baskatchewan as expressions of deep seated faults.
Moody and Hill (1956) have developed a hypothesis of eight directions of wrench faulting and four directions of compressional faulting within a single primary compressive stress of any tectonic regime.

Blanchet (1957) has defined fractures as the generally abundant natural lineation discernible on aerial photographs and explained that these are mostly related to rhythmic action of earth tides and such earth tides cause fracture systems in a systematic pattern.

Haman (1961) has made first time attempt to establish the stress environment responsible for the origin of fold and faults by preparing lineament density and lineament intersection density diagrams.

Again fracture systems of the earth were attributed to the extensional deep tectonics by Badgley (1962).

Gay (1973) has also similarly propounded that mostly the lineaments are related to vertical tectonic forces rather than horizontal movements.

Late Quaternary fault activities were identified through geologic and geomorphic evidences in Tehran, Iran by Pedrami (1981).

Marrs and Raines (1984) have found that the lineaments coincide with facies changes, folds and faults of Powder River basin, Wyoming area and further correlated them with plate tectonics.

Qiang and Zhang (1984) have classified the Quaternary faults of Northern China on the basis of rate of displacement and observed a Positive correlation between seismicities and high aero magnetic fields. In addition, they further observed that the N–S oriented Quaternary active faults generated the moderate to high intensity earthquakes in the area.

On the basis of their studies in parts of east African rift system, Berhe and Rothery (1987) reported that the lineaments control the sedimentation and tectonic evolution.

While evaluating the tectonic evolution of the Fennoscandian – Baltic shield in Denmark, Liboriussen et al (1987) have inferred the curvilinear lineaments to signify Late Cretaceous tectonics.
Rust and Stewart (1996) have attempted to estimate the slip rate along the active faults of southern California and central Greece.

Mueller and Talling (1997) have carried out exhaustive studies in Wheeler ridge of southwestern California. They inferred that the ongoing active tectonics in the form of N–S compression is causing the E–W rise of the Wheeler ridge. In this process, a series of N–S trending tear faults have also formed which act as wind gaps, main water gaps etc.

The evaluation of seismic potentials of the Kahrizak fault, Tehran, Iran by De Martini et al (1998) shows that as a consequence of northerly compressive force, there is an upliftment in hills in E–W direction as revealed by drainage anomalies. Again they observed progressive deformation as a result of NW–SE trending right lateral wrench fault.

Fault scarp cutting the recent alluvium in Sinai Peninsula was attributed to recent tectonic movements (Kusky et al 1998).

The Neotectonic faults were studied in conjunction with seismic scenario of the Eastern Tellian Atlas of Algeria and the studies revealed that mostly the transverse faults appear to be Neotectonically active; also have positive correlation with seismicities (Harbi et al 1999).

Azzaro et al (2000) have carried out trenching along Mt. Etna Volcano in southern Italy and brought out the vertical displacement, slip rate, slip per event of the Moscarello faults during the recent period.

Calamita et al (2000) have carried out correlative studies in between Quaternary faults and seismicity in Umbo – Marachean Apennines of central Italy and found that the NE – SW trending transverse faults of Quaternary age were more prone for seismicities.

From the point of palaeo seismic perspective, Machette (2000) has classified the global faults into active, capable and potentially active faults.

Han et al (2003) have developed certain newer methodologies for mapping the concealed active faults using drainage density in the North China Plain. On that basis, they
have identified a subsurface fault system with NE-SW and NW-SE orientations. They also further found more frequency of earthquakes along such NE-SW faults.

1.2.1.2 Drainage and Fluvial Geomorphic Anomalies and Neo–Active Tectonics

**Bowler and Harford** (1966) analysed the migratory pattern of Murry river, New South Wales and the diversion and preferential migration of rivers to the Late Pleistocene – Holocene upliftments along N–S faults.

**Panizza** (1978) has evolved a technique of identifying active tectonic features from various geomorphic anomalies in general and fluvial geomorphic anomalies in particular.

**Bull and Knuepfer** (1987) have inferred tectonic upliftment in Charwell river basin of New Zealand by using the well defined stream terraces as indicators.

**Reid** (1992) demonstrated the repetitive rise and subsidence of long valley Caldera Dome, California, on the basis of river migration, meandering and drainage avulsion.

**Chen and Stanley** (1995) have brought out the linkages between the Quaternary land subsidence and the related migration of Yangtze river in eastern China.

**Smith et al** (1997) have observed that the Okavango river got split up into four channels when crossing a graben and ultimately rejoined after crossing such graben in Botswana.

**Saintot et al** (1999) have observed the multivariate drainage anomalies in Crimea area to be the indicators of surfacial and sub surfacial active tectonic movements viz: annular, radial and centrifugal drainages indicating the phenomenon of sub surface doming, the rectilinear and deflected drainages suggesting the wrench faulting.

**Harbor** (1998) has brought out certain newer information on the interference between the active tectonic upliftments and the fluvial dynamics of the river Sevier, Utah.

**Matmon et al** (1999) have observed Late Pliocene and Pleistocene drainage reversals and attributed the same to tectonic arching along Galilee, northern Israel and further they inferred that the Pleistocene tectonism arched the Galilee region to 200 m above and over a wave length of 40–60 km.
Kusky and El-baz (2000) inferred the fluvial geomorphology of Sinai Peninsula of northeastern Africa that the most of the drainages have been blocked by the conjugate / shear faults giving rise to palaeo lakes.

On the basis of geological, geomorphological and geophysical data, Maruyama and Lin (2002) have identified the dextral shifting of Pre-Neogene basement rocks to the tune of 16-18 km and Pre-Mio-Pliocene elevated peneplains to the tune of 16–17 km along Arima–Takatsuki Tectonic Line (ATTL) in southwest Japan.

Twidale (2004) has made an exhaustive review on the drainage morphology / pattern and their signatures in understanding the Pleistocene–Holocene tectonic movements. He observed that

- The rivers in central east Australia are mostly controlled by the underlying lineaments / fractures
- The rivers and streams show deflection due to fractures / lineaments and their tectonic activities
- Again that the drainage flow modifications and headward erosions are controlled by tectonic upwarping
- The acute sinuosity in river Murry is directly controlled by the underlying faults.
- The orthogonal, rhomboidal and arcuate pattern observed in rivers and streams in Gawler Ranges, South Australia, is due to the ongoing tectonic movements.
- The rectilinear drainages in Flinders ranges, southern Australia were observed to be due to active faults.

1.2.1.3 Coastal Geomorphic Anomalies and Neo–Active Tectonics

Neev and Friedman (1978) have brought out uplifted Holocene beach terraces in the area between Bardawil Lagoon and Gabel Maghara of the Sinai sub plateau.

Shennan (1989) has brought out possible linkages between the sea level changes and Holocene earth movements by mapping and analyzing the ancient beach ridges in certain coastal part of Great Britain.

Berryman et al (1992) have observed a number of raised marine terraces in eastern north island, New Zealand and inferred it to be due to repetitive seismic activities.
Ota et al (1992) have carried out radiometric dating and morphostratigraphic analysis on the raised coral terraces of Huon Peninsula, Papua New Guinea and attributed such terraces to Late Pleistocene episodic and Holocene coseismic upliftments.

Repetitive Quaternary tectonism was brought out in the marine terraces of Ashizuri Peninsula, southwestern Japan, by Ota and Odagiri (1994).

The beach ridges building phenomenon in northern Gulf of California and Pacific coast of Baja California in USA was observed to be due to tectonics by Meldahl (1995).

Grossman et al (1998) have derived the palaeo sea level records for equatorial Pacific region by dating the beach ridges.

The studies carried out by Brunetti et al (1998) in back-barrier lagoon, Ravenna, Italy revealed that the barrier-lagoon was swollen in the Late Holocene period due to sea level rise of one to two millimeter per year associated with tectonic subsidence too.

Nguyen et al (2000) have brought out possible linkages between the rapid progradation of Mekong river delta during the last 4550 years and the recent tectonic movements and the related sea level changes in southern Vietnam.

Healy and Dean (2000) have developed a methodology for delineating the coastal hazards zones in open duned coast.

Rust and Kershaw (2000) have carried out extensive studies on the marine notches in coastal outcrop of northeastern Italy and brought out evidences for the Holocene upliftment.

Antonioli et al (2003) have brought out a tectonic model between the Holocene sea level changes and Neotectonics for Taromina area of northeastern Sicily.

Kontopoulos and Avramidis (2003) have studied that the Aliki lagoon, southern Gulf of Corinth, Greece has been undergoing changes from 5,000 years B.p onwards (during 4700, 3000, 2500 and 2350±40 years B.p) due to tectonic subsidence induced by the lagoon bottom Egion fault.

Teatini et al (2005) have observed that the lagoons located to the north and south of Venice show average shrinkage of 5 mm per year and at times vary to 10-15 mm per
year due to tectonic upliftment in Alpine foot hills, which is rising at the rate of less than 1 mm per year.

From the raised beaches and the coastal deposits, Late Holocene tectonic history including the upliftment was brought out by Yaltirak et al (2002) for southwestern Marmara sea.

1.2.1.4 Geophysical Anomalies and Neo–Active Tectonics

Turner et al (1982) have analysed the geophysical lineaments in conjunction with satellite derived lineaments and found positive correlation between the both in Northern Sonora of Mexico.

Lidiak (1989) has used geophysical lineaments for the tectonic modeling.

Drury and Walker (1991) have used geophysical images for bringing out the subsurface geology and structure of the Solway basin, England.

Lee et al (1991) have observed the concealed basement structures of eastern England in regional Aeromagnetic imagery.

On the basis of gravity studies and its correlation with borehole data, Cantini et al (2001) have inferred the tectonic activity during the Upper Pliocene–Lower Pleistocene in Lower Arno valley, Italy.

Nakada et al (2002) have used gravity anomaly to bring out the zones of aseismic crustal uplifting during the Late Pleistocene time on the basis of negative anomalies in the eastern part of Kyushu, Japan.

2D electrical resistivity tomography has been used by Caputo et al (2003) to detect and map the Late Quaternary tectonic activity in Tyrrnavos Basin, Greece.

Rizzo et al (2004) have used electrical resistivity tomographic method to identify the Quaternary faults in parts of Apennine chain, southern Italy.

Peters et al (2005) have used shallow geophysics in conjunction with palaeoseismology and structural analysis to identify and map the zones of Neotectonism in Western Border Fault (WBF) in Upper Rhine Graben, Germany.
1.2.1.5 Groundwater Anomalies and Neo–Active Tectonics

The Geoscientists from different parts of the world have observed the anomalous behaviour of groundwater systems due to active tectonics. They have inferred this phenomenon in the tectonic activities of little larger timeframe and also during the earthquakes.

Kafri (1970) has inferred that the active tectonic movements have substantially altered the Cenomanian – Turonian carbonate aquifer of Galilee region.

Similar modifications of groundwater flow due to recently renewed tectonic activities were observed by Kresic (1995) in Dinaric Karst of Balkans area.

Kissin et al (1996), on the basis of their studies in Main Kopetdag fault zone of Turkmenistan demonstrated that the groundwater level fluctuation can be used as precursor for earthquakes.

Similar observations were made on the various aquifer responses and health during both prior and after the 21st September 1999 Chi – Chi earthquake of China (Fu-qiong Huang et al 1999).

Gudmundsson (1999) has observed that the postglacial crustal doming and the related formation of fractures of Norway have substantially changed the groundwater behavior in the area.

In the recent years, in Pingtung plain, Taiwan, SAR interferometry studies were carried out to demonstrate the possible impacts of active tectonic movements over groundwater system (Chang et al 2004).

1.2.2 National

1.2.2.1 Lineament Anomalies and Neo–Active Tectonics

Carey (1958) has analysed the regional lineaments and identified that the Indian plate has rotated in counter clockwise direction during Post Mesozoic era.

Raiverman et al (1966) have prepared the fracture pattern map of Cauvery basin and they observed similarity with tectonics of Deccan traps and doubted for their possible Post Tertiary origin.
Vaidyanadhan (1967) has inferred that the southern Indian Peninsular in general was subjected to epirogenic uplifts since Jurassics.

The concept of rift valley was propounded by Yelur (1968) for the Narmada lineament zone.

Gubin (1969) has postulated a series of peripheral faults in South India through which the Nilgiris, Palani and Anamalai hills have risen and Palghat region has undergone subsidence.

Vaidyanadhan et al (1971) have recorded evidences for the time transgressive and repetitive reactivation of lineaments in southern Peninsular India.

Rubke (1974) has brought out a first time detailed picture on Lesser Himalaya and the Neo–Active faults too.

Srinivasan (1974) has interpreted an E–W graben in Attur valley and attributed its origin to ongoing N–S compressions.

The publications by NGRI (Anon 1975 and Anon 1978) have brought out significant information that the seismicities in Indian Peninsula are mostly related to transverse fault movements.

On the basis of the coincidences between the geothermal springs and lineaments, Guha (1977) has observed a number of active faults in Bihar and West Bengal.

Das and Ray (1977) interpreted the lineaments of entire Deccan traps of Maharashtra and part of Madhyapradesh and found that these are related to post Trappean tectonics.

Vemban et al (1977) have identified that many faults in Tamil Nadu are active and seismogenic.

On the basis of their studies in Gondwana basins, Ahmed and Ahmed (1977) have identified the regional faults in Peninsular India to be formed due to anticlockwise rotation of Indian plate.
Ahmed and Ahmed (1980) have again presented a picture on the Late Mesozoic faults with an over all fan shape in Arabian sea. They further observed that these fan faults are progressively younging towards north.

Powar and Patil (1980) on the basis of the Landsat imagery lineaments concluded that the Deccan volcanics has undergone a N–S compression and E–W cymatogenic arching.

Suryanarayan (1982) has brought out the Neotectonic picture of Dun valley from lineaments derived from satellite images and Aerial photographs.

Peshwa (1983), on the basis of the Landsat imagery interpretation in Koyna area, observed that most of the lineaments reflect the Neotectonic pulses along them.

Drury (1984) has interpreted the E–W, NNW–SSE and NNE–SSW trending dyke systems in parts of Tamil Nadu and from the same he has visualized the Crustal doming.

Bakliwal and Ramasamy (1987) have brought out the regional frame work of all the lineament systems for entire Rajasthan and Gujarat on 1:5,00,000 scale and inferred that the ENE–WSW lineaments are tectonically active; they have concluded so, on the basis of their coincidence with seismicities and geothermal springs.

Ghosh and Singh (1988) have attributed that the structures and geomorphic anomalies of the northwestern part of the Indo-Gangetic plains to the northward tilting of Bundelkhand region due to the reactivation of Narmada lineament.

Choudhary and Srivastava (1989) have propounded a hypothesis that the overturning in Assam Himalayas are due to northerly movement of Indian plate.

Thakur (1989) has inferred that the lineaments of Himalayan region in general reflect the Neo–Active tectonic movements and hence seismogenic.

On the basis of the coincidence between the earthquake occurred 30° due north of Trivandrum and NE–SW to ENE–WSW trending lineaments, Singh and Venkatesh Raghavan (1989) have observed that this is because of the reactivation of these lineaments in the area.
Nair (1990) has prepared detailed structural trendline and lineament maps for the entire Western Ghats of Kerala and observed that most of the NNW–SSE lineaments are related to Indian Plate movement.

The most of the fracture systems in southern Gujarat were attributed to the northeasterly movement of the Indian plate by Alavi and Merh (1991).

Ranadhir Mukhopadhyay and Khadge (1992) have identified ENE–WSW trending major depressions in central Indian Ocean basin to Post Cretaceous tectonics.

Ramasamy (1995a) have analyzed the lineaments in the Deccan volcanics of southern Saurashtra and from the same he identified a series of E–W to ENE–WSW oriented horsts and grabens and attributed to post collision tectonic of India.

The recent Jabalpur earthquake of May 22, 1997 was reported to be related to ENE–WSW faults (Gupta et al 1997).

Valdiya (2001) has observed a series of peripheral faults in South India, from which he inferred that the Nilgiris, Palani and Anamalai hills have risen and Palghat region has undergone a subsidence.

1.2.2.2 Drainage and Fluvial Geomorphic Anomalies and Neo–Active Tectonics

The anomalous compressed meandering observed in river Yamuna in Agra region was explained to be due to on going active tectonics of Great Boundary Fault and the related ENE–WSW spectrum of lineaments by Bakliwal and Sharma (1980).

Yashpal et al (1980), on the basis of remote sensing and archaeological data, have brought out a vast spread of palaeochannels in Gaggar basin of northwestern Rajasthan and demonstrated them to be the traces of Lost Sarasvati river.

The rectilinear pattern and regional deflections of river Brahmaputra were attributed to fault systems of NE–SW, NW–SE, E–W and N–S orientations by Murthy and Sastri (1981).

Barooah and Bhattacharya (1989) have demonstrated that the Brahmaputra valley has a number of horst and graben structures of Quaternary period.
Suryanarayan and Prabhakar Rao (1981) have observed drainage reversals in northern Tamil Nadu along N–S lineaments and suspected a tectonic wedging along N–S trending lineaments.

Prasannakumar and Mathai (1982) have doubted for possible tectonic movements along Bhavani lineament on the basis of certain changes in Bhavani river near Mukali area.

Rajaguru and Kale (1985) have observed five phases of fluvial activity since Middle Pleistocene in the upper parts of Krishna, Bhima and Godavari rivers of western Maharashtra.

Ramasamy et al (1987) have observed the northerly migration of Swamamuki river in the north and southerly migration of Palar river in the south to a probable E–W land arching in Chennai area.

On the basis of drainage anomalies in Luni - Jawai plains of Rajasthan, Amalkar (1988) has inferred Neotectonic activities along NE–SW lineaments / faults.

Ganapathy and Merh (1989) have observed various fluvial anomalies in Shetumj river in Saurashtra Peninsula and attributed them to the sea level changes and the compressed meanders to tectonism.

Philip et al (1989) have analysed the hierarchical changes in the courses of Ganga and Barhigandak rivers in middle Ganga basin and attributed the same to the ongoing tectonic movements.

The entrenchment of river Tawi and deep gorges at the exit of river Tawi in Jammu and Kashmir was explained to be the effect of Late Pleistocene tectonic activity by Ganjoo (1990).

Narasimhan (1990) has observed clockwise rotational migration of river Palar and explained it to be due to possible doming in parts of northern Tamil Nadu.

Ramasamy et al (1991) have analyzed the lineaments of entire western India in conjunction with migratory pattern of many western Indian rivers and brought out a number of active faults.
Radhakrishna (1992) has identified extensive rejuvenation of river Cauvery near Sivasamudram area (south of Bangalore) and inferred N–S trending cymatogenic arching in the area.

Pant et al (1992) have observed recent sinistral and dextral strike-slip movements along NNW–SSE trending Kaphlikot-Ramari and Ghatia Gad faults from drainage deflection and dextral shifting of colluvial fill of Badiyakot landslide in the Loharkhet area, Kumaun Himalaya.

Vaidyanadhan and Ghosh (1993) have observed anomalies in the rivers of Andhra Pradesh and brought out Neotectonic scenario of the area.

Harbor et al (1994) have brought out active tectonic windows from the fluvial anomalies of Indus river.

Ramasamy and Balaji (1995) have observed phenomenal preferential and anomalous migration of Palar, Ponnaiyar, Cauvery, Vaigai and many rivers in Tamil Nadu and attributed the same to the Pleistocene arching and complementary deepening with E–W orientation.

Singh et al (1996) have identified active tectonism with sinistral movements along NNE–SSW lineaments and dextral movements along NW–SE lineaments from the varied riverine anomalies in Indo-Gangetic plains. From the above they resolved the northerly compressive force related to the post collision tectonics.

Ramasamy and Karthikayan (1998) have interpreted a Holocene graben in between Pondicherry in the northeast and Kambam valley region in the southwest in Tamil Nadu on the basis of varied fluvial geomorphic anomalies.

Valdiya (1998) has observed various drainage anomalies in Bangalore peneplains and on the basis of that he has interpreted a number of Holocene uplifted faults to the tune of 300 – 400 m.

Ramasamy and Ramesh (1999) have inferred possible sinistral strike slip movements along the NE–SW fault during 1930–1992 AD on the basis of modifications of eyed drainage in river Coleroon in the area east of Tiruchirappalli.
Rachna Raj et al (1999) have studied the ravines in the Lower Mahi valley, Gujarat and from the fluvial anomalies they doubted for pulsatory tectonism during the Pleistocene period.


Ramasamy and Kumanan (2000) have demonstrated land subsidence in Tiruchirappalli area on the basis of mega eyed drainage in river Cauvery.

Sinha-Roy (2001) has visualized many NW–SE and NE–SW faults bounded horst and graben structures in Banas river basin in Rajasthan on the basis of longitudinal river profile morphology.

Valdiya (2001) has observed that the N–S tectonically active faults have blocked many river systems in upper reaches in Cauvery river and created ponded streams.

Valdiya and Kotlia (2001) have observed a lot of fluvial geomorphic evidences like dismemberment and dislocation of Late Quaternary fluvial terraces, lacustrine flats and colluvial cones, ponding of streams, etc. and attributed them to Late Quaternary tectonic movements or reactivation in Kumaun Lesser Himalaya region.

Rachna Raj et al (2003) have observed active tectonism along ENE–WSW and NNE–SSW faults on the basis of varying drainage anomalies in Karjan river basin of Lower Narmada valley in western India.

Jain and Sinha (2005) have identified a number of fluvial geomorphic anomalies like compressed meandering, knick points in longitudinal profiles, channel incision, anomalous variations in sinuosity, sudden change in river flow direction, river flow against local gradient and related flooding in adjacent areas, water logging, etc. in Baghmati river, north Bihār plains, eastern India and attributed all to active block faulting.

Ramasamy et al (2006b) have carried out regional interpretation of drainage anomalies viz: deflected drainages, eyed drainages and anomalous compressed meanders in parts of South India and from the same identified the active faults with vertical and transverse tectonic movements.
Ramasamy (2006b) has carried out remote sensing based interpretation of all the deltas of Tamil Nadu viz: Proto Palar, Palar, Ponnaiyar, Cauvery, Manimuttar and Vaigai rivers and identified the perceptible preferential migration in these rivers in their deltaic regimes, and therefrom he has brought out tectonic arching and subsidence, block faulting and transverse fault movements in the Middle–Late Holocene period.

Ramasamy et al (2006c) while interpreting the palaeochannels in Cauvery delta of Tamil Nadu, observed northerly rotational migration of river Cauvery and attributed the same to the ongoing upliftment of Pattukottai–Mannargudi Mio–Pliocene Sandstone in the south atleast since last 6000 years onwards.

1.2.2.3 Coastal Geomorphic Anomalies and Neo–Active Tectonics

Stoddart and Pillai (1972) have observed the upliftment of coral beds in Ramanathapuram – Rameswaram area, southeastern fringe of Tamil Nadu coast and explained it to be due to tectonic upliftment.

Lates Holocene tectonics and the associated sea level fall were inferred from the radiocarbon dating of raised beaches in Saurashtra coast by Gupta (1972)

Babu (1978) has observed evidences of coastal upliftments in parts of Cauvery Basin of Tamil Nadu on the basis of raised coral reefs, river terraces and beach ridges.

Again Prasad (1978) has made similar observations of shell beds in higher elevation in Portonovo / Cuddalore and explained them to be due to Neogene and post Neogene upliftment of east coast of Tamil Nadu.

Nair and Subramanian (1989) have observed a spectrum of ENE–WSW trending Neotectonic faults in Kerala coast on the basis of the anomalies in tidal flats, estuaries, backwaters, etc. and attributed them to the tectonism in Carlsberg ridge.

Ramasamy (1989), while bringing out the morphotectonic evolution of the east and west coasts of South India, observed some conspicuous mega geomorphic anomalies viz: convexities in the coasts and restricted marine regression along Chennai and Ramanathapuram parts of east coast of Tamil Nadu and doubted possible ongoing land arching in these sectors.
Babu (1991) has studied the evolutionary history of Cauvery delta and observed four major tectonic stages namely the rift-graben stage, cratonic basin stage, shelf stage and progradational stage.

Ramasamy (1991) has mapped and classified the Tamil Nadu deltas into lobate, arcuate, cuspatate, digitate and estuarine deltas and observed that these different deltas symbolize the land-ocean interactive processes along Tamil Nadu coast tutored by tectonic changes.

Subrahmanya (1994) has attributed sea level fall of 1.95 to 3.22 mm per year in Mangalore coast due to recent tectonic upliftment.

Vaz and Banerjee (1997) observed variations in sea level changes and desiccation in the sediment cycles almost since 6650 years B.p in Pulicat lake. However, in addition to estimating the sediment accumulation to the rate of less than 1 mm per year along the western half and 2.5 mm per year in its eastern margin of Pulicat lake region, they also observed evidences for marine regressions.

Ramasamy et al (1998b) have observed phenomenal land progradation to the tune of 58 km during the last 6085 years in Vedaranniyam coast of southeastern Tamil Nadu and heavy siltation in Vedaranniyam backwater and explained them to be due to ongoing tectonic upliftment of Pattukottai – Mannargudi Mio – Pliocene Sandstone in the area west of Vedaranniyam.

Rachna Raj et al (1999), on the basis of heavy sediment discharge in Mahi river, doubted for tectonic upliftment in parts of Gujarat.

Philip and Mazari (2000) have observed frequent variations in the aerial extent of the ancient lake falling in Indus suture zone of northwestern Himalaya and visualized ongoing tectonic compression in such collision zone.

Banerjee et al (2001), while evaluating the seismic risk of the Indian Peninsular coast, classified the coast into three as Type – I (stable coast), Type – II (Coastal tracks, where faults are active) and Type – III (Coast prone for seismic input) and they observed that the Pulicat lake area fall in Type – II. They have further identified such active faults
from the Pleistocene weathered cover, hot springs, leakages of native mercury and allochthonous geochemical anomalies of base metals, etc.

**Anbarasu and Rajamanickam** (2002) have brought out zones of cymatogenic down warping and river migration pattern along Pondicherry coast due to Neotectonic activity during Quaternary.

Whereas **Ramasamy** (2006a) has observed concavity in Manamelkudi coast and promontories and projections in Ramanathapuram coast and explained them respectively to be due to tectonic subsidence and emergence.

1.2.2.4 Geophysical Anomalies and Neo-Active Tectonics

**Qureshy** (1964), on the basis of various geophysical anomalies, brought out a number of peripheral faults in parts of Tamil Nadu and inferred that the northern Nilgiri massif and the southern Anamalai and Palani hill region of Western Ghat are uplifted with intervening subsidence along Palghat.

**Kailasam** (1975), on the basis of integrated geophysical surveys, has observed that the southern part of the Indian Peninsula was constantly subjected to vertical epirogenic movements from Late Proterozoic to present day.

**Kailasam et al** (1976) have brought out the possible linkages between the water percolation from the Koyna reservoir and their movements along the deep seated faults on the basis of deep electrical resistivity sounding in Deccan trap region.

Tectonic features of Cauvery basin was brought out by **Balakrishnan and Sharma** (1981) using Bouguer gravity anomaly map.

On the basis of the series of gravity highs and lows along Narmada valley, **Qureshy** (1981) has observed pulsatory tensional and distensional forces.

**Reddy and Ramakrishna** (1981) have identified the geophysical anomalies related to recent tectonic movements in parts of Great Indian Desert.

**Qureshy** (1982) has utilized the regional gravity and magnetic map of India to bring out the tectonic framework of the Indian subcontinent. The framework was well
correlating with surfacial lineaments deciphered from Landsat data. Further he also deciphered zones of tectonic rejuvenation from gravity and magnetic anomalies.

Ramachandran (1987), on the basis of lineaments interpreted from Landsat, Aeromagnetic, Bouger gravity and ground geological data, identified basement ridges in Pattukottai – Mannargudi, Pondicherry – Cuddalore and Thanjavur areas and depression in Ramanathapuram–Palghat region.

The crustal structures of Tamil Nadu brought out by Reddy et al (1988) on the basis of aeromagnetic data, have shown increase in crustal thickness towards north and northwest.

Singh et al (2001) have carried out resistivity sounding in the epicentral region of Bhuj earthquake of 26 January 2001 and inferred a low resistivity layer especially in the liquefaction sites and further they observed that along this site most of the houses were sunk, whereas elsewhere the damage pattern was totally different.

Anand et al (2002), on the basis of ground magnetic survey, identified the coastal structures in Mahanadi delta.

Balaji and Ramasamy (2005) have developed a new technique of creating GIS images from the resistivity data of various depths from ground level for the interpretation of basement folds and faults.

1.2.2.5 Groundwater Anomalies and Neo–Active Tectonics

In India too, the studies have been done on the general tectonics and the groundwater behaviours and in some areas, active tectonics and their impact over groundwater systems.

Usha et al (1989), on the basis of thematic correlations, inferred that the faults / fractures perpendicular to the fold axis are better groundwater prospects when compared to conjugate ones.

Ramasamy and Balaji (1993) have classified the lineaments of Tamil Nadu into Precambrian, Precambrian reactivation in Pleistocene and exclusive Pleistocene and observed that the exclusive Pleistocene lineaments have better groundwater prospects.
Again by analyzing the various azimuthal frequency of lineaments, Ramasamy et al. (2001) inferred that the groundwater behaviours are substantially modified by the Pleistocene faults of Tamil Nadu.

1.3 JUSTIFICATION OF THE PRESENT STUDY

The browsing of the earlier works carried out broadly around the world and also in different parts of the Indian subcontinent showed that the different scientists have followed different techniques to identify and map the areas of Neo-Active tectonics. Some workers have confined their studies to lineament anomalies, some on the anomalies displayed by rivers and streams, some on the geophysical signatures and so on. Even while applying Remote Sensing technology that has advanced credentials in explicitly showing the areas of such tectonic activities, again only stand alone approaches seem to have been made either on structural anomalies or geomorphic anomalies, etc. But, it is very important to interpret and analyse all the possible signatures / anomalies so that such zones of active tectonics can be brought out fairly to a reasonable precision. At the same time, the study of detecting and mapping the Neo–Active tectonics has become very important in the context of the fast recurring earthquakes and further earthquake induced Tsunami’s around the world as well as in India.

So taking advantages of the credentials of Remote Sensing technology in mapping various anomalies and the unique virtues of GIS technology in coding, manipulating, modeling and visualizing a large amount of geospatial data, the present research study was undertaken. In the present study it was envisaged to interpret all possible tectonic and geomorphic anomalies from the remotely sensed data and create geospatial databases, generate 3D visualized GIS images on resistivity and groundwater and finally integrate all again using GIS to finally bring out a fair picture on Neo–Active tectonics. Basically, this study is aimed at developing a methodology for Neo–Active tectonic mapping which is the potential baseline data in seismic hazard zonation mapping.

For this purpose of developing concepts / methodologies for Neo–Active tectonic mapping, the southern part of the Peninsular India falling in parts of Tamil Nadu and adjacent areas was identified as it is basically a hard rock area, exposing crystalline rocks of Arachaceozoic–Proterozoic period. So once this concept is established in such a hard
rock terrain, where it is fairly difficult to cull out signatures related to Neo–Active tectonics, it can be extended to any part.

1.4 ABOUT THE STUDY AREA

For the purpose of present concept based research study, the area falling in between Chennai in the east and Bangarapet in the west (Karnataka) was selected (Fig.1.1).

1.4.1 Location and Accessibility

In the study area, falling in between Chennai in the east and Bangarapet in the west, five study sectors were identified such as

- Sector – I and II covering respectively 10,600 sq km (95.5 x 111 km) and 3,900 sq km (27.85 x 140) area for studying both lineaments and drainage and fluvial geomorphic anomalies
- Sector – III covering 3,250 sq km (162.5 x 20 km) area for studying the coastal geomorphic anomalies
- Sector – IV covering 40,000 sq km area enveloping all the sectors (I, II, III & V) and some additional area in the south, for studying the resistivity anomalies and
- Sector – V covering 12,210 sq km (110 x 111 km) area to evaluate the groundwater anomalies (Fig.1.1).

The overall study area is bounded by north latitudes of 11° 30'00" and 14°00'00" and east longitudes of 78°00'00" and 80°30'00". This area, as is located close to Chennai Metropolis and also falling south of Chennai–Bangalore Main Trunk road, the study sectors can be easily approached by road and train.

1.4.2 Lithology

Geologically, the study area is covered predominantly by hard crystalline rocks belonging to Precambrian in the central and western parts and the Cretaceous, Tertiary, Pleistocene (Laterite) and recent alluvium are exposed in the eastern parts as shown in Fig.1.2 (Anon 1972 and 2000).

While the Charnockites of the Precambrians form high order hill ranges, the Granites and Gneisses belonging to again Precambrians form the vast Pediplain called as Peninsular Gneissic Complex (PGC). Again in the eastern fringe, while the Cretaceous rocks form pediment surfaces, the Mio-Pliocene formation (Cuddalore Sandstone) forms
Fig. 1: Study area

- Sector □□□□ Studied for Lineaments & Geomorphic Anomalies
- Sector □□□□ Studied for Coastal Geomorphic Anomalies
- Sector □□□□ Studied for Geophysical Resistivity and Seismic Anomalies
- Sector □□□□ Studied for Groundwater Anomalies
Fig. 1.2 - Lithology map of the study area
marginally raised uplands. Further, Laterite of Pleistocene age forms a marginally hard and compact rock either forming rocky pediments or gravelly horizons and the recent alluvium are mostly sands, silts and clays related to fluvial activities.

1.4.3 Structure and Tectonics

The regional structure and tectonics of the study area have been studied by many (Narayanaswami 1959&1966, Grady 1971, Borodin et al, 1971, Srinivasan 1974, Rao 1977, Sugavanam et al 1977, Vemban et al 1977, Katz 1978, Drury 1984, Ahmed et al 1986, Ramachandran 1987, Ramakrishnan 1988, Ramasamy et al 1999, Ghosh et al 2004 and many others from Geological Survey of India too). While most of the workers have concentrated generally on structure and metamorphism, the structure and tectonics were attempted specifically to bring out the evolution of fold belts by Sugavanam et al (1977) and Ramasamy et al (1999). Sugavanam et al (1977) have observed that the fold belts of South India have evolved through more than five episodes of deformation. But Ramasamy et al (1999) have analysed the structural trendline pattern and lineaments interpreted from IRS-1B satellite imagery for entire South India falling in parts of Mangalore–Chennai–Cape Comorin triangle and brought out three well defined fold belts in South India namely Chitradurga fold belt in the north, Mangalore – Ootacamund – Bangalore fold belt in the centre and Cochin–Cape Comorin–Madurai–Tiruchirappalli–Salem fold belt in the south (Fig.1.3). They have observed that these three fold belts contain domes, basins, anticlines and synclines within them and all the three fold belts have their axis of refolding in NNW – SSE direction. From the same, Ramasamy et al (1999) have inferred that the fold belts of South India were formed by two episodes of deformation with the first N–S compression causing chains of E–W folds and the second ENE–WSW violent compression refolding the F1 (E–W) fold into NNW–SSE oriented major three fold belts with NNW–SSE regional fold axis. Ramasamy et al (1999) have further observed that the second deformation was more penetrative and caused lineaments with three major azimuthal frequencies viz:

1. ENE–WSW extensional fractures
2. NE–SW dextral and NW–SE sinistral strike slip faults and
3. NNW–SSE release fractures.
Fig. 1.3 - Fold belts of South India
Earlier, Ramasamy and Balaji (1995), on the basis of various regional geomorphic anomalies observed in satellite data, classified the lineaments of South India into four azimuthal groups of probable Pleistocene origin or reactivation viz:

- N–S extensional / block faults
- NE–SW sinistral and
- NW–SE dextral strike slip faults and
- E–W release fractures filled with dyke swarms.

Under this tectonic frame work, the study area falls in the eastern limb of the Cochin–Cape Comorin–Madurai–Tiruchirappalli–Salem fold belt (Fig.1.3).

1.4.4 Physiography and Geomorphology

By interpreting the IRS-1B FCC satellite imagery, the geomorphology map was prepared for the overall study area (Fig.1.4) and the same shows that the Precambrian rocks (Predominantly Charnockite) form the higher order structural hills in the western part of the study area and these only form the outer most eastern limb of the Cochin–Cape Comorin–Madurai–Salem fold belt. On the contrary, the Precambrian gneisses form the vast pediplain / pediment-inselberg complexes. While the Mio–Pliocene Sandstone and the Laterite form the rolling upland along the east coast, the Pleistocene sediments are of colluvial fills, alluvial plains and deltaic plains of Ponnaiyar, Palar and Proto Palar river system. The Pleistocene sediments form the coastal plains comprising backwaters, creeks, beach ridge complexes etc. The river systems which are responsible for the fluvial landforms (colluvial fills, flood plains, alluvial plains and deltaic plains) are Palar river in the north and Ponnaiyar river in the south, as far as the study area is concerned.

The major palaeochannel seen branching off from river Palar from west of Kanchipuram / Walajapet in the south to north of Chennai in the north indicates that the river Palar has earlier flowed northeasterly along Walajapet – Chennai.

Foote (1873) was the first person to visualize a major old river system in this area. Vaidyanadhan (1971) and Ramasamy et al (1992) have subsequently made detailed interferences that the river Cauvery earlier has flowed along this tract and subsequently migrated towards southerly to flow along Tiruchirappalli–Thanjavur plains; hence they
Legend
- Structural hills
- Residual hills
- Pediplain / Pediment inselberg complex
- Colluvial fill
- Mio-Pliocene Sandstone / Lateritic uplands
- Flood plains
- Backwater
- Alluvial plains
- Deltaic plains
- Coastal plains
- Beach ridges
- Palaeochannels

Fig.1.4 - Geomorphology of the study area
called this palaeochannel as “Proto Cauvery” and the deltas found west of Chennai as “Proto Cauvery deltas”. But in contrast, Thirunaranan (1938) earlier and Narasimhan (1990) recently have referred that this Palaeochannel found branching off from river Palar at Walajapet as Palar’s old course and called it as “Proto Palar”. However, in the present study, it is referred to as “Proto Palar” only as the present study is concerned more with river migration as an anomaly and not its parentage.

The Cheyyar, a tributary of river Palar, flows rectilinearly and meets the parent river Palar in the area east of Kanchipuram.

The Ponnaiyar river which is another major river in the study area flows easterly and again in its deltaic regime it has vividly developed bundles of palaeochannels only to the northern part of its present course indicating the preferential southerly migration.

In the Proto Palar and the Palar drainage system, the rivers like Araniar, Nagari, Korttalaiyar, Cooum and Adyar are flowing as misfit streams. By and large, the Charnockitic hills are forming higher order mountains in the west central part whereas rest of the eastern plain of the study area is a smooth easterly gradient one facilitating the birth and well evolved growth of the above river systems.

1.5 AIMS AND OBJECTIVES

Under such scenario that:

➔ All the earlier studies have mostly restricted to one or two anomalies to map Neo–Active tectonics,

➔ The Remote Sensing, while has greater potentials in revealing various geological and geomorphological anomalies, the GIS technology has enormous virtues to amalgamate and visualize various Earth system dynamics related phenomena,

➔ The Peninsular India has become more prone for earthquakes and

➔ No clear methodology has been developed so far for Neo–Active tectonic mapping which can give excellent baseline information on seismic vulnerability of a region,

the present research study was taken up. And in addition, as the preliminary observations made in the area indicated the possible linkage between recent tectonic movements and the environmental systems, a new first time attempt was also made on this aspect too.
Hence the main aims of study are

(1) To develop concepts / methodologies for Neo–Active tectonic mapping
   - using all possible anomalies viz: tectonic, fluvial and coastal geomorphological, geophysical, groundwater anomalies, etc. with the help of Remote Sensing and GIS

(2) To develop a possible Neo–Active tectonic model for the study area and validate it

(3) To carve out a suitable methodology for Neo–Active tectonic mapping and

(4) To evaluate the linkages between such Neo–Active tectonics and the environmental systems of the area, as the preliminary observations have shown some signals in this direction.

1.6 METHODOLOGY IN BRIEF

The methodology adopted in the present research is shown in the form of flow chart in Fig. 1.5. In the study IRS-1B four band raw and digitally processed data of 1992 were used extensively for detecting and mapping the tectonic and geomorphic (fluvial and coastal) anomalies. IRS data (Band 1 with 0.45 – 0.52 μm, Band 2 with 0.52 – 0.59 μm, Band 3 with 0.62 – 0.68 μm and Band 4 with 0.77 – 0.86 μm) were firstly analysed as raw bands, then by density sliced modes (in which the dynamic range of spectral reflectance values were classified equally and given different colours), False Colour Composite (in which band 2, 3, 4 were respectively exposed in blue, green and red filters and a combined image was generated), ratioed images \((1/2, 1/3, 1/4, 2/3, 2/4 \text{ and } 3/4 – \text{ratioing of spectral reflectance values})\), etc. Such various types of processed out puts were generated from IRS data using ENVI Image Processing software.

The possible anomalies used by many workers around the world as well as in India for Neo–Active tectonic and seismic zonation mapping in respect of tectonic, fluvial and coastal geomorphic, geophysical and groundwater anomalies were cataloged. The anomalies observed by the earlier workers in parts of South India were also taken into account. In addition, a lot of newer anomalies and a number of newer GIS based visualization techniques were used in the present study to identify newer and characteristic anomalies which can signal such Neo–Active tectonic zones.

By duly interpreting such raw and digitally enhanced IRS-1B satellite images, the lineament map was prepared for the study area and from the same, various anomalies such
Methodology

Neo - Active tectonic mapping

Detection of anomalies

- Tectonic anomalies
- Drainage and fluvial geomorphic anomalies
- Coastal geomorphic anomalies
- Geophysical anomalies
- Groundwater anomalies

Data integration and detection of zones of Neo-Active tectonics and model building

Model Validation through gravity and historical seismicity data

Impact of Neo - Active tectonics over the environment

Fig.1.5 - Methodology
as fracture swarms, curvilinear lineaments, branch off lineaments, radial lineaments, etc., were interpreted and probable zones of Neo–Active tectonics were deduced therefrom.

In the same way, various drainage / fluvial and coastal geomorphic anomalies were interpreted such as radial drainages, palaeochannels, deflected drainages, compressed meanders, eyed drainages, etc. and the anomalies seen in deltas, backwaters, creeks, beach ridges, etc. All such anomalies were amalgamated together using GIS and areas of tectonic weak zones were identified as far as fluvial and coastal systems are concerned.

The geophysical resistivity data were collected for 1100 locations for the study area and 3D GIS images were generated for multiple depths viz. 25, 50, 75 and 100 m and anomalous zones were picked up. Groundwater level data were collected from 61 numbers of wells for the years of 1975, 1980, 1985, 1990 and 1995 and independent 3D GIS images were generated using ArcGIS software, anomalies were interpreted and finally all were integrated together to identify probable tectonic weak zones from resistivity and groundwater hydrology points of view.

All these anomalies picked up from lineaments, fluvial and coastal geomorphology, geophysical resistivity and groundwater were integrated using Arc-GIS and zones of coincidence were identified as probable zones of Neo–Active tectonics in the study area.

In addition to building up the concept for Neo – Active tectonic mapping, the Neo–Active tectonic model brought out for the study area was also validated with the help of historical seismicities and gravity data.

At the next stage, impacts/contributions of Neo–Active tectonics over the environmental systems were analyzed such as

- Soil erosion,
- Reservoir Siltation,
- Sediment dumping in to the Ocean,
- Shrinkage of backwaters,
- Modifications in creeks,
- Aquifer leakage into ocean, etc.
and the significances of such Neo-Active tectonics over environmental systems were also brought out under the caption of “Environmental Tectonics”.

1.7 SYNTHESIS

The fast recurring seismicities all over the world have started causing greater concern to the scientists and planners as well. Even in the southern part of the Indian Peninsula (Present study area), which has all along been thought as tectonically inert and seismically safe, a large number of seismicities numbering to the tune of 250 (more than 2.5 in magnitude) have occurred during the last 200 years or so. In addition, many disastrous earthquakes have also started occurring in many parts of Peninsular India. Hence it has become very much important to understand the seismic vulnerability of the region, so that possible mitigation strategies can be evolved. At the same time, globally and in India too, a lot of studies have been conducted and these studies seem to have used either tectonic or geomorphic or geophysical or instruments based mapping and hence these earlier methods seem to have some imperfections. Further, the newer technologies like Remote Sensing and GIS and the advanced credentials of GIS visualizations and integration have not been done in the past.

Hence, the present study has been undertaken by taking a number of test site / sectors in northern Tamil Nadu and all the possible anomalies were studied to evolve precise concepts / methodology for Neo–Active tectonic mapping.